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COST, SCHEDULE, AND PERFORMANCE TRADEOFFS IN THE ACQUISITION OF MAJOR WEAPON SYSTEMS

by

Jeffrey D. Voltz

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Thesis Advisor: Dan C. Boger

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In the current period of fiscal restraint, the acquisition of weapon systems has come under ever increasing scrutiny. Costs of these systems are influenced by performance characteristics of the system and schedule demands placed on the acquisition process. The objective of this thesis is to investigate previous research performed in the area of cost, schedule, and performance tradeoffs in the acquisition of major weapon systems. Results of the literature review indicate that several cost-schedule-performance models have been performed in two areas: aircraft airframes and aircraft turbine engines. Those models are compiled and explained. Methodological problems associated with tradeoff studies of this type are discussed. An annotated bibliography of relevant source documents is also provided.

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22a. NAME OF RESPONSIBLE INDIVIDUAL
Dan C. Boger

22b. TELEPHONE *(Include Area code)*
(408) 646-2607

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Jeffrey D. Voltz
Lieutenant, United States Navy
B.S., University of Delaware, 1983

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Author: ______________________________
Jeffrey D. Voltz

Approved by: ______________________________
Dan C. Boger, Principal Advisor

____
Michael G. Sovereign, Associate Advisor

____
David R. Whipple, Chairman
Department of Administrative Sciences

ABSTRACT

In the current period of fiscal restraint, the acquisition of weapon systems has come under ever increasing scrutiny. Costs of these systems are influenced by performance characteristics of the system and schedule demands placed on the acquisition process. The objective of this thesis is to investigate previous research performed in the area of cost, schedule, and performance tradeoffs in the acquisition of major weapon systems.

Results of the literature review indicate that several cost-schedule-performance models have been performed in two areas: aircraft airframes and aircraft turbine engines. Those models are compiled and explained. Methodological problems associated with tradeoff studies of this type are discussed. An annotated bibliography of relevant source documents is also provided.

TABLE OF CONTENTS

I. INTRODUCTION

In the current period of fiscal restraint, the acquisition of weapon systems has come under ever increasing scrutiny. Costs of these systems are influenced by performance characteristics of the system and schedule demands placed on the acquisition process. This thesis will review how the acquisition community can trade *off performance for cost* and trade off schedule for cost so as to stay within the binding budget constraints that will exist for procurement of major weapon systems.

The primary focus of this thesis is to conduct a literature review of studies and models which have been performed in the past and to relate those to current and future acquisitions. Specifically, this thesis attempts to investigate how the defense acquisition community can better use these studies to make more informed decisions regarding the potential costs of particular tradeoff options.

A. BACKGROUND

The changing military threat to the United States and increased attention to domestic issues have brought the Department of Defense budget under considerable pressure. Reductions in the budget of twenty-five percent by fiscal year 1995 are a certainty, and it is all but certain that further reductions will be imposed. This declining budget environment forces the Department of Defense, and particularly the acquisition community, to make decisions on weapon systems which will have lasting impact on both future budgets and future capabilities. The President has highlighted this fact with the announcement in his 1992 State of the Union address that:

- The B-2 program will be terminated at 20 aircraft.
- The Small ICBM program will be canceled entirely.
- Production of the W-88 warhead for Trident II SLBMs will be terminated.
- Purchases of the Advanced Cruise Missile beyond those already authorized will cease. (Cheney, 1992, p. 20)

These cuts are in addition to the over one hundred weapon system program terminations which have occurred in the last two years. The cuts taken together amount to a $50 billion savings in fiscal years 1993 through 1997. (Cheney, 1992, p.33) Unfortunately, decreasing or canceling procurements will, over the long term, lead to what Chairman of the Joint Chiefs, General Powell, called a "hollow force." It is for this reason that the Secretary of Defense stated before the House Budget Committee that:

> The military technological revolution will continue to pose challenges to our forces both to keep up with competing technologies and to get the greatest potential from the systems we have; and, that a continued and substantial research and development effort...will be required to maintain our advantage. (Cheney, 1992, p. 17)

Given that continued monies must be spent on new weapon systems, the question then becomes how best to spend those monies and what can be gained or lost by trading off schedule considerations and performance parameters against limited budgets.

B. OBJECTIVE

The relationship between cost, schedule, and performance parameters for a given weapon system is a complicated one. Generally speaking, cost and schedule and cost and performance are directly linked while the schedule versus performance parameters are indirectly linked through cost. One can easily conceptualize the link between cost as the dependent variable and schedule as the independent variable if the performance parameters are held constant. In this situation, as schedule increases, overhead costs over the longer schedule will tend to drive costs up. Alternatively, if the schedule is compressed, more work will have to be accomplished in less time and again it is likely that the costs will increase. When the schedule is held constant, achieving "better" performance will undoubtedly cost more. These relationships imply that there is at least one point where cost is minimized for a certain schedule and set of performance parameters. In theory, this point is established as a result of the contract between the government and the contractor. Moving away from this point in any direction usually entails trading off the design, cost, or delivery of the particular weapon system. The objective of this thesis is to investigate the conceptual foundations of models which attempt to quantify the tradeoffs between cost, schedule, and performance.

C. SCOPE AND LIMITATIONS

As previously mentioned, the scope of this thesis is to investigate, through a detailed review of the literature, what studies have been performed with respect to the tradeoffs between cost, schedule, and performance characteristics in the acquisition of weapon systems. The thesis attempts to answer the questions: What studies have been performed?; What are the cost estimating relationships (CERs) involved?; and How can the defense acquisition community use these studies to make informed decisions regarding particular tradeoff options?

This thesis is not intended to question strategic planning policy nor predict future funding levels or force structures. Nor does it attempt to measure cost versus effectiveness of a particular weapon system.

D. RESEARCH METHODOLOGY

Computerized literature searches were the primary method for collecting information and models on the effects of cost, schedule, and performance on weapon system acquisition. Searches were made of the Defense Logistics Studies Information Exchange (DLSIE), Defense Technical Information

Center (DTIC), and the National Technical Information Service (NTIS). A secondary method was a personal review of the Rand Corporation yearly Indexes from 1946 through 1990. Keywords used included combinations of the following; cost estimating relationship, CER, weapon acquisition, weapon systems, cost and performance, cost and schedule, and tradeoffs. The references of relevant works found by the above methods were also examined to complete the search.

E. ORGANIZATION OF THE THESIS

In order to better understand the trends that weapon system procurement has followed, Chapter II provides a brief discussion of the acquisition experience of the last few decades. It also highlights some of the more important *foundations of cost estimation* and their applications to weapon systems. The remaining chapters are dedicated to discussion of the various cost, schedule, and performance tradeoff models, problems with their use and potential for the future.

Many equations with complex variables are presented in this thesis. The confusion which surrounds the variables has been minimized by presenting definitions in the body of the thesis adjacent to each equation. It is hoped that the reader will find this method more acceptable than if the definitions were listed together in an Appendix.

Appendix A contains selected regression equations by Alexander and Nelson for aircraft turbine engines which supplement those in the body of the thesis. Appendix B contains Bureau of Labor Statistics based price indices for the years 1946 through 1973. Appendix C provides an annotated bibliography which provides references in addition to those cited in the body of the thesis which have either theoretically or quantitatively described the relationship between or among the three variables of cost, schedule, and performance.

II. WEAPON SYSTEM PROCUREMENT

This chapter will investigate cost and schedule growth trends in weapon systems procurement over the last few decades as well as discuss some of the recurring themes in the cost estimating process. It is important to understand the environment within which cost estimating relationships were prepared. Thus, Chapter II sets the stage for further discussion of specific cost, schedule, and performance models.

A. GROWTH TRENDS

Several studies have been performed which have compared rates of cost and schedule growth at different periods in time. One of the first was a 1972 General Accounting Office (GAO) Report which quantified, on a large scale, the weapon system acquisition experience. Schedule slippage was a problem, especially for missiles, electronics, and vehicles and ordinance systems. Figure 1 shows this schedule slippage between the planned Initial Operating Capability (IOC) date and the then current estimate of IOC. (GAO, 1972, p. 45)

While this figure shows growth numbers which cause some concern, the fact is that the cost of this schedule growth was far less than either the costs of quantity or estimating changes. One must also keep in mind that the initial

