AFIT/GCA/LAS/93S-2

# SCHEDULE ESTIMATING RELATIONSHIPS FOR THE ENGINEERING AND MANUFACTURING DEVELOPMENT OF BOMBER, TRANSPORT, TANKER, AND SURVEILLANCE AIRCRAFT SYSTEMS

THESIS

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THESIS

Presented to the Faculty of the School of Logistics and Acquisition Management
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Master of Science in Cost Analysis

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# *Preface*

While the parametric estimation of costs is thoroughly established in the development and acquisition of defense systems, as well as in other fields, parametric analysis has not been so well extended to the estimation of other variables critical to successful management. In this thesis we attempt such an extension of parametric estimation to the area of the schedule of weapon systems in the engineering and manufacturing development (EMD) phase.

These parametrically-developed models will be called schedule estimating relationships (SERs). This thesis describes the process used to arrive at SERs for nontactical aircraft. The SERs developed explain four well-defined schedule phases of EMD.

We are grateful to our advisors, Major Wendell P. Simpson III, USAF, Ph.D., and Major Kevin P. Grant, USAF, Ph.D. They helped us better appreciate the nuances and the power of regression analysis, as well as the magnitude of our work. We are deeply appreciative for the support and the patience of our families: Michele, Linda, and Kyle.

D. Scott Boyd and Brian D. Mundt

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## *Abstract*

This study developed parametric schedule estimating relationships (SERs) for the engineering and manufacturing development (EMD) phase for nontactical aircraft systems. The potential value of this nontraditional approach to estimating schedule duration has been established by previous applications to tactical aircraft, air-launched munitions, and office buildings. Prior research suggested acquisition strategy parameters to be significant schedule drivers. For this study, data on EMD milestone dates and potential schedule drivers were collected on 56 bomber, transport, tanker, and surveillance aircraft systems. Several SERs were developed for these systems using linear regression analysis. The EMD phase was divided into subphases based on significant milestones such as first prototype flight, first production-article flight, first production-article delivery, and first delivery to the operating command. The final SERs include explanatory variables that capture the acquisition strategy and physical characteristics of the systems. The SERs can be applied by program managers to estimate the EMD schedule of nontactical aircraft systems before entry into EMD.

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## *I. Background and Problem Statement*

### *A. Introduction and Objective*

*1. General Issue.* In any major project or program, performance, cost, and schedule must be weighed against one another. A project that meets the desired cost to benefit ratio is of no use if it cannot be obtained when it is needed. That is, the project's availability or completion schedule must be traded-off against its performance and its cost. The program manager needs to be able to estimate the schedule if he or she is to make tradeoffs.

This is true for major Air Force weapon systems. For example, the Air Mobility Command (AMC) needs a system that will transport a given tonnage a given distance in a given time, and in a cost-effective manner. Furthermore, AMC has determined that it needs the system within the next five years. Therefore, AMC may need to tradeoff the system's performance and/or its cost to meet that tight availability schedule.

To conduct such tradeoff analyses, the DOD must be able to estimate the system's schedule, given the system's parameters. Decision makers make decisions based on the best information they can get. They may make the wrong decision if they are unable to obtain an accurate estimate of the duration of their program. Unfortunately, the estimation of schedules is not accurate (Biery, 1974:13).

The answer to the classic question of "how long" can be arrived at in many ways. Examples include (1) a guess by someone who is experienced, (2) a buildup estimate of each task and its relationship to each of the other tasks (commonly referred to as network-based scheduling), or (3) an analogy may be made to a project completed in the past. However, despite advances in network scheduling, the schedules for recent major DOD programs grew one-fifth beyond their original schedule estimate (Biery, 1986:21). This problem is further exacerbated in estimating development schedules. While detailed data is available for networking the production schedule, such details have yet to be decided for development (Nelson, 1986:1-1).

If a better method of predicting schedules could be developed, program managers would be better able to make decisions concerning their programs and would better understand what effects different elements of the program have on the program schedule. One possible alternative is the use of parametric techniques to construct a mathematical relationship between independent variable/s and the duration time of an event, that is, develop a schedule estimating relationship (SER).

***2. Research Objective.*** The objective of this research is to produce schedule estimating relationships (SERs) to estimate the duration of the engineering and manufacturing (EMD) phase for bomber, transport, tanker, and surveillance aircraft. These relationships are intended to support program managers by providing estimates of EMD subphases based on system and program characteristics that are known before EMD contract award. SERs developed using independent variables not known to the program manager when he or she must employ this tool are of little use (Orczyk and Chang, 1990:M.4.1).

### *B. Scope*

After reviewing the literature, it was noted that SER research was limited to tactical aircraft and to air-launched munitions (Harmon and others, 1989:257, and Harmon and Ward, 1990:115). A logical extension--given that SERs have not been accomplished for nontactical aircraft--was to model SERs for nontactical aircraft: bomber, tanker, transport, and surveillance aircraft. These aircraft, although not normally thought of as in the same class, are considered here in the same class because they are all nontactical aircraft. The Aeronautical Systems Center (ASC) applied the tactical-aircraft SERs to the F-22 program (Graham, 1991). ASC was interested in extending SERs to large aircraft systems and so sponsored this research.

This thesis will also explore only the engineering and manufacturing development (EMD) phase of a major weapon system, as broken down into logical subphases. Previous SER research was similarly limited to EMD. SERs are not necessary for production scheduling since detailed information is available for network scheduling.

### C. *Definition of Terms*

There are several terms for which operational definitions are needed. These terms and short definitions of each follow:

***1. Schedule Estimating Relationship (SER).*** A mathematical model developed to express the relationship of independent variable/s to a dependent variable (a defined duration of time).

***2. EMD Contract Award.*** The date the contract to begin the EMD phase of the program is signed by the contractor. Formerly called full-scale development (FSD) contract award. For purposes of clarity and consistency, the design phase will, from now on, be referred to by its current name of EMD.

***3. First Prototype Flight.*** The date the first developmental aircraft flew. This aircraft represents a near production-ready aircraft. Some programs have no prototypes.

***4. First Production Flight.*** The date the first aircraft produced using production tooling flew.

***5. First Production Delivery.*** The date the first production aircraft was delivered to the purchasing military service [for example, Air Force Materiel Command (AFMC)].

***6. First Delivery to the Using Command.*** The date the first delivery of a fully operational aircraft was delivered to the using command's [for example, Air Combat Command (ACC)] operational base.

### *D. Overview*

There are three areas in which parametric analysis has been applied to schedules. One common complaint has been that it takes too long to develop and produce a new weapon system after a threat has been assessed and a decision to counter the threat has been made (Smith and Friedmann, 1980:1). These complaints have been heard and studies have been performed to decide if the acquisition process is taking longer: these studies employed parametric techniques to test the hypothesis that weapon system development times are lengthening. The second area of tangent research has been in the identification of independent variables significantly related to the schedule of a program. These studies discovered that the performance variables normally related to the cost of a system are not necessarily related to a system's schedule (Drezner and Smith, 1990:45). The third area in which research has been performed is the area of parametrically-developed SERs; this third area is also the subject of this thesis. The work in this area has uncovered that the estimation of schedules can be accomplished and that these models can have respectable statistical properties. These three areas and the research accomplished in each are the subject of Chapter II.

Chapter III will explain the data collection, variable identification, and methodology used to arrive at the schedule estimating relationships. Chapter IV relates the analysis and findings when the methodology was performed on the data collected. Chapter V will provide suggested applications for the models developed and will suggest further research in the schedule estimating area.

# *II. Literature Review*

## *A. Introduction*

While much has been written on how to build and estimate the schedules of major programs, most theory and application have been in network scheduling (such as PERT). Only a handful of researchers has plied their regression tools to the task of parametric estimation of schedule durations. Much literature has bemoaned the lengthening of the acquisition process or analyzed schedule data to learn and compare mean durations. Several went on to propose factors that directly lengthen or shorten schedule durations. Only two sets of researchers--Harmon, Ward, and Palmer in the aerospace industry, and Orczyk and Chang in the construction industry--have developed workable parametric estimators of schedule durations.

Many major programs are risky ventures. Much of the program is uncertain as it progresses through development: the requirements for the system are uncertain, the system is politically and economically uncertain, and the system's technology and design are uncertain. Such uncertainty is further compounded by the uncertainty inherent in the estimator's craft. This uncertainty contributes to the variance between a program's planned schedule and its actual schedule.