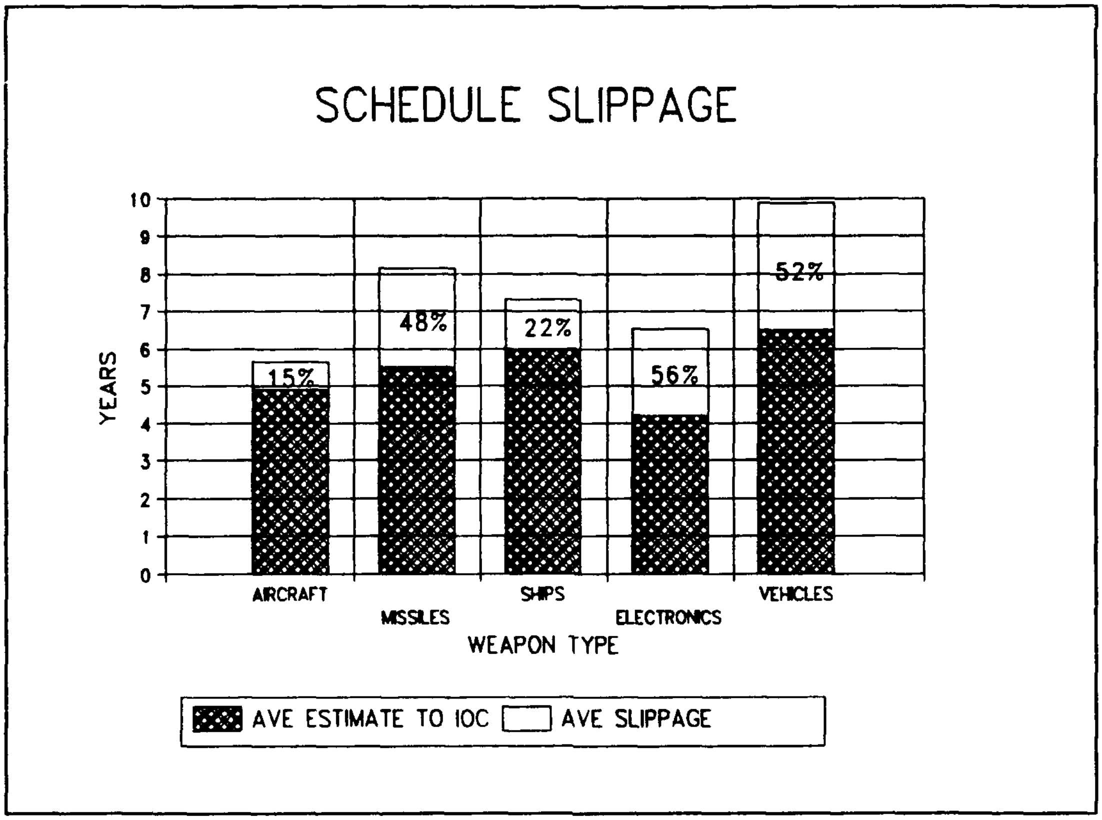

Figure 1

estimates may be at fault and therefore, relative increases in schedule may be misleading.

A 1979 study by Rand Corporation tracked the performance, schedule, and cost results for 1970s programs. When result to goal ratios were calculated, the means in Table 1 were obtained.

The figures in Table 1 are not weighted by the size of the program budget. "When weighted by program cost, the average cost-growth ratio for the 31 programs was about 1.14, reflecting somewhat lower cost growth in the high-value programs." (Dews, et al., 1979, p. 26)

Reductions in development cost, development schedule, production cost and production schedule growth rates have generally continued into the 1980s. There is however, conflicting data on cost and schedule growth rates, particularly for programs in the 1970s. An Institute for Defense Analysis Report provided the rates in Table 2 based on 42 programs during the 1970s. (Tyson, et al., 1989, p. IV-2)

Table 1. RESULTS TO GOALS RATIOS

	MEAN
PERFORMANCE	1.00
SCHEDULE	1.13
COST	1.20

A cursory look at Tables 1 and 2 will reveal that there are significant differences in what appear to be similar measures. This demonstrates one of the problems associated with statistically based studies. In this case, the results are based on different samples, 31 and 42 respectively, but the later must contain most, if not all of the former's samples. Even with similar databases, differences in the underlying assumptions about the data, treatment of outliers, and specific definitions of the variables can yield different results. This topic will be revisited later in the thesis when specific cost models are examined.

B. COST ESTIMATION METHODS AND MODELS

The above discussion of growth trends only hints at the various methods and models used to track and predict weapon systems costs. Methods include analogy, bottom-up engineering estimates, and statistical analysis. While all three are means toward the same end, the amount of time and resources required of each vary greatly. Analogy may have its basis in either or both of the other two methods but it is simply an expert's opinion, based on comparison with other similar systems, as to what a new system should cost. Engineering estimates require the most time and resources to complete. They are detailed estimates at the lowest levels of the work breakdown structure, aggregated to form an estimate of the total system. They rely on a host of experts and managers at all levels of an organization to estimate costs based on a proposed design. Statistically based estimates, on the other hand, do not necessarily require intimate knowledge of the

Table 2. COST AND SCHEDULE GROWTH RATES FOR 1970s PROGRAMS

	MEAN
DEVELOPMENT COST GROWTH	1.26
DEVELOPMENT SCHEDULE GROWTH	1.33
PRODUCTION COST GROWTH	1.63
PRODUCTION SCHEDULE GROWTH	1.73

particular system to be costed. Instead, they seek to explain cause-effect type relationships between various parameters and some independent variable. Preparation of these models require a moderate level of effort, particularly in the data gathering phase. The quality of statistically based estimating relationships is of course a function of the data set employed. This idea will be revisited in later chapters.

The purpose for which costs are to be estimated largely determines the method employed. The focus of this paper will be on statistical methods which enable one to evaluate the cost of various input alternatives.

This leads to the question--Inputs at what level? Resources required for a weapon system can be categorized in many different ways. Models can be created at the system, sub-system, or cost element levels of the work breakdown structure, by procurement phase, or some combination of both. Each successive drop in the work breakdown structure requires additional data which may not be comparable or even available. Similarly, availability of downstream operating and support and disposal costs was limited. Therefore, the studies found in the course of research all concentrated on sub-system level or higher estimates of the weapon system development and production procurement phases.

C. TECHNOLOGICAL ADVANCE

One theme which underlies the cost, schedule, and performance tradeoff is that of technological or state-of-the-art advance. In 1966, the conventional wisdom was that "we simply cannot see a quantitative solution to the problem of relating performance characteristics desired from a development to state-of-the-art advance." (Glennan, 1966, p. 9) As a result, early attempts to place a value on this advance were subjective estimates based on expert opinion. However, in the early 1970s, one study related technological parameters in aircraft turbine engines to the time to pass its 150-hour Model Qualification Test. (Alexander and Nelson, 1972) This study and further refinements have replaced subjective evaluations with objective measurements of technological advance. This theme will be evaluated in more detail in the following discussion of the various models.

D. OBJECTIVE

The underlying objective in weapon system cost estimation is that one should be able to predict costs as a function of the performance parameters of a system. Ideally, in terms of minimizing cost and effort, those parameters should reflect the performance of the system as a whole. Unfortunately, the performance of a system is a function of design characteristics which are inexorably linked with each other, and with technological capabilities which impact on schedule.

In the end, only one set of technical specifications is selected and the system is delivered on one date. This makes comparisons of tradeoffs difficult since one can never know for certain what a system with different specifications would have cost nor when it would have been delivered.

The literature linking cost, performance, and schedule is by no means abundant. This is due in large part to the sheer complexity of the interrelations between performance characteristics and technical specifications as well as the unique missions of the wide variety of weapon systems. Prior large scale tradeoff studies have focused on the aircraft industry. In particular, cost estimating relationships have been studied for the airframe and turbine engine subsystems. One might expect that aircraft would be more widely studied than, for example, missile systems. The technology is more directly transferable to civilian application, pertinent data with respect to costs and specifications are more easily accessible, and the industrial base has been more widely developed. More recent works on the subject typically refine and adjust earlier studies.

III. AIRCRAFT TURBINE ENGINE COST MODELS

This chapter will investigate the theories behind several aircraft engine cost models and the tradeoffs between and among the three pillars of cost, schedule, and performance. The chapter is organized in three sections, each dealing with a specific set of cost or schedule estimating relationships.

A. TIME VERSUS PERFORMANCE

This first section on cost models relates the performance of aircraft turbine engines to some measure of time. Two assumptions are necessary at this point: first, that the engine may be described by some combination of performance parameters and *second*, that the marginal increase in performance over time displays some historical continuity (Alexander and Nelson, 1972, p.3). By definition, these two assumptions must hold for essentially all parametric-based cost estimating relationships if they are to be effective and reliable.

When seeking to describe the performance characteristics of a particular engine, several key factors come to the forefront. Among these are engineering considerations such as turbine inlet temperature, maximum thrust, weight, fuel consumption, speed, and a pressure term. Other characteristics which may not reflect performance include such dimensions as length and diameter. None of the above parameters explicitly brings the technical complexity of the system nor time to develop into the equation. It is with this foundation that Alexander and Nelson sought to quantify the relationship between the "technology index" and some bundle of performance parameters and physical characteristics.

1. The Technology Index

In Measuring Technological Change: Aircraft Turbine Engines, Alexander and Nelson defined the technology index as number of calendar quarters (4th quarter 1942 equals one) to achieve the 150-hour Model Qualification Test (MQT).* Their attempt to relate performance parameters to a length of time implicitly attempts to explain the time versus performance tradeoff. As a result, input variables can be varied to achieve desired results in terms of time to the 150-hour MQT, or alternatively, time to MQT can be predicted based on a given set of input variables.

a. *Technology Trend Model*

Several methodologies were used to determine the best fit model for describing performance versus time. Linear, quadratic, semi-logarithmic, and full logarithmic forms were tested with the expectation that one would produce a significantly better correlation between performance and

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*The MQT is the final military qualification, after which the engine is considered to be sufficiently developed for installation in a production aircraft.

time. Appendix A contains the full set of selected regression equations cited by Alexander and Nelson. They include equations which incorporate cruise variables, pure performance variables, as well as technical parameters. Equation (1) below shows the result of the best regression to be in the semi-logarithmic form (Alexander and Nelson, 1972, p. 21):

$$\text{Tech} = -1187.5 + 156\ln(\text{Temp}) + 18.8\ln(\text{Thrust}) - 26.5\ln(\text{Wgt}) - 20.6\ln(\text{SFC}) + 11.7\ln(Q) + 13.0(\text{Prop}) \quad (1)$$

Where:

Tech = Quarters to MQT; (4th quarter 1942 = one).