To reduce the risk and the variance, the DOD has standardized and institutionalized the acquisition process over time (Tyson and others, 1989:II-8). This is why many had hoped to see--all other things being equal--the acquisition schedule getting shorter. In the 1960s, Secretary of Defense Robert McNamara implemented the Planning-Programming-Budgeting System (PPBS) and the Five-Year Defense Plan (FYDP). He also introduced the Selected Acquisition Reporting (SAR) system to track cost, schedule, and performance data for major systems, as well as introduced concurrency (that is, overlapping the program's phases, typically development and production). In the early 1970s, Secretary of Defense David Packard de-emphasized concurrency, emphasized prototyping (or producing a full-scale model for development and/or test purposes before production), established the Cost Analysis Improvement Group (CAIG), and encouraged design-to-cost as a criterion. In the late 1970s, the Congress increased its oversight of the acquisition process, and production *stretchouts became acceptable. Competition--as recommended* by the Grace Commission in 1984 and by the Packard Commission in 1986--became an emphasis in the 1980s.

Indeed, much improvement has been made. DOD acquisition schedules for major programs grew in the 1950s an average of 54 percent beyond their original estimate (Biery, 1986:21). McNamara's initiatives are credited with cutting overall schedule growth (that is, the increase of the actual schedule beyond the planned schedule) to 32 percent by the late 1960s (Smith and Friedmann, 1980:4). Subsequent policy initiatives--such as Packard's emphasis on prototyping--further cut overall schedule growth to 19 percent in the late 1970s (Biery, 1986:21). So while marked improvement has been made, there is still room for improvement. These developments in acquisition strategy--which came about in response to increasing costs and lengthening schedules--can have considerable influence in the schedule.

### *B. Analysis of Schedule Variance*

Despite these initiatives, it is still common belief that the acquisition process is taking longer and longer as time passes. The RAND Corporation was tasked to quantitatively verify this commonly-held hypothesis. What followed were three RAND studies, issued over a period of ten years, which cited statistics showing that (1) virtually no schedule growth has occurred in the development phase and (2) while the overall process may be lengthening slightly, the causes for the schedule growth are primarily due to factors outside the DOD's control.

***1. Smith and Friedmann, 1980.*** The first RAND study, published in 1980, compiled schedule data for 67 major programs: 18 Air Force and Navy fighters; two Navy patrol aircraft; five Air Force bombers; six Air Force and Navy attack aircraft; five Air Force transports; 18 Army, Air Force, and Navy helicopters; and 13 Air Force and Navy missiles. The data sample covered major systems entering EMD from 1944 through 1978.

RAND found the planning phase (that is, Phase I) to be increasing at a rate of ten months per decade, with a significance level for the model of less than one percent (Smith and Friedmann, 1980:15). As a scheduling heuristic, the planning phase was found to take 25 to 33 percent of a program's total acquisition time (Smith and Friedmann, 1980:34). On the other hand, the analysis did not discover any significant growth in the development phase (that is, Phase II) over time (Smith and Friedmann, 1980:25). An increased emphasis on prototyping and testing does not seem to significantly lengthen the development phase. However, the production phase (that is, Phase III) was increasing at a rate of six months per decade, with a model significance level of eight percent (Smith and Friedmann, 1980:30). The schedule growth in production paralleled the increase in average unit price (Smith and Friedmann, 1980:v).

*2.* ***Rothman, 1987.*** RAND's follow-up research, published in 1987, updated and expanded the data base. It now included schedule data for 107 major programs: 24 fighters and attack aircraft; three patrol aircraft; seven bombers; eight transports and tankers; three trainers; 16 helicopters; and 46 Air missiles. RAND's data set now extended through programs entering EMD in 1986.

This time RAND explicitly studied the relationship between phase duration and the year the program entered EMD. However, RAND's analysis failed to show a significant relationship between the length of the various intervals and calendar time, even after using categorical variables to adjust to pre-1960 and post-1960 program starts (Rothman, 1987:15 and 18). The calendar date at which Milestone II occurs was therefore deemed an inadequate proxy for the bundle of programmatic factors (Rothman, 1987:15).

*3.* ***Drezner and Smith, 1990.*** RAND's second follow-up analysis, published in 1990, focused on those factors that result in schedule delays. This study, using the 1987 data base, found the duration from Milestone I (that is, the go-ahead decision to enter the Demonstration-Validation Phase) to the first delivery of a production article (that is, the end of the EMD Phase) to be increasing at a rate of one month for each successive year--the same rate as the first RAND study found (adjusted $R^2=.10$, two-percent confidence level) (Drezner and Smith, 1990:9). Comparing the pre-1970 program starts with the post-1970 program starts, RAND found Phases I and II each roughly took one year longer when the program was started in the 1970s and 1980s than those started in the 1950s and 1960s (confidence levels of one and five percent, respectively) (Drezner and Smith, 1990:9 and 11). However, as a proxy, the year of program start fails to capture 90 percent of schedule variance.

RAND went on to examine, in depth, the planning and development phases of ten programs and potential schedule drivers. They omitted the production phase because its schedule is dictated by funding availability rather than by factors under the program's control (Drezner and Smith, 1990:15). They identified 16 factors that influence the original schedule and/or subsequent deviations, as shown in Figure 1 below.

**Drezner and Smith's Schedule Factors**

**Six factors driving the original schedule are:**

1. If the acquisition strategy includes competition.
2. If the acquisition strategy includes concurrency.
3. The adequacy of the funding.
4. If the acquisition strategy includes prototyping.
5. If the program's phases were contracted separately.
6. The service priority. (Drezner and Smith, 1990:21-22)

**Five factors driving deviation from the original schedule are:**

1. The contractor's performance.
2. External events.
3. Funding stability.
4. Major requirements stability.
5. Program manager turnover. (Drezner and Smith, 1990:23-24)

**Five factors that influence either the original schedule and/or subsequent deviations are:**

1. External guidance.
2. If the acquisition strategy includes joint program management.
3. The administrative complexity of the program.
4. The technical difficulty of the program.
5. The stability of the system specification. (Drezner and Smith, 1990:23)

Figure 1. Drezner and Smith's 16 Schedule Factors

While the inadequacy of the available documentation prevented significant analysis, they could discern trends for many drivers. Their statistical analysis of the ten programs suggested the following factors had the following influences on the original schedule estimate: (1) competition lengthens the schedule, (2) concurrency shortens the schedule, (3) prototyping lengthens the schedule, and (4) being a service priority shortens the schedule (Drezner and Smith, 1990:31). The data was inconclusive for the other seven factors theorized to drive the schedule estimate.

Their study showed the following factors resulted in schedule slips: (1) unstable funding, (2) technical difficulty, (3) external guidance, and (4) external events (Drezner and Smith, 1990:33). The data was inconclusive for the other six factors thought to slip the schedule.

RAND also reviewed the ten programs for support of two common-wisdom hypotheses. No evidence was found to support the common wisdom that programs with longer planning phases have less schedule slippage (Drezner and Smith, 1990:40). Contrary to the 1980 RAND study, no relationship was found between cost growth and schedule growth (Drezner and Smith, 1990:45).

***4. Tyson, Nelson, Om, and Palmer, 1989.*** At roughly the same time as the third RAND report, the Institute for Defense Analyses (IDA) was also examining schedule variances and their causes. They focused on six qualitative factors: (1) prototyping, (2) competition, (3) multi-year procurement, (4) design-to-cost, (5) sole-source procurement and fixed-price development, and (6) contract incentives (Tyson and others, 1989:II-9 - II-10). IDA collected a database of nine tactical aircraft, nine electronic aircraft, five helicopters, eight other aircraft, 16 air-launched tactical munitions, 18 surface-launched tactical munitions, ten electronic or avionic systems, ten strategic missiles, and four satellites.

IDA first broke the database into four periods, roughly tracking the changes in emphasis the DOD placed on the acquisition process: the 1960s, the early 1970s, the late 1970s, and the 1980s. They found the development schedule grew beyond the original estimates by 46 percent in the 1960s, by 24 percent in the early 1970s, by 37 percent in the late 1970s, and by 21 percent in the 1980s (Tyson and others, 1989:IV-

2). Similarly, production schedule growth was 64 percent in the 1960s, 84 percent in the early 1970s, 69 percent in the late 1970s, and seven percent in the 1980s (Tyson and others, 1989:IV-2).

IDA went on to analyze the various acquisition strategies as factors that result in schedule growth. Before they examined their theorized six factors, they compared aircraft schedules to see how modifying existing systems saves time versus new developments: modified systems suffer six percent less schedule growth in development and 36 percent less schedule growth in production (Tyson and others, 1989:IV-8).

As for the qualitative factors, multiyear-procurement programs experienced seven percent less production schedule growth (Tyson and others, 1989:VI-8). Competitive programs exhibited 43 percent more design-schedule growth and 39 percent more production schedule growth than programs that were not competed (Tyson and others, 1989:VII-7). Prototyping was found to reduce the development phase by 11 percent and the overall schedule by 15 percent (Tyson and others, 1989:VIII-6 - VIII-7). Contrary to intentions, design-to-cost increased development schedule growth by 12 percent and production schedule growth by two percent (Tyson and others, 1989:IX-11). If sole-sourcing was used as the acquisition strategy, production schedule growth was cut by 27 percent (Tyson and others, 1989:X-7). If the development effort was done under a fixed-price contract, development schedule growth was reduced by six percent (Tyson and others, 1989:X-13).

For some reason, while they examined the impact of contract incentives on cost growth, no mention was made of the impact on schedule growth. While their results are noteworthy, the reported statistics reported did not include the significance of the differences between the means.

*5. **Overall Findings.*** The result of the first two RAND reports was that the common wisdom that program durations are significantly lengthening is not statistically supported; in fact, the EMD-phase length has remained relatively static since the 1950s.

The third RAND study found there are six factors that influence the original schedule. It also identified five factors that cause deviation from the original schedule. Unfortunately, several of these factors are not known until toward the end of EMD, when hindsight is 20/20. The third RAND report also found no support for the common wisdom of program schedules lengthening.

The IDA research in this area aimed at discerning in which direction programmatic variables influence the program duration. They identified six qualitative factors (such as prototyping and modifications of existing programs) which were statistically significant in influencing the schedule length. The next area of research extended RAND's and IDA's research in the area of identification of schedule drivers.

### *C. Identification of Schedule Drivers*

*1. **Nelson, 1986.*** Beyond the schedule drivers (that is, those parameters considered to "drive" the dependent variable) discussed in the RAND and IDA reports above, others have researched potential schedule drivers. In the 1980s, the Aeronautical System Division (ASD) tasked The Analytic Sciences Corporation

(TASC) to improve ASD's Independent Schedule Assessment (ISA) capability for the EMD phase. The two resulting TASC papers provide the preliminary steps for modeling SERs, but no actual SER development was reported.

TASC developed a schedule data base of 17 aircraft systems, a literature review, and an identification of potential drivers. TASC's studies were the first to refer to the parametric estimation of schedules as schedule estimating relationships (Nelson, 1986:3-1). TASC found the popular drivers used in cost estimating relationships (CERs)--for example, continuous physical parameters--to be only marginally significant in SERs (Nelson, 1986:3-2).

***2. Nelson and Trageser, 1987.*** TASC then broke the EMD phase into six intervals: (1) Milestone II to EMD contract award, (2) EMD contract award to first flight, (3) first flight to first production unit, (4) first production unit to initial operating capability (IOC), (5) EMD contract award to IOC, and (6) Milestone II to IOC. Unfortunately, they failed to differentiate between first prototype flight and first production-article flight, or between first production delivery to the system manager and first production delivery to the using command--which confounds the data base (Nelson and Trageser, 1987:2-7).

TASC cataloged potential schedule drivers into six categories: (1) technical complexity, (2) degree of technological change, (3) system mission, (4) period of procurement, (5) acquisition strategy, and (6) funding profile (Nelson and Trageser, 1987:2-8).

TASC conducted a correlation analysis between the six EMD durations and the six categories of drivers. Using performance as a surrogate for technical complexity, speed, range, and payload to be correlated to EMD schedule durations (Nelson and Trageser, 1987:3-5 - 3-6). Like earlier RAND studies, they did not find a significant pairwise relationship between EMD schedule durations and the year the program entered EMD (Nelson and Trageser, 1987:3-10; and Smith and Friedmann, 1980:25). They defined mission type to be a categorical variable, not a linear variable as they had hypothesized (Nelson and Trageser, 1987:3-11). Funding stability proved a difficult parameter to estimate (Nelson and Trageser, 1987:3-13). No significant relationships existed between prototyping and EMD schedule durations--in contrast to later RAND studies (Nelson and Trageser, 1987:3-13; and Drezner and Smith, 1990:30).

Finally, TASC identified independent variables for the six EMD schedule durations. Finding no significant drivers for the duration between Milestone I and the award of the EMD contract, they recommended using program averages (Nelson and Trageser, 1987:4-4). For the duration between EMD contract award and first flight, they recommended mission type and avionics complexity (Nelson and Trageser, 1987:4-4). They suggested mission type and avionics complexity again for the period between the first flight and delivery of the first production unit (Nelson and Trageser, 1987:4-4 - 4-5). For the duration between first production unit and IOC, the mission type, the complexity of the avionics, and the period of the procurement were found related (Nelson and Trageser, 1987:4-5). For the two overall durations of Milestone II to IOC and of EMD contract award to IOC, they recommended using mission type, avionics complexity, and the period of the acquisition (Nelson and Trageser, 1987:4-5).

All in all, no simple combination of parameters considered were found to significantly account for the variance in EMD schedules (Nelson and Trageser, 1987:5-1). The best drivers identified tended to be categorical variables, not continuous.

Although research identifying independent variables and trends for differing phase durations is important, decision makers need to have answers regarding the duration of the phases for their programs. The next section reviews actual SER development. The statistics reported are those provided in the literature--in many cases, not all of the statistics conventionally provided (for example, the F- and the t-statistics) were reported.

### *D. Previous SER Research*

***1. VMSC, 1972.*** The earliest reported effort at using parametric relationships to estimate schedules was done by the Vought Missiles and Space Company (VMSC) for the NASA Space Shuttle Program in 1972. Earlier efforts for NASA resulted in relationships with low coefficients of correlation, thus deemed not accurate enough for use as the sole scheduling methodology *(Expansion and Refinement,* 1972:165).

VMSC cited several critical assumptions and criteria for their approach to Time Estimating Relationships (TERs), as they termed the parametric relationships. While qualitative factors such as optimum design, funding adequacy, and acquisition strategy account for schedule variation, VMSC considered them too subjective to address and focused on physical and performance parameters. Because computing power was limited in the early 1970s, VMSC explicitly sought to minimize the number of parameters and transformations. The TERs developed were for the prime mission product--VMSC did not attempt to provide system-level TERs.

The TER for the schedule duration from Authority to Proceed (ATP) to the first horizontal flight (roughly equivalent to the duration from start of EMD to first prototype flight in aircraft):

$$\hat{Y} = -16.30 + 0.89(R_{UL/SW}) + 14.35(C_X) + 0.01(T_{MAX}) + 8.02(N_{ENG}) \tag{1}$$

where

$\hat{Y}$ = *the schedule duration from ATP to the first horizontal flight* (months)

$R_{UL/SW}$ = *ratio of useful load to structure weight* (that is, the difference between gross weight and empty weight, divided by empty weight)

$C_X$ = *structure complexity factor* (a measure of the percentage of state-of-the-art materials used in the structure)

$T_{MAX}$ = *maximum exposed surface temperature* (°F)

$N_{ENG}$ = *number of engines (Expansion and Refinement,* 1972:224)

The TER was modeled on four large transports, two high-performance bombers, four launch vehicles, one manned rocket research aircraft, and two manned space vehicles. The (unadjusted) $R^2$ is .87 and the standard error of the estimate (SEE) is 7.09 (the significance levels of the model or of the parameters were not given).

The TER for the schedule duration from ATP to the 95 percent drawing release for the airborne equipment is:

$$\hat{Y} = 15.41 + 4.08(\ln W_{EMP}) + 15.24(\ln R_{UL/SW}) + 58.67(\ln C_X) - 1.39(R_{UL/SW}) + 11.47(R_{T/W}) - 24.01(C_X) \tag{2}$$

where

$\hat{Y}$ = *the schedule duration from ATP to the 95% drawing release for airborne equipment* (months)

$W_{EMP}$ = *empty weight* (thousands of pounds)

$R_{UL/SW}$ = *ratio of useful load to structure weight*

$C_X$ = *structure complexity factor*

$R_{T/W}$ = *thrust to weight ratio (Expansion and Refinement,* 1972:231)

The model was developed on two large transports, two high-performance bombers, three fighters, four launch vehicles, one manned rocket research aircraft, and two manned space vehicles. The (unadjusted) $R^2$ is .95 and the SEE is 3.11 (the significance levels of the model or of the parameters were not given).