Temp = Turbine inlet temperature; Degrees Rankine.

Thrust = Military sea level static thrust; Lbs.

Wgt = Engine weight; Lbs.

SFC = Specific fuel consumption at military sea level static thrust; (Lb/hr)/Lb thrust.

Q = Maximum dynamic pressure; lb/ft^2.

Prop = Dummy variable; one if turboprop, zero otherwise.

The R-squared value for equation (1) was reported as .903 with a standard error of the regression of 9.6. While the high R-squared value is impressive, the standard error of 9.6 quarters (roughly 2.4 years) implies that approximately two thirds of future developments could be predicted within a five year range. This is by no means satisfactory when a project manager is faced with a decision concerning the tradeoff between performance and schedule. However, the incremental changes in schedule (MQT) when altering performance parameters may provide a more acceptable measure on which to base tradeoff decisions.

b. Revised Technology Trend Model

Nelson refined the earlier time-performance model and related it to development and production costs of aircraft turbine engines. This later work, entitled Relating Technology to Acquisition Costs: Aircraft Turbine Engines, made extensive use of the previous data base but some revisions require mention. Some of the more important changes were:

- 12 turboprop/turboshaft engines were removed because detailed development and production costs were not available;
- 4 engines were removed because they failed the 150-hour MQT;
- 5 engines were removed from the military sample and included in a commercial sample. (Nelson, 1974, p. 6)

The resultant data base consisted of twenty-six military turbojet and turbofan engine programs plus eleven commercial engine programs ranging from the 1940s through the late 1960s. Also of note were two changes made to the performance parameters. Maximum thrust was substituted for military sea level static thrust and a new pressure term was introduced.[*] As with the previous study, a stepwise least

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[*] This term is the product of the maximum dynamic pressure of the flight envelope and the pressure ratio of the engine.

squares procedure was used to determine the best fit equations. Further, the technology index was renamed Time of Arrival (TOA) to more accurately reflect that it is indeed a measure of time, which substitutes for technology. Equations (2) and (3) below are the results of the regression procedure and they reflect the TOA for the twenty-six military engines (TOA_{26}) and the thirty-seven military and commercial engine (TOA_{37}) databases, respectively.

$$TOA_{26} = -856.4 + 110.11\ln(TEMP) + 11.41\ln(TOTPRS) - 26.08\ln(WGT) - 16.02\ln(SFCMIL) + 18.37\ln(THRMAX) \quad (2)$$

$R^2 = .96 \quad SE = 6.9$

$$TOA_{37} = -772.85 + 98.15\ln(TEMP) + 11.97\ln(TOTPRS) - 26.47\ln(WGT) - 15.67\ln(SFCMIL) + 19.04\ln(THRMAX) + 9.86(MCDUM) \quad (3)$$

$R^2 = .96 \quad SE = 6.1$

where MCDUM*=military-commercial dummy (1=comm., 0=mil.)

The revision to the original data has led to an increase in the coefficient of determination, but perhaps just as importantly, it has decreased the standard error of the estimate.

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*Other variables are as previously defined.

B. COST VERSUS PERFORMANCE MODELS

Watts attempted to relate the cost of aircraft turbine engines to several technical and performance parameters in his 1965 work entitled Aircraft Turbine Engines-Development and Procurement Cost. Many of the technical parameters have been discussed in the previous sections, however, it is necessary at this point to define and discuss the various cost variables used in his study. The availability of cost data is perhaps the most binding constraint when attempting to quantify a cost/performance relationship. There are no hard and fast numbers like thrust or temperature which can be easily measured (or designed) to calculate costs. Instead, the cost estimator is forced to rely on values generated by contractor cost accounting systems, supplemented by contract values from government procuring agencies. Because of the incomplete data availability at the cost element level (i.e., engineering, production, tooling, etc.), Watts concerned himself with costs at the aggregate level. He divided these costs into two categories--development and procurement--the sum of which is total acquisition cost.

1. Development Costs Defined

It is often difficult to distinguish where development ends since designs are frequently subject to engineering modifications after one or more lots have been produced. Watts treats all product improvements over the life of the system as development costs. Specifically, those production costs include:

> ...initial contractor preliminary design, subsequent engineering, prototype tooling, material, fabrication, assembly and bench testing of scale or full-size components or complete engines to and including qualification testing to military acceptance specifications. Also included is the cost of production tooling. Afterburners or nozzles are considered as part of the basic engine, as is the reduction gear on a turboprop. Sustaining engineering involving factory liaison, training, preparation of manuals, etc., are not considered as development but as part of the production cost. (Watts, 1965, p. 8)

Five dates at which development costs were measured were the Preliminary Flight Rating Test (PFRT), the MQT, and the times of delivery of 100, 500, and 2000 engines.

2. Procurement Costs Defined

Simply defined, the procurement cost was "the total cost to fabricate and assemble complete engines including labor, materials, overhead and profit." (Watts, 1965, p. 9) Adjustments due to inflation were made using the average hourly earnings for aircraft engines and parts production workers. All adjustments were made to obtain values in 1964 dollars.

3. Cost Models

Multivariable cost models were discarded as either unreliable or unreasonable due to the small sample size.*

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*The data was divided into samples of eight turbojets and six turboprops.

For that reason, "it was decided to relate development and procurement cost to a single technical parameter that would describe the size of the engine--the most obvious ones being thrust or horsepower." (Watts, 1965, p. 40) However, quantity was entered as a second independent variable in an attempt to account for the difference in development costs at different quantities.

a. Development Cost Model

Development costs versus engine size and quantity equations are presented below for the turbojet and turboprop engine samples.

Turbojet: $Y_{dev}=0.13937T^{0.74356}Q^{0.07751}$ (4)

$R^2=0.92$ SE=47.25 CV=24.11%

Turboprop: $Y_{dev}=2.82917E^{0.35497}Q^{0.09334}$ (5)

$R^2=0.95$ SE=11.06 CV=16.99%

Where:

Y_{dev} = cumulative development cost ($million)

T = maximum thrust (lbs)

E = equivalent shaft horsepower

Q = quantity

b. Procurement Cost Model

The procurement cost models were separated into two turbojet (those with and those without afterburners) and the turboprop categories. Results of these models were:

Turbojet with afterburner:

$$Y_{proc}=0.18700T^{0.84845}Q^{-0.13255} \tag{6}$$

$R^2=0.80$ SE=84.78 CV=46.84%

Turbojet without afterburner:

$$Y_{proc}=0.31979T^{0.81626}Q^{-0.12912} \tag{7}$$

$R^2=0.78$ SE=80.47 CV=48.92%

Turboprop:

$$Y_{proc}=4.86224E^{0.45873}Q^{-0.10945} \tag{8}$$

$R^2=0.95$ SE=11.91 CV=11.58%

Where:

Y_{proc}= cumulative average cost/engine ($thousand)

c. Acquisition Cost Models

The acquisition cost model is merely the algebraic sum of the development model and the procurement cost model evaluated at varying quantities. Figure 2 graphically depicts this relationship for turboprop engines at acquisition of 100, 500, and 2000 engines, respectively.

Large, in his 1970 work entitled Estimating Aircraft Turbine Engine Costs, used Watts' work as a starting point for developing his own cost estimates. By 1970, the database available for study had grown to twenty-two turbojet engines. This made a more statistically reliable model possible.