The TER for the schedule duration from the 95 percent airborne-equipment drawing release to the first horizontal flight is:

$$\hat{Y} = -3.39 + 11.53(\ln R_{UL/SW}) - 0.67(R_{UL/SW}) + 0.01(A_{PLAN}) + 12.40(C_X) - 11.44(N_{ENG}) \tag{3}$$

where

$\hat{Y}$ = *schedule duration from the 95% airborne-equipment drawing release to the first horizontal flight* (months)

$R_{UL/SW}$ = *ratio of useful load to structure weight*

$A_{PLAN}$ = *planform area* (square feet), roughly equivalent to wingarea in aircraft

$C_X$ = *structure complexity factor*

$N_{ENG}$ = *number of engines (Expansion and Refinement,* 1972:236)

The model was developed on five large transports, two high-performance bombers, five fighters, five launch vehicles, and two manned space vehicles. The (unadjusted) $R^2$ is 0.89 and the SEE is 3.58 (the significance levels of the model or of the parameters were not given).

Unfortunately, no documentation could be found as to the application of VMSC's three TERs--let alone follow-up studies--so one must surmise these TERs were not used (Nelson, 1986:3-2). Furthermore, the models would need to be recalibrated for aircraft systems.

***2. Harmon, Ward, and Palmer, 1989.*** The Institute for Defense Analyses (IDA) performed two sets of SER research, the first for tactical aircraft and the second for air-launched missiles. The first SER paper by IDA covered tactical aircraft. The data set contained nine tactical aircraft programs developed in the 1950s through the 1980s: the F-4, the F-111, the F-14, the S-3, the F-15, the A-10, the F-16, the F/A-18, and the AV-8B. The programs chosen were so selected because of their recency, historical importance, and anticipated data availability (Harmon and others, 1989:259).

Harmon and others' potential schedule drivers were six program characteristics and six aircraft characteristics, as shown in Figure 2 below.

**Harmon and Others' Schedule Drivers**

1. The using military service.
2. The prime contractor.
3. Whether the system was prototyped.
4. If the acquisition strategy included contractor teaming.
5. If there was a separate engine development.
6. The number of EMD aircraft built.
7. The empty weight.
8. The combat weight.
9. The maximum speed.
10. The thrust to weight ratio at combat weight.
11. The mission radius.
12. The percentages of titanium and composites used in the airframe structure. (Harmon and others, 1989:261)

Figure 2. Harmon and Others' 12 Schedule Drivers

They compiled the following calendar months and years for the programs' milestones: (1) Milestone I, (2) pre-EMD activity start [such as request for proposal (RFP) or prototype start], (3) contract award or EMD start, (4) critical design review (CDR), (5) first flight, (6) first production delivery, (7) twenty-fourth production delivery, and (8) initial operational capability (IOC) (Harmon and others, 1989:263). The data was gathered from government sources, the prime contractors, and RAND's 1980 database.

The schedule durations before EMD were de-emphasized because they were theorized to be primarily driven by political factors (Harmon and others, 1989:262). As a result, dates for Milestone I or its equivalents were hard to pin down. CDR was used because that is when the government formally agrees the airframe's design meets specifications. IOC was a highly variable date since different operating commands [for example, Strategic Air Command (SAC) and Military Airlift Command (MAC)] define IOC differently. As a result, the date of the delivery of the twenty-fourth production article was used as a proxy of the delivery of the first squadron of aircraft and instead of IOC.

Five EMD durations were considered: (1) the duration before the start of EMD, (2) the duration from the EMD start to the first flight, (3) the duration of the development test and evaluation (DT&E), (4) the duration required for lot production, and (5) the total EMD phase, as defined as the duration from the start of EMD to the delivery of the twenty-fourth production article. Obviously, these intervals are not necessarily mutually exclusive and may overlap considerably.

The duration of pre-EMD activity was found to be:

$$PEMD = 13.0 + 19.33(PROTO) \tag{4}$$

where

*PEMD* = *length of the pre-EMD activity* (months)

*PROTO* = *prototyping,* that is, an indicator variable for if prototyping was used as an acquisition strategy (*PROTO*=1 for three data points) (Harmon and others, 1989:271)

The model was developed on a sample size of nine aircraft, the intercept is significant at $p<.0002$, the *PROTO* variable is significant at $p<.0005$, the adjusted $r^2$ is .81, and the standard error of the estimate (SEE) is 4.55. The SER may be interpreted such that the pre-EMD duration usually takes 13 months and prototyping adds another 19 months.

When developing the SER for the duration from the start of EMD to the first flight, aircraft characteristics were found insignificant as continuous independent variables. The authors theorized this was because the narrow focus of the small sample set did not provide for much variation in the independent variables' ranges (Harmon and others, 1989:272).

The SER for the interval from EMD start to the first flight is:

$$TFF = 25.1 + 6.9(MCAIR) - 2.7(PROTO) + 2.9(TEAM) \qquad (5)$$

where

*TFF* = *time to first flight* (months)

*MCAIR* = *McDonnell Douglas Aircraft Corporation,* that is, an indicator for those programs for which McDonnell Douglas is the prime contractor (*MCAIR*=1 for four data points)

*PROTO* = *prototyping,* which indicates those programs that were *prototyped* (*PROTO*=1 for three data points)

*TEAM* = *teaming,* which indicates when contractor *teaming* arrangements were used (*TEAM*=1 for three data points) (Harmon and others, 1989:273)

The sample size was nine, *MCAIR* is significant at $p<.002$, the intercept is significant at $p<.0001$, *PROTO* is significant at $p<.065$, *TEAM* is significant at $p<.060$, the adjusted $R^2$ is .89, and the SEE is 1.6.

Thus, the time to first flight typically takes 25 months, it will take about seven months longer is McDonnell Douglas is the prime contractor, but three months shorter if the program was prototyped, and an additional three months if the contractors were teamed. McDonnell Douglas agreed the *MCAIR* finding is consistent with McDonnell Douglas' development philosophy (Harmon and others, 1989:274). Because of the longer logistics tail between the contractors, it is intuitive that *TEAM* adds time.

The DT&E interval can be derived from the relationship

$$Flt\ Test\ Duration = \frac{(Required\ Nr\ of\ Flt\ Test\ Hours)}{(Monthly\ Flt\text{-}Hr\ Rate) * (Nr\ Test\ A/C)} \tag{6}$$

where the required number of flight test hours and the number of test aircraft are understood to be dictated by authorities outside the program office (Harmon and others, 1989:274).

To estimate the monthly flight-hour rate, they developed three relationships. The first relationship measures the average monthly flight-hour rate for the air vehicle test:

$$AHM = 5{,}486 * (EWT)^{-.61} \tag{7}$$

where

*AHM = average monthly flight-hour rate for the air vehicle test*

*EWT = empty weight* (pounds) (Harmon and others, 1989:274)

The model was developed on a sample of six aircraft, the intercept is significant at $p < .002$, *EWT* is significant at $p < .007$, the adjusted $r^2$ is .83, and the SEE is .14.

The relationship for the average monthly flight-hour rate for the avionics test is:

$$AVHM = 4{,}915 * (EWT)^{-.57} \tag{8}$$

where

*AVHM = average monthly flight-hour rate for the avionics test*

*EWT = empty weight* (pounds) (Harmon and others, 1989:275)

The sample size for the model was six aircraft, the intercept is significant at $p < .005$, *EWT* is significant at $p < .019$, the adjusted $r^2$ is .73, and the SEE is .17.

The relationship for the average monthly flight-hour rate for the armament test is:

$$ARHM = 330 * (EWT)^{-.36} \tag{9}$$

where

*ARHM = average monthly flight-hour rate for the armament test*

*EWT = empty weight* (pounds) (Harmon and others, 1989:275)

The model's sample size was five aircraft, the intercept is significant at $p < .054$, *EWT* is significant at $p < .14$, the adjusted $r^2$ is .42, and the SEE is .21.

The SER for the length of production for each lot is:

$$PT = 19.3 * (Q)^{-.094} * (CUMQ)^{-.063} * 1.16(MCAIR) * 1.21(TEAM) \tag{10}$$

where

*PT = production time for the production lot* (months), analogous to the first unit cost ($T_1$) of a learning curve

*Q = lot quantity*

*CUMQ = cumulative quantity as of the last delivery of the previous lot* (thus the SER measures production time for EMD and early production lots)

*MCAIR = McDonnell Douglas*

*TEAM = contractor teaming* (Harmon and others, 1989:276)

Twenty-two aircraft were used in developing this model, the intercept is significant at $p<.0001$, $Q$ is significant at $p<.0009$, $CUMQ$ is significant at $p<.0002$, $MCAIR$ is significant at $p<.0036$, $TEAM$ is significant at $p<.0004$, the adjusted $R^2$ is .85, and the SEE is .07. The model may be interpreted such that McDonnell Douglas' production time per lot is 16 percent longer than for other prime contractors and production under teaming arrangements takes 21 percent longer than where teaming is not used.

Finally, the SER for overall EMD length:

$$T24 = 22.1 * (A)^{-.141} * 1.15(MCAIR) * .89(PROTO) \tag{11}$$

where

*T24 = the duration from the start of EMD to the delivery of the twenty-fourth production article* (months)

*A = shape parameter governing time to peak expenditure rate*

*MCAIR = McDonnell Douglas (MCAIR*=1 for three data points in the sample of nine)

*PROTO = prototyping (PROTO*=1 for two points) (Harmon and others, 1989:278)

Eight aircraft were used to develop this model, the intercept is significant at $p<.0011$, *A* is significant at $p<.054$, *MCAIR* is significant at $p<.035$, *PROTO* is significant at $p<.075$, the adjusted $R^2$ is .91, and the SEE is .05.

The *A* shape parameter is necessary because the EMD program expenditure rate dictates the length of EMD (Harmon and others, 1989:276). *A* can be estimated using nonlinear least squares and was derived from the following formula for the buildup of research and development expenditures:

$$Y_t = K*(1-e^{-A*t^2}) \tag{12}$$

where

$Y_t$ = *cumulative expenditure at time t*

$K$ = *total expenditure at the end of development*

$t$ = *time from the program start* (months)

$A$ = *shape parameter governing the time to peak expenditure rate* (Harmon and others, 1989:277)

Again, the SER may be interpreted such that EMD under McDonnell Douglas takes 15 percent longer than when under other prime contractors, but prototyping cuts the length of EMD by 11 percent.

***3. Harmon and Ward, 1990.*** After their success at developing SERs for tactical aircraft in EMD, Harmon and Ward went on to develop SERs for air-launched missiles. Their methodology paralleled their previous work.

Harmon and Ward collected data for seven air-to-air missile programs (the AIM-7F, the AIM-7M, the AIM-9L, the AIM-9M, the AIM-54A, the AIM-54C, and the AIM-120) and for seven air-to-surface missile programs (the AGM-65A, the AGM-65D, the AGM-69, the AGM-84, the AGM-86, the AGM-88, and the AGM-114). These systems were developed from the late 1960s to the late 1980s. The potential schedule drivers included seven program characteristics (using service, prime contractor, if it was prototyped, the number of prototype missiles, the number of prototype launches, the number of development missiles produced, the number of development launches, and the launch platforms used during EMD) and nine missile characteristics [primary targets, guidance type, length, diameter, total weight, guidance weight (a proxy for technical complexity), missile cross-section, the ratio of guidance weight to cross-section, and total impulse] (Harmon and Ward, 1990:122-125). The six schedule milestone months and years gathered included the prototype start, the first prototype launch, the start of EMD, the first guided EMD launch, the first production delivery, and IOC. Besides gathering data from government sources and prime contractors, the 1987 RAND database was also used.

The four EMD intervals were defined as (1) the time to the first guided launch, (2) the length of the DT&E program, (3) the early production time, and (4) the overall EMD length. These intervals are not mutually exclusive and may be concurrent. They could not develop a relationship for the total EMD schedule: the time from EMD start to first launch is a function of physical and performance characteristics, while the remainder of the EMD effort is a function of the number of missiles launched in DT&E (Harmon and Ward, 1990:153).

The SER for the time to the first guided launch *(TFGL)* is:

$$TFGL = 4.6 + .11(GWt) + 8.1(GCPLX) + 9.5(NEWAA) \qquad (13)$$

where

*TFGL* = *time from EMD start to the first guided launch* (months)

*GWt* = *gross weight* (pounds)

*GCPLX* = *ratio of guidance weight* (pounds) *to the missile cross-section* (square inches), a proxy for guidance complexity

*NEWAA* = *indicator for those air-to-air programs that were new starts* (*NEWAA*=1 for two data points of the sample of 12) (Harmon and Ward, 1990:141)

The sample set used to develop this model contained 12 systems, (the significant for the intercept was not given), *GWt* is significant at $p < .01$, *GCPLX* is significant at $p < .04$, *NEWAA* is significant at $p < .03$, the adjusted $R^2$ is .87, and the standard error of the estimate (SEE) is 3.2. Having only two data points for *NEWAA* severely limits the interpretation that *TFGL* is three times as long for new air-to-air developments as for other air-launched munitions.

The flight test duration is derived from the following relationship:

$$\textit{Test Phase Duration} = \frac{\textit{Nr Test Launches} - 1}{\textit{Launch Rate} \,/\, \textit{Month}} \qquad (14)$$

(Harmon and Ward, 1990:141).

The launch rate per month may be estimated from:

$$\begin{aligned} LRATE = {} & 12.7 * (GWt)^{-.36} * (NSITES)^{.54} * e^{(.80 * SHIP)} * e^{(-.52 * AA)} \\ & * e^{(-1.35 * PFSD)} * e^{(-.78 * DTE)} * e^{(-.5 * JOINT)} \end{aligned} \qquad (15)$$

where

*LRATE* = *monthly launch rate*

*GWt* = *gross weight* (pounds)

*NSITES* = *number of major sites from which launch testing takes place*

*SHIP* = *indicator for those programs with test launches performed from surface ships*

*AA* = *indicator for air-to-air programs*

*PEMD* = *indicator for those programs with pre-EMD testing*

*DT&E* = *indicator for those programs with testing during EMD*

*JOINT* = *indicator for those programs that had testing before and during EMD* (Harmon and Ward, 1990:143-145)

The constant term has already been adjusted for log-log bias in the model (Harmon and Ward, 1990:144). The model was developed on a sample of 30 systems, (the significance for the intercept was not provided), *GWt* is significant at $p<.01$, *NSITES* is significant at $p<.04$, *SHIP* is significant at $p<.01$, *AA* is significant at $p<.01$, *PEMD* is significant at $p<.01$, *DT&E* is significant at $p<.01$, *JOINT* is significant at $p<.03$, the adjusted $R^2$ is .75, and the SEE is .32. It is interesting that five of the seven variables in the model are indicator variables.

No statistical relationships were found between production times and program characteristics, missile characteristics, or cumulative quantities (Harmon and Ward, 1990:151). Rather, arithmetic means appear to adequately estimate production times.

Similarly, they were unable to develop an SER to estimate EMD length from EMD start to first production delivery. The duration from the first launch to the delivery of the first production article is a function of the number of missiles used in flight testing:

$$FLFDEL = 27.7 + .0115 * (NMISSL)^{1.02} * (GWt)^{.77} * e^{(.94 * AA)} \tag{16}$$

where

*FLFDEL* = *duration from first launch to first delivery* (months)

*NMISSL* = *number of missiles launched at long-lead release*

*GWt* = *gross weight* (pounds)

*AA* = *indicator for air-to-air missile programs* (Harmon and Ward, 1990:153)

Note this is a nonlinear, least-squares model. The sample set used in model building included 11 data points, the intercept is significant at $p<.01$, *NMISSL* is significant at $p<.05$, *GWt* is significant at $p<.02$, *AA* is significant at $p<.01$, and the (unadjusted) $R^2$ is .97.

While the required number of test launches, one of the parameters in Equation 16, is usually dictated from outside the program office, that too may be estimated via:

$$NMIS = 24.6 * (NPLATFORM)^{.62} * e^{(-.43 * MOD)} * e^{(.79 * AA)} \tag{17}$$

where

*NMIS* = *required number of missile test launches*

*NPLATFORM* = *number of kinds of launch platforms used*

*MOD* = *indicator for those programs that are modifications*

*AA* = *indicator for air-to-air missile programs* (Harmon and Ward, 1990:148)

Eleven systems were used to develop this model, (the significance for the intercept was not given), *NPLATFORM* is significant at $p<.01$, *MOD* is significant at $p<.04$, *AA* is significant at $p<.01$, the adjusted $R^2$ is .80, and the SEE is .24.

The research by Harmon and others is impressive: the models are statistically significant and the statistics, such as the $R^2$, are very respectable. Unfortunately, several parameters were modeled off few data points, severely limiting the models' robustness.