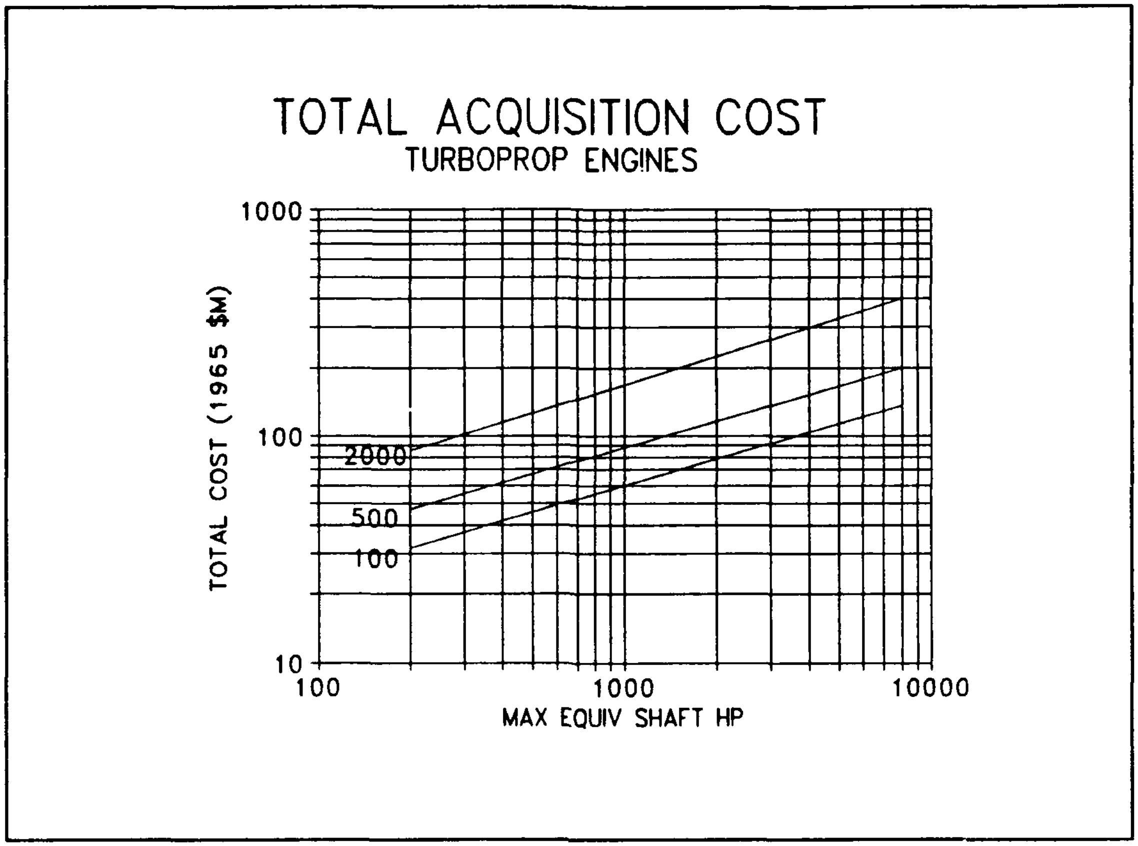

Figure 2

Like Watts, Large related development costs[*] at five milestones to engine performance parameters. Adjustments were made for price-level changes and differences in quantity. In particular, the development cost at MQT (D_{MQT}) equations he found all had thrust as one explanatory variable with either speed, altitude, or thrust per unit of outflow as the other. The best fit equation is shown below.

$$D_{MQT}=0.73F^{.38}A^{1.09} \tag{9}$$

---

[*] Production tooling costs were excluded from development costs.

$R^2=.95$ SE=29 (1969 \$M)* CV=14%

where:

F= maximum thrust (thousands of lbs)

A= absolute altitude (thousands of feet)

Development costs at other quantities can be calculated using the above equation and the development cost ratios listed in Table 3. The ratios were based on eight engines' total cost of development through the indicated quantity compared to development cost through MQT.

Table 3. DEVELOPMENT COST RATIOS

	PFRT	MQT	100 ENGINES	500	2000
MEAN RATIO	0.61	1	1.25	1.54	2.07

Because extrapolation between the above quantities is rather difficult, Large added quantity to the development cost estimating relationship. The resultant equation, shown below, is:

$$D_Q= 0.24F^{.31}A^{1.37}Q^{.1} \quad (1969\ \$M) \qquad (10)$$

The decrease in the R^2 value to .85 and increase in the standard error to \$52 million reflect the uncertainty introduced by the substitution of a third explanatory variable.

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*To convert 1965 dollars to 1969 dollars, multiply 1965 dollars by 1.22. This index is based on production workers' average earnings.

When production costs were examined, Large states:

> After duly attempting to correlate cost and every combination of engine characteristics that appeared reasonable or unreasonable, we believe it is fair to say that no single or multi-variable estimating equation can predict the cost of all engines in the sample with acceptable accuracy (Large, 1970, p. 15).

As a result, the sample was broken down into three classes based on technical design features and material composition. Class I engines (three) all had one stage compressors and were considered obsolete for military usage. All four of the Class III engines had similarly large proportions of expensive superalloys and titanium. Class II engines contained both afterburning and non-afterburning samples, but in general they had larger turbine inlet temperatures than Class I, more common metals as compared to Class III, and comparable multi-stage compressors within their class.

Large used the samples from Class II to determine the regression equation which best fit those points. Parallel lines were then hand fit to the points in Classes I and III. Quantity was introduced as a second explanatory variable resulting in the equation for Class II of:

$$C_u = 2.61F^{.60}Q^{-0.154} \tag{11}$$

where C_u=unit cost in thousands.

At this point, the R-squared value for Class II engines was 0.90, the standard error was $31 thousand, and the coefficient of variation was 14%. In order to convert unit cost to cumulative average cost, unit cost was multiplied by the quantity (1/b+1). Simplifying further, the total cost of development and production (C_T) for the three classes can be summarized as follows;

Class I: $C_T=.24F^{.31}A^{1.37}Q^{.1} + .096F^{.60}Q^{.846}$ (12)

$C_T=27.8F^{.55}M^{.62}Q^{.1} + .096F^{.60}Q^{.846}$ (13)

Class II: $C_T=.24F^{.31}A^{1.37}Q^{.1} + .194F^{.60}Q^{.846}$ (14)

$C_T=27.8F^{.55}M^{.62}Q^{.1} + .194F^{.60}Q^{.846}$ (15)

Class III: $C_T=.24F^{.31}A^{1.37}Q^{.1} + .355F^{.60}Q^{.846}$ (16)

$C_T=27.8F^{.55}M^{.62}Q^{.1} + .355F^{.60}Q^{.846}$ (17)

where M = maximum speed in Mach number and other variables are as previously defined. The additional developmental cost equation, incorporated into the total cost equation, provides the estimator with two methods to better estimate a range of likely engine costs.

Up until this point, we have presented different models of performance versus time and cost versus performance relationships for aircraft turbine engines. What remains now is to link the three characteristics together so that tradeoffs between cost, performance, and schedule may be comparatively measured.

C. COST, SCHEDULE, AND PERFORMANCE MODELS

Nelson, in Relating Technology to Acquisition Costs. Aircraft Turbine Engines validated the variables that Large found to be important predictors of cost. However, the addition of the time-of-arrival variable eliminated the need to separate engines into different classes. In effect, this eliminated one source of variability from the total cost equation. As with the previous cost studies, two adjustments were made to the data--one for price level changes* and the other for quantity and engine configuration (homogeneous models).

Three different cost models were presented. They included a standard variables model, a time-of-arrival model , and a technology parameters model. The standard variables equation included explanatory variables which were proven to be important in past studies plus development time and/or quantity. The time-of-arrival equation includes the standard variables plus TOA and/or ΔToa**. The technology parameters equation included a mixture of explanatory variables present in the other two models.

Development cost equations were prepared for two milestones--those costs up to MQT and total development cost. Development cost to MQT included design, engineering, tooling, materials, fabrication, and assembly and testing of components and complete engines. They also include overhead and profit since the equations predict total cost to the government. Similarly, production costs were total cost to the government

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*See Appendix B for price level adjustment factors.

**ΔTOA is the difference between actual and predicted dates of arrival at MQT.

through Q units. Nelson used two methods to estimate production costs. The first method involved an estimate of the 1000th unit cost and an estimate of the slope of the cumulative average production unit progress curve. The second and more straightforward method predicted cost as a function of quantity plus other explanatory variables. The former method will be omitted because of its complexity. The procedures do yield similarly significant results. Nelson states:

> As an overall measure of comparability between these two approaches, the TOA equation *for unit 1000 cost and* the technology parameters equation for slope were used to predict the costs of the 88 input observations for the cumulative cost regressions. The calculated coefficient of determination is 0.968, which compares favorably with the R^2 for the TOA cumulative production cost equation (0.978). (Nelson, 1974, p. 49)

1. Development Cost Models

Below are the three development-cost-to-MQT equations presented by Nelson.

Time-of-Arrival Model:

$$\ln D_{MQT}=-1.4461+.08538T_D+.49630\ln \text{THRMAX} +.04099\Delta TOA_{26}+.41368\ln \text{MACH} \qquad (18)$$

$R^2=0.961$ SE=0.182 (+20%, -1%)

Technology Parameters Model:

$$\ln D_{MQT}=-1.5723+.07184T_D+.81292\ln \text{THRMAX} +.58532 \ln \text{MACH} -.26470 \ln \text{WGT} \qquad (19)$$

$R^2=0.882$ SE=0.317 (+37%, -27%)

Standard Model:

$$\ln D_{MQT} = -1.0779 + 0.07463 T_D + .47611 \ln THRMAX + .5112 \ln MACH \qquad (20)$$

$R^2 = 0.858$ SE=0.329 (+39%, -28%)

where D_{MQT} = development cost to MQT (1973 $M)

T_D = development time from start to MQT (quarters)

MACH = maximum flight envelope Mach number

THRMAX = maximum thrust, sea level static (lbs)

By adding quantity into the stepwise regression procedure, Nelson found total development costs (TD$) as follows:

Time-of-Arrival Model:

$$\ln TD\$ = 0.23198 + 1.0193 \ln MACH + 0.06228 \ln Q + .44251 \ln THRMAX + 0.01418\ TOTDEVTIME \qquad (21)$$

$R^2 = 0.927$ SE=0.209 (+23%, -19%)