Furthermore, several variables used in these models are not known before entry into EMD, such as the expenditure rate. The intent of SERs is to provide decision makers with useful information regarding the estimated duration of their programs. Estimating error is compounded when an analyst must use a parametric model to estimate not only the duration time, but also the variables used in the model.

***4. Orczyk and Chang, 1990 and 1991.*** The defense and the construction industries are the two fields which regularly use parametric estimating techniques such as cost estimating relationships (CERs). Independent of the previous VMSC and IDA research in TERs and SERs, Orczyk and Chang developed an SER which estimates the schedule duration for the construction of a low-rise office building.

Analogous to the system acquisition phases of planning, development, and production are the conceptual, bidding, and construction phases in construction. While it is easy to build schedules in the construction phase via networks, network scheduling is an impossible task in the conceptual phase, given the few hard facts. Similarly, the owner needs an independent schedule estimate to analyze alternate programs, to judge the bids, and to appraise the contractor's performance. Currently, construction schedules are typically estimated as a function of the total cost; one such cost-schedule relationship has an (unadjusted) $r^2$ of .39 (Orczyk and Chang, 1990:M.4.3). Orczyk and Chang sought to increase the coefficient of determination by moving to a multivariate model.

However, any SER must first meet three criteria to be useful (Orczyk and Chang, 1991:41). First, the SER can require only information available before entering the development phase. Typically only significant performance and program characteristics are known. Construction CERs--using only five physical parameters--reliably account for 85 percent of the variance in a program's cost (Orczyk and Chang, 1991:41). Second, the SER must be inexpensive to run. Given modern computers, this is no longer the problem it once was. Third, the SER must be able to predict not only the overall duration, but also intermediate milestones.

After experts identified 43 potential schedule drivers and 32 important milestones, Orczyk and Chang surveyed 54 large builders--representative of each climatic zone of the United States--to pare the number of potential parameters and milestones down to 15 each. Frequently cited parameters included total floor area and the type of framing system (Orczyk and Chang, 1990:M.4.3). They surveyed 1,498 builders for parameter and milestone data, 74 responded and 69 data sets were usable.

Using the stepwise selection procedure in the $SPSS^X$ statistical software system, they developed an SER for total program duration:

$$\begin{aligned} PROJDUR = {} & -.22 + .38[\ln(TFA)] - 2.17(SCW) - 1.77(CW) \\ & - .79(PCWP) - 1.07(BVMB) - 2.12(BVSB) - 1.62(EISSB) \\ & + 1.76(SSF) + 1.70(CPCF) - .62(DF) + .16(NF) \\ & + .41(TFA * SCW) + .41(TFA * CW) + .22(TFA * PCWP) \\ & + .30(TFA * BVMB) + .48(TFA * BVSB) + .38(TFA * EISSB) \\ & - .38(TFA * SSF) - .36(TFA * CPCF) + .12(TFA * DF) \\ & - .22(TFA * NF) \end{aligned} \tag{18}$$

where

*PROJDUR* = *total project duration* (weeks)

*TFA* = *total floor area* (square feet)

*SCW* = *indicator for start of construction in the winter*

*CW* = *indicator for curtain walls*

*PCWP* = *indicator for precast concrete wall panels*

*BVMP* = *indicator for brick veneer with masonry backup*

*BVSB* = *indicator for brick veneer with stud backup*

*EISSB* = *indicator for exterior insulation system with stud backup*

*SSF* = *indicator for structural steel frames*

*CPCF* = *indicator for cast-in-place concrete frames*

*DF* = *indicator for deep foundations*

*NF* = *number of floors* (Orczyk and Chang, 1991:44-45)

Sixty-nine cases were used to develop this model. While the significance of the individual parameters was not given, the overall model is significant at $p < .001$, the (unadjusted) $R^2$ is .72, and the standard error of the model is 69. Of particular interest is that *TFA* accounts for 45 percent of the variation in the construction schedule of low-rise office buildings, which is consistent with construction CERs, where *TFA* accounts for 38 percent of total cost variation (Orczyk and Chang, 1991:42 and 46).

### *E. Conclusion*

One underlying motif which carries through all the above literature is that schedule is driven by factors that do not lend themselves to being measured using a continuous scale. For many of these factors, the best one can do is to define a categorical measure of the factor. The literature provides a solid list of probable independent variables for an EMD SER: competition, concurrency, prototyping, modification of an existing system, if McDonnell Douglas is the prime contractor, the mission, the service priority, the funding stability, external guidance (such as design-to-cost), the technical complexity (using physical or performance characteristics as a proxy), the number of engines, and the year the program enters EMD (although the literature is divided on this as a schedule driver).

Figure 3 below summarizes the parameters theorized in the literature to drive schedule length. As can be seen, 12 of the 16 parameters theorized to drive the acquisition schedule are qualitative.

**Schedule Drivers in the Literature**

| Parameter | Qualitative | Relationship | # Citations |
|---|---|---|---|
| Size | No | Positive | 12 |
| Technical Performance | No | Positive | 6 |
| Prototyping | Yes | (Depends) | 5 |
| Modification | Yes | Negative | 4 |
| Year EMD Entered | No | Positive? | 4 |
| Competition | Yes | Positive | 4 |
| McDonnell Douglas | Yes | Positive | 3 |
| Funding Stability | Yes | Negative | 2 |
| Quantity | No | Negative | 2 |
| Combative Mission | Yes | Positive | 1 |
| Concurrency | Yes | (Depends) | 1 |
| Priority | Yes | Negative | 1 |
| Joint Program | Yes | (Depends) | 1 |
| Sole Sourcing | Yes | Negative | 1 |
| External Guidance | Yes | Positive | 1 |
| External Events | Yes | (Depends) | 1 |

Figure 3. Schedule Drivers Theorized in Literature

The literature also had some limitations to the future extension of their findings. As is fairly common in defense acquisition research, most of the models were built with small sample sizes, especially so for some significant parameters. Of the 15 SER models developed in the literature, 10 were built with less than 30 data sets. Five SER parameters were modeled off three or fewer data points.

Probably due to computing limitations at the time of the research, significance levels of the parameters and of the model are often not cited--one may suspect several parameters are not significant. Furthermore, several factors used as variables--while significant in explaining the schedule's variation--are not accurately known as the program nears the end of the planning phases (for example, the funding adequacy or stability).

The next chapter discusses the methodology used for this thesis' research. It parallels that of the methodology used in most of the literature.

# *III. Methodology*

## *A. Introduction*

This chapter will explain the methodology used to arrive at models that capture the amount of time required for each of the four subphases depicted in Figure 5. As in the literature, regression analysis is the primary tool for modeling SERs. For reasons of reference and because of its explication, the regression-analysis methodology found in *SAS System for Regression*, by Rudolf J. Freund and Ramon C. Littell, will be followed.

Freund and Littell use principal component analysis, also known as factor analysis, as their first step to separate the variables into differentiated categories. Freund and Littell go on to use a technique that selects models with the highest R-square value. Although Freund and Littell's general methodology will be followed, there are some minor deviations from their techniques. In cases where this thesis' methodology differs from Freund and Littell's outline, the steps are clearly identified.

For example, one area of which Freund and Littell spoke little is the identification of the independent variables. Since this process must be accomplished before any statistical analysis can be done, this task was accomplished during the early stages of this research effort. A discussion of data sources, identification of categories to measure each subphase of EMD, and the individual independent variables chosen to measure each category will be provided first. After this step, Freund and Littell's method will be followed.

The following paragraphs discuss the data sources used, the categories which best explain each subphase of EMD, as well as the points considered important when selecting the individual independent variables to measure each of these categories.

### *B. Data Sources*

There are many sources of data that often provide conflicting information. Therefore, official records were deferred to. The information in the ASC publication Air Force Guides 1 and 2, *USAF Standard Aircraft Characteristics*, is garnered from the individual system program offices (SPOs) which worked to acquire the aircraft. There are several guides in this series. The guides which were used for this thesis' data base are referred to as the *Brown Book* and the *Green Book*. The *Brown Book* provides data on transports (that is, aircraft belonging to the former MAC). The *Green Book* provides data on bomber, tanker, and surveillance aircraft (that is, aircraft belonging to the former SAC). The guides are updated regularly for classification and new information purposes.