Technology Parameters Model:

$$\ln TD\$ = -10.485 + 1.0098 \ln MACH + 0.07119 \ln Q + 0.43019 \ln WGT + 1.5642 \ln TEMP \qquad (22)$$

$R^2 = 0.930$ SE=0.204 (+23%, -19%)

Standard Model:

$$\ln TD\$ = 0.79747 + 1.2867 \ln MACH + 0.08146 \ln Q + 0.39884 \ln THRMAX \qquad (23)$$

$R^2 = 0.858$ SE=0.329 (+39%, -28%)

2. Procurement Cost Models

Cumulative production costs were based on 88 data points from 18 turbojet and turbofan engines. Several items should be noted regarding these curves and the statistical evidence supporting them. First, since the data points are cumulative measures of costs and quantities, there is a potential problem with multicollinearity. As a result, errors in the data points can not be assumed to be independent--the effect being that the standard errors are suspect. Second, engines with more data points will have a stronger effect on the outcome of the regression line coefficients. The first three production cost equations contain a dummy variable for engine manufacturer--its value being one for Pratt & Whitney and zero for all others. No explanation is given for the difference in production costs between contractors. The four procurement cost models do have R^2 values greater than or equal to 0.948 so there is the potential to estimate a reliable range of values for procurement costs. The four models in order of their R^2 values are:

Time-of-Arrival Model with Manufacturer Dummy:

$$\ln PROC\$ = -7.9854+0.92753 \ln Q +0.77831 \ln THRMAX +0.01542\Delta TOA_{26r} + MFRDUM +0.37779 \ln MACH \quad (24)$$

R^2=0.978 SE=0.198 (+22%, -18%)

Technology Parameters Model with Manufacturer Dummy:

$$\ln \text{PROC\$} = -25.130 + 0.86943 \ln Q + 0.86883 \ln \text{THRMAX} \qquad (25)$$

$$+ \text{MFRDUM} + 0.30170 \ln \text{MACH} + 2.2107 \ln \text{TEMP}$$

$$R^2 = 0.968 \qquad SE = 0.235\ (+27\%,\ -21\%)$$

Standard Model with Manufacturer Dummy:

$$\ln \text{PROC\$} = -8.5461 + 0.87079 \ln Q + 0.90865 \ln \text{THRMAX} \qquad (26)$$

$$+ \text{MFRDUM} + 0.24242 \ln \text{MACH}$$

$$R^2 = 0.963 \qquad SE = 0.251\ (+29\%,\ -22\%)$$

Standard Model without Manufacturer Dummy:

$$\ln \text{PROC\$} = -7.9417 + 0.84172 \ln Q + 0.84755 \ln \text{THRMAX} \qquad (26)$$

$$+ 0.21462 \ln \text{MACH}$$

$$R^2 = 0.948 \qquad SE = 0.295\ (+34\%,\ -26\%)$$

where $\text{PROC\$}$ = procurement costs through Q engines (1973 \$M)

ΔTOA_{26r} = time-of-arrival index of last growth engine (calendar quarters)

It should be stressed that the TOA variable, being a function of temperature, pressure, thrust, weight, and fuel consumption is confounded with THRMAX in equation (24). Similarly, any measure of time must also be confounded to some extent with other variables in the equation. That is to say, one can not say for sure what the real effects of time are on the dependent variable. This is a possible explanation of why the development time variable is linearly related to development cost when we would intuitively expect it to be quadratic in form. A second interpretation of this linear relationship is that it approximates the upward sloping right half of the quadratic. This effect does not undermine the values of the coefficients or the forms of the variables, but it does affect the reliability and precision of the standard error term.

IV. AIRCRAFT/AIRFRAME COST ESTIMATING MODELS

Initial aircraft cost models focused on production and generally related direct labor hours per pound to production quantity. These plots resemble the familiar learning curve and were of the form $y=Ax^b$. Over a period of years, the "A" value increased significantly for fighter aircraft indicating that it was taking more direct labor hours per pound to complete an aircraft. When further analyzed, speed of the aircraft was indicated as a possible explanatory variable.

A. COST VERSUS PERFORMANCE

Virtually all of the airframe cost models have both weight and speed as explanatory variables. While speed is most definitely a performance variable, weight seems more like a technical variable. However, weight and particularly ratios involving weight (i.e., thrust/weight) can also describe the performance characteristics desired of an aircraft and therefore it should be considered as one possible measure of system performance.

Glennan found the following relationships[*] using weight and speed as explanatory variables (Glennan, 1966, p. 8):

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[*] The database consisted of the F-84, F-86, F-86D, F-89, F-100, F-101, F-104, F-105, F-106, B-47, B-52, B-58, and F-4.

$$\log E_{25} = .41 + .83 \log W + 1.97 \log S \quad (27)$$

$$\log E_{100} = .46 + .91 \log W + 1.84 \log S \quad (28)$$

$$\log C_{25} = .72 + 1.04 \log W + 1.42 \log S \quad (29)$$

where E_{25} = Cost of engineering including flight test through 25 aircraft (1962 $M)

E_{100} = Cost of engineering including flight test through 100 aircraft (1962 $M)

C_{25} = Cost of airframe program through 25 aircraft (1962 $M)

W = AMPR weight of aircraft (thousands of lbs)

S = Maximum speed of aircraft (Mach)

The R^2 values for equations (27), (28), and (29) are .92, .94, and .97, respectively. However, the large range of the dependent variable produces deviations in the 20 percent range. Notice that the dependent variable E is an attempt to break down costs by functional cost element. This is a result of the databases available at the time. Also notice that the accuracy (R^2) of the total cost is better than the engineering cost element. Large states;

> The accuracy of the overall estimate is always better, however, than the accuracy of the individual elements, because the data are inconsistent at the cost-element level. What one company calls engineering, another company calls tooling, or a given company will change definitions to conform to cost accounting standards, and it has never been possible to adjust the data to eliminate all discrepancies. [Therefore,] at the highest level--aircraft cost--comparisons are most valid. (Large, 1981, p. 18)

More recent total cost/performance relationships involving weight and speed are presented below. The first, equation (30), represents a 1976 study which contained 24 airframes.

The second airframe relationship, equation (31), relies on a sample of 13 post-1960 airframes which is considered to be a better predictor of future aircraft. (Hess and Romanoff, 1987, p. 45)

$$PROG_{100} = 6.22\ AUW^{.728}\ SP^{.737} \tag{30}$$

$$R^2 = .88 \qquad SE = .27$$

$$PROG_{100} = 2.57\ AUW^{.798}\ SP^{.736} \tag{31}$$

$$R^2 = .85 \qquad SE = .36$$

where $PROG_{100}$ = Cumulative total program cost for 100 aircraft (1977 $thousand)

AUW = Airframe unit weight (lb)

SP = Maximum speed (knots)

B. TIME VERSUS PERFORMANCE

The search for a technology index for aircraft roughly paralleled that of the time-of-arrival method for turbine engines. The natural equivalent to TOA was first flight date. Stanley and Miller sought to quantify this technological change in fighter aircraft in their 1979 work entitled Measuring Technological Change in Jet Fighter Aircraft. All combinations of linear and logarithmic variables were tested. They determined that "the log-linear equation form unambiguously characterized the growth in U.S. fighter technology better than the other equation forms." (Stanley and Miller, 1979, p. 21) They also performed several regressions to determine from which point in time the first flight date would be measured. Ultimately, and after careful analysis, January 1, 1940 was selected as the date from which first flights would be measured. The database consisted of 25 new designs with first flights ranging from 1946 to 1976. Six technology equations were presented with R^2 values ranging from .945 to .882 and standard errors ranging from .117 to .160. The first equation only is presented below:

$$\ln(t) = 3.878 + .065[(\text{Thrust})(V_{max})/100W_{cbt}] + .406[BR/1000] + 1.409[SLF/10] + .939[PF] - .093[\text{carrier capability}]^{*} \quad (32)$$

where t = months since 1 JAN 1940

W_{cbt} = combat weight (lb)

BR = Breguet range**

SLF = Sustained load factor***

PF = Payload fraction (Max gross weight-full internal weight divided by maximum gross weight)

The remaining five equations all contain the thrust and velocity variables, either Breguet range or Breguet range factor as well as some combination of payload fraction, internal or total fuel fraction, sustained load factor, and carrier capability.

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[*] 1 denotes no capability, 0 denotes capability.

[**] The range calculated using the Breguet range equation assuming all internal fuel is used at cruise conditions and the aircraft is initially loaded to its maximum gross weight.

[***] The maximum load factor the aircraft can sustain in level flight at an altitude of 25,000 feet and at a Mach number of .8 at its combat weight.

It is evident from the above definitions that both performance and technical characteristics must be known before equation (32) can be used. This equation truly displays the paradox in cost estimating relationships. Namely, attempts to locate better predictors will invariably make the equation so cumbersome that its use as a simple estimating tool becomes futile. Nevertheless, these somewhat obscure variables all seek to describe some measure of output desired from an aircraft.

C. COST, SCHEDULE, AND PERFORMANCE MODELS

Only one of the following models explicitly includes some measure of development time as an explanatory variable for cost. However, the inclusion of a measure of time, in the form of a technology index, does provide some foundation with which one can attempt to trade off certain design parameters or performance characteristics with cost and schedule.

Glennan was among the first to include some measure of state-of-the-art advance and performance characteristics to airframe costs. He added another variable "A" to equation (29) which was a subjective measure of state-of-the-art advance obtained by polling experts in the field.* He states;

> Their rankings showed a high degree of consistency which could be considered as giving us greater confidence in the measure than if there had been little correlation between their responses. On the other hand it might simply

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*The variable "A" ranged from zero to twelve.

> indicate that they had all formed opinions based upon the difficulty the developers had with the development. (Glennan, 1966, p. 9)

The resultant equation for cost through 25 airframes is;

$$\log C_{25}^{*} = .89 + 1.07\log W + 1.45 \log S - .25 \log A \qquad (33)$$

$$R^2 = .97$$

Glennan sought to obtain a more objective measure of technology and he subsequently replaced "A" with the variable "T" which he defined as the number of months from January 1944 to the first flight date of the aircraft. This equation is shown below;

$$\log C_{25} = .12 + .96\log W + .94 \log S + .39 \log T \qquad (34)$$

$$R^2 = .98$$

Glennan noted that the coefficient for "T" "appears to have drawn some of its statistical significance from other factors which were changing over time and which tended to drive development costs upward." (Glennan, 1966, p. 12) This relates to the problem of confounding as described earlier.

In the only attempt to relate development time (D)[**] and performance to cost, Glennan found that the coefficient of development time was never significant. This suggests, at least based on the 13 pre-1955 aircraft samples, that changes

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[*] Recall that C_{25} is measured in 1962 dollars.

[**] Arbitrarily defined as time in months from letter contract to delivery of 25 aircraft.

in development time do not affect costs significantly. The equation for comparison purposes is;

$$\log C_{25} = .91 + 1.10 \log W + 1.46 \log S - .15 \log D \quad (35)$$

$$R^2 = .97$$

In 1973, a J.W. Noah model was prepared for the Navy (Large, 1981, p. 18). It separated costs into two categories--recurring and non-recurring. The model contained two subjective measures. The first, a technology index, was essentially a time based number which rated all fighter aircraft through the F-14. The second was a dummy variable which held the value of zero or one depending on the complexity of the airframe design. The remaining explanatory variables were speed and some measure of weight. The Noah model equations are;

$$C_1 = +5.945 + .00663S + .05138T - 1.4071R + 6.7492d \quad (36)$$

$$C_2 = 105.05 + .11557S + 1.2034T - 1.0248A + 97.631d \quad (37)$$

where C_1 = Non-recurring \$/lb of airframe weight (thousands)

C_2 = Recurring \$/lb of airframe weight (Cumulative average cost at 100 airframes)

S = Maximum speed at altitude (knots)

T = Technical index

R = Gross takeoff weight divided by airframe weight

A = Airframe weight

d = Complexity dummy (0 or 1)

These equations do not stand alone when one has to estimate the total cost of procurement. Since quantity is not explicitly defined, some characteristics of the production learning curve must be known (or estimated) to predict total cost. While this may not be as elegant as an equation using quantity, it does provide the estimator with a second method with which to evaluate program costs.

The most recent work on airframe cost estimating relationships by Hess and Romanoff was published in 1987. Their recommended cost model for program costs was previously presented as equation (31). However, they did produce equations which incorporated a time variable. It is important to highlight these results because they show how the form of a cost estimating relationship can affect the outcome of a cost estimate. Two equations are presented below--the first with a linear incorporation of first flight date (FFD) and the second with a logarithmic incorporation of FFD.

Linear Incorporation of FFD:

$$PROG_{100} = 2.82\ EW^{.802}\ SP^{.649}\ e^{.00140(FFD)} \qquad (38)$$

$R^2 = .89 \qquad SE = .27$

Logarithmic Incorporation of FFD:

$$PROG_{100} = .647\ EW^{.791}\ SP^{.636}\ FFD^{.371} \qquad (39)$$

$R^2 = .89 \qquad SE = .27$

where $PROG_{100}$ = Cumulative total program cost for 100 aircraft (1977 $thousand)

EW = Empty weight (lb)

SP = Maximum speed (knots)

FFD = months since 1 January 1940

Note that the R^2 value and the standard error of the regression are identical for both forms. However, these only explain the variance within the database. Figure 3 shows the effect when points outside the range of the database are estimated based on these equations.[*] The linear incorporation of FFD implies an acceleration of costs over time while with

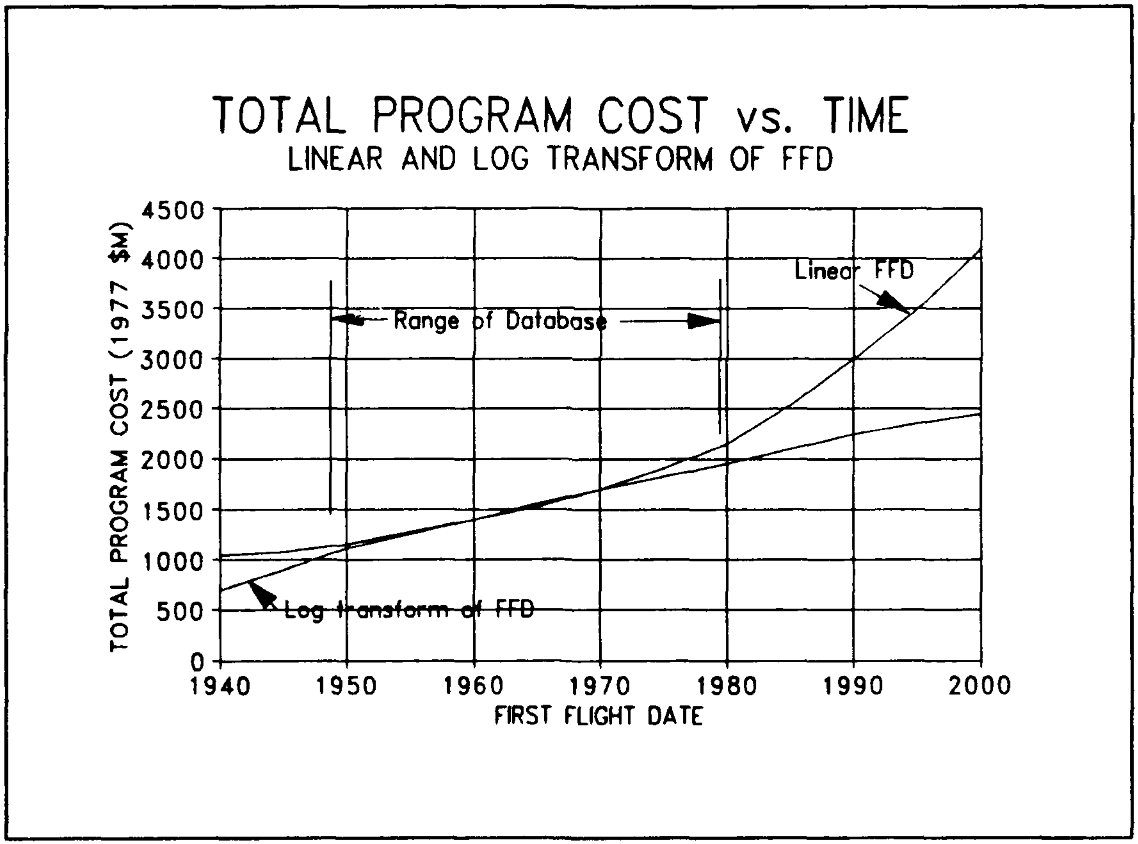

Figure 3

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[*] The curves in Figure 3 are actually based on the sum of engineering, tooling, labor, material, development support, flight test, and quality control cost equations with the indicated incorporation of FFD.

the logarithmic transformation of FFD, costs remain nearly proportional to time.

When an aircraft with an estimated FFD of 1995 is considered, the linear incorporation of FFD produces an estimate of program costs approximately 50 percent greater than the equation with the logarithmic transformation. The large variation in estimates for those aircraft with projected first flight dates outside the range of data is a problem common to all equations which include a measure of time as an explanatory variable. This is of course true for any cost estimating relationship. Any number of equation forms may adequately represent a set of points within their range. However, when those equations are used to predict values far outside the range of available data, the level of uncertainty increases. Even though we must rely on the assumption of continuity, there must also be some subjective notion on the likelihood of expected outcomes. Hess and Romanoff were "unable to say which of the two FFD forms [would] more accurately reflect future industry experience" and thus recommend that equations incorporating the FFD variable not be used. (Hess and Romanoff, 1987, p. 50)

One way to reduce this difference is to update the regression equations after some period of time. Certainly, as new aircraft are introduced, the equations can and should be recalculated.

V. TRADEOFFS--PROBLEMS OR PROGRESS

This thesis has attempted to compile and explain the best models which relate performance characteristics, cost, and schedule in the acquisition of weapon systems. The theory that these variables are interrelated is well documented; however, quantitative solutions involving all three are rare. There are numerous reasons why this situation exists, however, some progress has been made. The following sections describe my assessment of some of the problems with quantifying tradeoffs as well as some of the progress made in the area.