Supplementary data sources include (1) RAND's *Aerospace Weapon System Acquisition Milestones: A Data Base,* (2) *Jane's All the World's Aircraft,* and (3) the *Encyclopedia of U.S. Air Force Aircraft and Missile Systems*. The RAND data base was used by subsequent RAND and IDA schedule research. *Jane's* lists current information on aircraft produced by aircraft manufacturers around the world and is updated annually. *Jane's* is considered an authority in the aircraft industry due to the publication's long history. The information contained in the *Jane's* is accurate at the time of publication, therefore each airplane had to be researched sequentially through each annual publication. The *Encyclopedia of U.S. Air Force Aircraft* was published under the auspices of the Air Force Office of History and thus may be considered an accurate portrayal of the history of each aircraft.

These data sources provided data for 56 aircraft. See the appendix for the aircraft and their parameters. The primary criterion for inclusion in the database was that the aircraft be a bomber, transport, tanker, or surveillance aircraft acquired by the DOD, with production occurring after World War II. Aircraft were considered such if their primary designator was B (for bomber), C (for cargo), K (for tanker), E (for electronic surveillance), or P (for patrol). Attack (A) and trainer (T) aircraft were considered if they were multi-engined, had mission profiles similar to the other aircraft (for example, the A-3), and/or were modifications of existing cargo aircraft (for example, the T-43).

The secondary criterion for inclusion in the database was that at least one EMD date beyond the EMD-start date must be available. After that, the rest was relatively straight forward. Multiple observations on the same aircraft system (for example, the B-52A and the B-52G) were included if the subsequent modification represented a significant change in the system, rather than an evolutionary improvement. The database represents the full range of nontactical aircraft, with wide ranges of size (as measured by empty weight or wing span) and of performance (as measured by speed or range). In comparison to historical schedule information, the potential driver data was relatively easy to collect.

### *C. Dependent Variables*

***1. Subphases.*** Initially, the subphases of design, test, and low-rate initial production (LRIP) were considered the intuitive breakdowns of the EMD phase. The design subphase begins at EMD contract award and ends with completion of the critical design review (CDR). The test subphase begins with the completion of CDR and ends with the completion of the functional configuration audit (FCA). The LRIP subphase of EMD begins with the completion of the production readiness review (PRR) and ends with the roll-out of the first production article. These initial subphases of EMD are depicted in Figure 4 below.

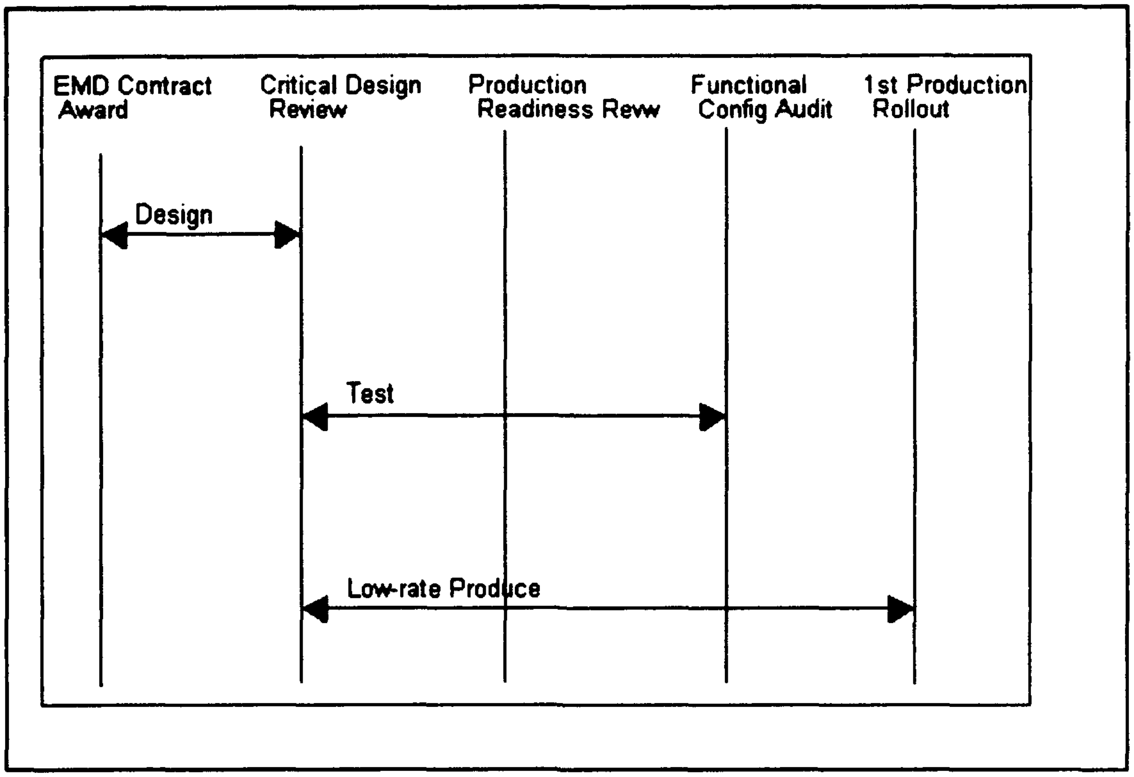

Figure 4. Original Conception of EMD Subphases

Unfortunately, these three subphases of EMD were difficult to define clearly for older programs and the collection of beginning and ending dates for older programs proved impossible. Upon further examination of the available schedule information, several reliable sources were found to provide and corroborate the EMD [formerly known as full-scale development (FSD)] contract award date, the first prototype flight date, the first production article flight date, the first production delivery date, the first delivery to the user date, and the initial operational capability (IOC) date. During further review, it was discovered the IOC date is defined differently by each using command [for example, between the former Strategic Air Command (SAC) and the former Military Airlift command (MAC)], therefore, the IOC date was not considered further.

Thus, as depicted in Figure 5 below, SERs were developed for four EMD subphases: (1) the duration from the start of EMD to the first prototype flight, referred to as *DurProF*, (2) the duration from the start of EMD to the first production article flight, referred to as *DurPdnF*, (3) the duration from the start of EMD to the delivery of the first production article to the acquiring agency, referred to as *DurPdnD*, and (4) the duration from the start of EMD to the delivery of the first production article to the user, referred to as *DurUsrD*. The duration to first production flight *(DurPdnF)* interval is equivalent to Harmon and others' time-to-first-flight *(TFF)* duration (see Equation 5) and the duration to first user deliver is similar to Harmon and others' time-to-twenty-fourth-delivery *(T24)* duration (see Equation 11). Although these dates do not coincide with the originally-conceived subphases of EMD, the design, test, and LRIP subphases are built from the dates of the first prototype flight, the first production flight, the first production article delivery, and the first delivery to the using command.

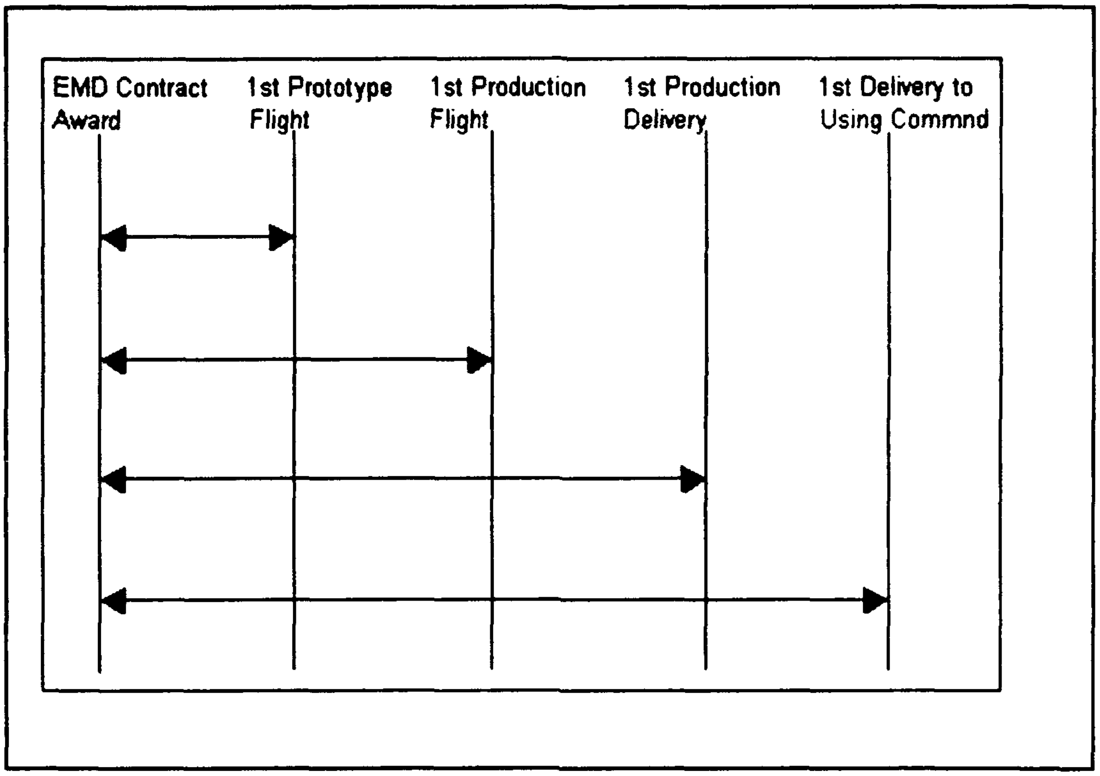

Figure 5. EMD Subphases

*2. **Dependent Variables.*** The dates in the database (see the appendix) are the decimalized equivalent of the Julian dates. The first two digits represent the year and the decimalized portion represents the month and date. For example, 10 May 1957 would be 57.353 and 19 August 1991 would be 91.630.