A. PROBLEMS

There are several fundamental problems with trying to quantify the tradeoff between schedule and either cost or performance. The following list is not intended to be comprehensive, but rather, it highlights those problems which have a major impact on the accuracy and applicability of tradeoff models. Among some of the problems are:

- cost accounts and allocations
- database integrity and homogeneity
- schedule networks
- funding instability
- risk
- baselines

Cost accounts and allocations and database integrity and homogeneity have been touched on in the previous chapters. The remaining four problems are common threads which run through the weapon acquisition cost estimating process. The effect of each is to add a measure of uncertainty and variance to the data which can never fully be factored out. Each of these items will now be covered in more detail.

1. Cost Accounts and Allocation

The desire and, in fact, need in cost estimating is to compare apples with apples. While the cost accounting systems imposed by the government on contractors go a long way towards standardization, there is still substantial latitude in cost allocation schemes. This makes inter-contractor comparison of costs at the detailed levels more cumbersome because differences between accounting systems can never fully be factored out. The contractor "dummy" variables in several equations support this idea. As we have already seen, this results in cost estimating relationships which are generally more accurate at the total cost level.

2. Database Integrity and Homogeneity

In simple terms, one could say that database integrity* and homogeneity are inversely related to uncertainty. One can regress a non-homogenous sample to

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*Integrity in this context is used to mean the degree to which the database is suitable for accurately predicting costs of future systems.

determine a relationship between two or more variables which may potentially be very accurate for predictive purposes. However, an estimate based on a non-homogenous sample must also carry with it a high level of uncertainty. Similarly, one could regress homogenous sub-samples and be just as uncertain about a prediction because of a small number of sample points. This is the problem with the samples described in the previous chapters. The trend has been to incorporate some variable (technology) which describes differences between the sub-samples and allows the full database to be included. Because of the use of non-homogenous samples the general goal for accuracy has been approximately plus or minus 20 percent. (Large, 1981, p. 28)

Creating and maintaining database homogeneity is perhaps the most difficult and time consuming process for cost estimators. Factors such as where research and development ends and where production begins is a matter of considerable judgement. The MQT date for aircraft engines and first flight date for aircraft seem to be the least ambiguous estimates of this point. Costs of producing an engine or aircraft to meet their respective requirements may logically fall into the research and development phase. However, it may be just as reasonable to allocate these to production costs. Thus some judgement is required to keep these costs comparable among contractors.

The recent requirements for minimizing life cycle costs puts an additional subjective measure on cost estimating. Certainly pre-planned product improvements (P^3I) may add substantial costs to the initial versions of a weapon system, but in the long run they reduce the cost of what may have been expensive modifications. The question then becomes how can the cost of research and development of the P^3I be properly allocated between the initial system and its later improved versions? Attempting to quantify these short term costs which have their basis in long term designs adds another measure of variance to the total cost equation.

3. Schedule Networks

The development of any weapon system is comprised of a network of precedence related elements or activities. The duration of each element is a function of resources such as labor, materials, equipment, and money. By definition, one or more of these paths through the elements must be critical. That is to say that any delay in one of these critical elements, will cause a delay in the overall project. Similarly, any reduction in the duration of a critical element may cause a shortening of the overall project.

There are normally three durations when describing a project--what the government thinks (or requires) it should be, what the contractor believes it will take, and finally, what the negotiated agreement states it will be. Along with the negotiated duration, there is also an associated cost. If the negotiated agreement is longer than what the contractor believes it should take, there is an implied slack in the contractor's schedule. Theoretically, if this is the case, schedule compression imposed on the contractor would have no real effect on the price to the government. Even if the schedule is compressed beyond the point that the contractor believes the project should take, he still may have latitude, without increasing costs, in reassigning resources (manpower, equipment, etc.) to those activities on the critical path. However, one must keep in mind that there are opportunity costs for the contractor. The resources diverted to one project may adversely impact upon several others in terms of cost, time, or both. Schedule stretchout also implies opportunity costs for the contractor. Idle equipment, inefficient utilization of manpower, and cost of money are very real effects of stretching out a project. It is precisely the difficulty in analyzing and quantifying those opportunity costs for one, let alone many contractors, which makes estimating a cost-schedule tradeoff function so difficult.

4. Funding Instability

Funding instability is perhaps the most nebulous in its impact on system acquisitions. One Rand report states:

> No major acquisition program can be planned and managed with high efficiency if it faces frequent and

> unpredictable changes in year-by-year program funding and production scheduling, even if total program funding eventually reaches the originally planned amount. Schedule slippage and cost growth are the closely related and mutually reinforcing effects of program funding instability. (Dews, et al., 1979, p. xi)

The effect of unpredictable funding is to increase the risk to the contractor that planned purchases will not occur or that the program may be canceled entirely. This short term budget focus makes long term efficient and effective planning difficult, if not impossible. Cost estimating relationships have not been able to take into account the effect uncertain budgets have on schedule slippage and cost growth.

5. Risk

The idea of risk management in defense acquisition is not a new one. Both performance risk and schedule risk have cost-measurable implications. Therefore, risk-oriented tradeoffs are both possible and desirable from program management perspective.

Many developments are on the cutting edge of technology and as such, it would be unfair to place all the risk of such a development solely on a contractor. Recognizing this, the acquisition community has adopted several types of cost sharing or incentive type contracts. Thus, the selection of a particular contract type influences the amount a weapon system will cost. Without specific information regarding the type of contract used, and its attendant risk, the cost of that risk ultimately gets hidden in some other variable in the cost equation. When data on two otherwise similar weapon systems are compared, the use of different contract types implies different costs, and by extension, different tradeoff possibilities.

6. Baselines

The Concept, Development, and Production Baselines, approved at Milestones I, II, and III, respectively, set out key objectives for cost, schedule, and performance parameters (DODINST 5000.2, 1991, p. 11-A-1). These objectives, within certain tradeoff limits (thresholds) must be met in order to reach the next Milestone. Cost estimating relationships which seek to quantify the tradeoff relationships in either development or production can not hope to describe the many different sets of tradeoff options available during each phase. Data is not sufficiently available at these levels to quantify a tradeoff relationship for each phase. Instead, the data must be aggregated across Milestones--the effect being that there is an additional measure of uncertainty when a tradeoff equation is applied at one particular Milestone or during one particular phase. To put it another way, the tradeoff options during the Demonstration and Validation Phase and the Engineering and Manufacturing Development Phase are quite different. One equation applied to both must necessarily be a compromise between the two.

A second point regarding the use of baselines is highlighted by the growth models presented in Chapter II. One thing that must be kept in mind, particularly when referring to schedule or cost growth, is the original estimate. Many studies which attempt to show trends in cost or schedule growth use ratios of actual to estimated. The problem here is quite obvious: which one is really being measured, the quality of the estimate or the trend in actual data? Does a high growth rate reflect spiraling costs or just a bad estimate? An overly conservative estimate would, other things being equal, yield a lower growth rate. Two things compound this problem. First, estimates at completion are constantly updated, and second, different organizations use different bases. It is often difficult to discern which base or estimate is being used and therefore it is difficult to make comparisons between estimates.

B. PROGRESS

Given all of the above mentioned problems, the question remains as to whether or not any progress has been made in quantifying the cost-schedule-performance tradeoff surface. Certainly, cost-performance models have been improved over the years but this is largely a function of improvements in program data tracking and a larger database. Cost-schedule and schedule-performance models have not, unfortunately, evolved to a point where their estimating effects are significant. The inclusion of a technology parameter in the form of time is a first step in quantifying a cost-schedule-performance relationship.

In this research, the author did not set out to exclude any types of systems from consideration. In fact, any model which attempted to introduce schedule (time) into a cost-performance relationship would have been compiled and explained, whether or not it described a weapon system. However, this research was quickly focused on aircraft engines and airframes simply because these were the only two which included some measure of time.

The possibility that airframe cost estimating relationships will improve in the near future is severely limited. There is a hope that new variables will somehow improve the existing estimates but these new variables will most certainly be more complex than the parameters of weight and speed. Thus, there appears to be no simple way, given the data available today, to quantify accurately and reliably the interwoven effects of schedule, cost, and performance.

VI. CONCLUSION

"One of the most difficult aspects of planning military procurement would be overcome if a satisfactory method could be found for estimating costs incurred by increased specifications." (Arrow, 1950, p. 2) No one since has stated the problem any more clearly. Many have attempted to quantify the cost of increased specifications. The literature is abundant with cost/performance models for items ranging from reconnaissance drones to jet fighters. Relatively new to the end user, statistical packages enable anyone to "invent" cost estimating relationships for their particular area of interest. The purpose of this thesis was not to review and describe the myriad of cost relationships for each type of platform. Instead, its primary focus was to compile and explain those models which incorporated schedule along with cost and performance. A careful review of the models described in this thesis will show that only five[*] equations out of all those presented explicitly had a measure of development time as an explanatory variable. Many others, however, incorporated a time-based measure of the technology. Either approach allows tradeoffs[**] to be made between

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[*] Equations (18) through (21) and equation (35). Note that in equation (35), development time was found not to be significant as an explainer of cost.

[**] Within the respective range of accuracy.

schedule, cost, and performance. The wide ranges of data or the small sample sizes do not lend themselves to the levels of significance required for use by a program manager for possible tradeoffs on specific weapon systems. These equations are sufficient for long range planning and possible ranking of alternative designs with respect to expected costs.

A. FUTURE RESEARCH

As discussed in Chapter V, it is the opportunity cost of the unchosen alternative that is so difficult to quantify. A possible method for estimating these costs could be obtained by analyzing contractual changes (modifications) due to performance changes or schedule changes. It is well known that there are typically many modifications to each contract. Some involve schedule extensions while others modify performance parameters. It is possible that a relationship may exist between the dollar amounts of modifications and the reason for that modification. Take, for example, a government caused delay which requires a modification to the contract. There is some negotiated cost that is ultimately assigned to that delay. Over a full range of contracts and contractors, there may be a sufficient database to develop a cost per time estimate. Data gathering may be quite a task, but agencies such as the Defense Contract Audit Agency may be able to provide some assistance.

The studies reviewed in the course of this thesis all revolve around research and development and production costs and schedules. Operating and support and disposal costs have since become more available. It now may be possible to incorporate these costs into equations to quantify procurement tradeoffs to minimize weapon system life-cycle costs.

APPENDIX A

This appendix contains selected regression equations which include a measure of technological trend as presented by Alexander and Nelson. (Alexander and Nelson, 1972, p. 21)

<u>Best Equation</u> (semi-logarithmic)

$$\text{Tech}= -1187.5 +156\ln(\text{Temp}) +18.8\ln(\text{Thrust}) -26.5\ln(\text{Wgt}) -20.6\ln(\text{SFC}) +11.7\ln(Q) +13.0(\text{Prop}) \qquad (1)$$

$R^2=.903 \quad SE=9.6$

<u>Linear</u>

$$\text{Tech}= -77.1 + .077(\text{Temp}) +.00066(\text{Thrust}) -.006(\text{Wgt}) -34.4(\text{SFC}) +.0094(Q) +1.77(\text{Prop}) \qquad (2)$$

$R^2=.832 \quad SE=12.6$

<u>Cruise variables</u>

$$\text{Tech}= -1501.8 +213\ln(\text{Temp}) +.86\ln(\text{Thrust}^*) -8.4\ln(\text{Wgt}) -27.6n(\text{SFC}^*) -3.10\ln(Q^*) -24.3(\text{Prop}) \qquad (3)$$

$R^2=.835 \quad SE=12.5$

<u>Date of first flight</u>

$$\text{Flight}= -1245.6 +163.7\ln(\text{Temp}) +20.7\ln(\text{Thrust}) -29.2\ln(\text{Wgt}) -20.3\ln(\text{SFC}) +11.7\ln(Q) +11.8(\text{Prop}) \qquad (4)$$

$R^2=.891 \quad SE=10.7$

<u>Pure performance</u>

$$\text{Tech}= -38.9 +33.4\ \ln(\text{Thrust}) -39.0\ln(\text{Wgt}) -38.9\ln(\text{SFC}) +13.9\ln\ (Q)+16.5(\text{Prop}) \qquad (5)$$

$R^2=.691$ SE=16.9

Technical

$$Tech= -1121.9 +152.9\ln(Temp) +18.6\ln(Pressure) -7.17 \ln (Airflow) +16.0 (fan) \quad (6)$$

$R^2=.831$ SE=12.4

Where:

Airflow= Total airflow through engine (lb/sec)

Fan = Dummy variable; 1 if turbofan, else 0.

Flight = Date of first flight (4th quarter 1942 =1)

Tech = Quarters to MQT; (4th quarter 1942 = one).

Temp = Turbine inlet temperature; Degrees Rankine.

Thrust = Military sea level static thrust; Lbs.

Wgt = Engine weight; Lbs.

SFC = Specific fuel consumption at military sea level static thrust; (Lb/hr)/Lb thrust.

Q = Maximum dynamic pressure; lb/ft^2.

Prop = Dummy variable; one if turboprop, zero otherwise.

Pressure = Overall pressure ratio.

* = indicated parameter at cruise speed

APPENDIX B - PRICE INDICES

PRICE LEVEL ADJUSTMENT INDEX* FOR AIRCRAFT ENGINES

YEAR	INDEX	YEAR	INDEX
1946	3.824	1960	1.832
1947	3.623	1961	1.779
1948	3.289	1962	1.718
1949	3.185	1963	1.672
1950	3.012	1964	1.618
1951	2.703	1965	1.577
1952	2.577	1966	1.506
1953	2.513	1967	1.462
1954	2.439	1968	1.370
1955	2.348	1969	1.292
1956	2.232	1970	1.220
1957	2.128	1971	1.147
1958	1.992	1972	1.064
1959	1.894	1973	1.000

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* This index is based on Bureau of Labor Statistics data for average hourly earnings of production workers in the aircraft engine industry.

APPENDIX C - ANNOTATED BIBLIOGRAPHY

This annotated bibliography attempts to provide references in addition to those cited in the body of the thesis which have either theoretically or quantitatively described the relationship between or among the three variables of cost, schedule, and performance.

A. THEORETICAL WORKS AND GROWTH MODELS

1. **Peck, M. J., and Scherer, F. M., The Weapons Acquisition Process: An Economic Analysis, The President and Fellows of Harvard College, 1962.**

This 736 page book describes the overall nature of the weapon system acquisition process. In particular, it describes the theory behind the production possibilities curves as a function of input resources and the conceptual foundations of tradeoffs between and among those resources.

2. **Zschau, E. V. W., Project Modelling: A Technique For Estimating Time-Cost-Performance Trade-offs in System Development Projects (RM-5304-PR), The Rand Corporation, Santa Monica, Ca., July 1969.**

Zschau outlines a methodology for estimating time-cost-performance tradeoffs. The theoretical model he proposes is an extension of the common linear programming approach; namely, that each set of desired system output parameters can be described as some function of the vast combination of input variables and constraints. Problems associated with the interdependence of the input variables and the nonlinearity of equations have limited the applicability of this modelling approach.

3. **Payne, I. S., Investigation of the Short Range Cost Impact of Program Stretchout, Graduate Paper, Air Force Institute of Technology, Wright-Patterson AFB, OH, September 1975.**

Payne examines the impact of program schedule on cost from the corporate financial perspective. The effects of program stretchout on several cost categories are investigated. Those categories include fixed, direct, indirect, overhead, and opportunity costs as well as the effect of reduced overhead allocation bases.

4. **Asher, N. J., and Maggelet, T. F., On Estimating the Cost Growth of Weapon Systems (P-1494), Institute for Defense Analysis, Alexandria, Va., June 1980.**

This paper documents schedule and cost growth in then current major weapon system acquisition programs which had attained initial operating capability. Note: Two other studies on this subject were cited in Chapter II.

5. **Glover, W. L., and Lenz, J. O., Cost Growth Model for Weapons System Development Programs, Graduate Paper, Air Force Institute of Technology, Wright-Patterson AFB, OH, August 1974.**

In this work, a model is presented which attempts to express final development costs as a ratio of initial cost estimates to program entropy. Here, entropy is defined as a measure of uncertainty or a lack of order in the information available to the program manager. The measure of entropy is based on subjective, personal probability statements from experts in the field.

6. **Naval Underwater Systems Center, Cost/Schedule Growth Prediction Methodology (NUSC-TR-8435), Newport, RI, October 1989.**

The theme of this report was the occurrence of risk in research and development and initial production phases of the weapon system acquisition process. The probabilities of various risks are combined to quantify cost and schedule growth.

B. SPECIFIC APPLICATIONS

1. **Mullineaux, R. W., and Yanke, M. A., Proposed Methodology for the Estimation of Jet Engine Costs in the Early Phases of the Weapons System Acquisition Process, Graduate Paper, Air Force Institute of Technology, Wright-Patterson AFB, OH, June 1976.**

This study found that in addition to performance variables, raw material related variables were highly correlated with system cost. It also investigated and recommended the use of confidence intervals when estimating system costs.

2. **Shishko, Robert, Technological Change Through Product Improvement in Aircraft Turbine Engines (R-1061-PR), The Rand Corporation, Santa Monica, Ca., May 1973.**

This work is a continuation and extension of Alexander and Nelson's 1972 report which is described in Chapter III. The concept of technological advance is investigated for a set of engines which went through product improvement. The study found that these growth engines displayed less technological advance and generally lower development costs than did newly designed engines.

3. **Hess, R. W., and Romanoff, H. P., <u>Aircraft Airframe Cost Estimating Relationships: All Mission Types (N-2283/1-AF)</u>, The Rand Corporation, Santa Monica, Ca., December 1987.**

This work is a companion note to the 1987 work by the same authors which is cited in Chapter IV. It provides the detailed results of the cost estimating relationships for aircraft airframes of all mission types.

4. **Blalock, C. D., <u>Analysis of Schedule Determination in Software Program Development and Software Development Estimation Models</u>, Graduate Paper, Air Force Institute of Technology, Wright-Patterson AFB, OH, September 1988.**

This work analyzed five software development models and compared estimates to actual results. Cited were twelve factors which most commonly impact on software delivery schedules, the most important delay being in the requirements definition phase.

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