Since all dates could not be obtained for all 56 systems, the four dependent variables have slightly different sample sets. There are 38 observations for our first dependent variable, the duration to the first prototype flight *(DurProF)*, which range from -0.14 years (the KC-135, an initiative on Boeing's part) to 7.75 years (the B-2), with a mean of 2.58 years and a standard deviation of 1.85 years. There are 37 observations for the duration to the first flight of the first production article *(DurPdnF)*, which range from 0.29 years (the E-4) to 8.31 years (the C-17), with a mean of 2.91 years and a standard deviation of 1.79 years. There are 37 observations for the duration to the delivery of the first production article to the acquiring agency *(DurPdnD)*, which range from 0.28 years (the C-20) to 8.41 years (the C-17), with a mean of 3.44 years and a standard deviation of 1.83 years. There are 39 observations for the duration to the delivery of the first production article to the using command *(DurUsrD)*, which range from 0.67 years (the C-23) to 7.09 years (the B-58), with a mean of 3.77 years and a standard deviation of 1.87 years.

## *D. Categories of Drivers*

The intent of the EMD phase is to transform a technology or technologies developed in a laboratory or near-laboratory environment into a well-tested, integrated system and to setup the initial production facilities. The key here is that the EMD phase is the transition phase from a planning environment to a production environment. In recognition of its purpose, the categories that might best explain this transition phase include (1) the program characteristics, (2) the technological characteristics, and (3) the physical characteristics. These categories parallel those theorized in the literature (for example, Nelson and Trageser, 1987:2-8).

The programmatic category captures the choices made by the program manager and the contractor which influence the length of EMD, for example, the acquisition strategy used. Most acquisition strategies evolved to serve some greater good, such as a better product or to reduce cost and/or schedule. This category should be related to all of the subphases of EMD because the programmatic choices made influence the program throughout the EMD phase.

The technological category might be more related to the earlier subphases, such as EMD contract award to first prototype flight. The general idea is technologically-advanced systems take longer than those that are not. This category might also be related to the later phases due to the complexity involved in manufacturing a technologically advanced aircraft.

The physical category should be more related to the later subphases, perhaps the amount of time required from EMD contract award to first production flight, production delivery, and delivery to the using command. This is so because a larger aircraft would require more production facilities--taking longer to acquire and put in place. These variables are often referred to as size variables.

### *E. Independent Variables*

The independent variables should measure at least one of the stated categories above. The independent variables must be logically related to the dependent variables being explained. One would expect if the independent variable is to be a statistically-significant coefficient, it would also be correlated to the dependent variable. The independent variables selected should also be easily defined and the relationship between these variables and the dependent variables should be understood by the analysts building the estimating relationship.

Furthermore, consideration should be given to the problem of data availability, that is, the data itself must be obtainable from a reliable source with a reputation for measuring the characteristics of the items being estimated. Variables should also be considered if the literature prescribed them as influential.

After addressing each of these considerations the following independent variables were chosen as candidate measures for each of the categories. The following figure depicts the 15 parameters collected and the initial logic, as will be discussed later, with respect to EMD durations. Compare Figure 6 below with Figure 3, which catalogs the parameters theorized in the literature.

**Summary Table of Independent Variables**
**Initial Interpretation**

| Variable Name | Type | Measures | Relationship |
|---|---|---|---|
| *McDAC* | Indicator | Programmatic | Positive |
| *Mod* | Indicator | Programmatic | Negative |
| *Nonoff* | Indicator | Programmatic | Negative |
| *Proto* | Indicator | Programmatic | Positive |
| *NrProto* | Continuous | Programmatic | Positive |
| *WingSpan* | Continuous | Physical | Positive |
| *WingArea* | Continuous | Physical | Positive |
| *EmpWgt* | Continuous | Physical | Positive |
| *NrEng* | Continuous | Physical | Positive |
| *MaxThr* | Continuous | Technology | Positive |
| *AvgSpd* | Continuous | Technology | Positive |
| *MaxSpd* | Continuous | Technology | Positive |
| *CmbtRad* | Continuous | Technology | Positive |
| *Range* | Continuous | Technology | Positive |
| *EMD** | Continuous | Technology | Positive |

* Note: Not included in the duration from EMD contract award to first prototype flight model; results in a perfect linear combination.

Figure 6. Initial Interpretation of Independent Variables

### 1. *McDonnell Douglas, "McDAC"*

***a. Variable Selection.*** The use of indicator variables in regression models signifies that the particular characteristic being measured cannot be directly observed. In their research for tactical aircraft SERs, Harmon and others found whether McDonnell Douglas is the prime contractor to be a significant driver of EMD schedule intervals (Harmon, Ward, and Palmer, 1989:273). Since their hypothesis was that McDonnell Douglas' EMD is a more thorough effort for tactical aircraft, it is reasonable that it should extend to nontactical aircraft also.

***b. Definition.*** This variable is categorical and is measured as a one or a zero. A one indicates the prime contractor was McDonnell Douglas. A zero indicates the prime contractor was someone other than McDonnell Douglas.

***c. Relationship to the Dependent Variables.*** Based on the findings of Harmon and Ward, it is anticipated that the schedule duration should be longer if McDonnell Douglas is the prime contractor.

### 2. *Modification of an Existing Aircraft System, "Mod."*

***a. Variable Selection.*** This variable attempts to measure how much time is saved or lost by choosing to modify an existing commercial aircraft instead of developing a new aircraft. Often the program manager does not have a choice of modifying an existing aircraft, so this variable measures the uniqueness of the aircraft entering EMD. Using modification as a driver was previously theorized by Tyson and others in 1989 and by Harmon and Ward in 1990.

***b. Definition.*** This variable is measured as a one or a zero. A one indicates the aircraft was developed from an existing aircraft system, for example, the

KC-10 is a modification of the DC-10. A zero indicates the aircraft was developed for the Air Force by a manufacturer without reliance on an existing design.

*c.* ***Relationship to the Dependent Variables.*** If the value of this variable is one--the aircraft is a modification of an existing system--the time required for EMD should be shorter than if the aircraft is built without prior knowledge of the design.

### 3. *Nonoffensive Mission-Profile, "NonOff."*

*a.* ***Variable Selection.*** This variable is used to measure the mission type of the aircraft. An offensive aircraft is expected to be able to conduct some evasive maneuvers and to be able to provide penetration into hostile territory. Because these aircraft must withstand more stresses due to combat, they will need more time to be developed. Many aircraft that do not serve an offensive role are commercial aircraft modified to serve a military application, therefore this variable measures some of the same characteristics as the above indicator variable. Nelson (in 1987) and Harmon and Ward (in 1990) previously theorized the mission profile would be a driver.

*b.* ***Definition.*** This variable can take only the value of either one or zero. If the value is one, the particular aircraft is not designed to meet an offensive role.

*c.* ***Relationship to the Dependent Variables.*** If the value of this variable is zero, the aircraft is designed to play an offensive role and the EMD phase of the program should take longer. If an aircraft must be able to withstand combat, the manufacturers must design into the aircraft more robust systems and engineer the aircraft to withstand more stresses. The requirements of such an aircraft are more stringent than for nonoffensive aircraft, and thus the EMD phase should take longer. *NonOff*, by itself, is not correlated with any of the four EMD durations.

### *4. Number of Prototypes, "NrProto" and "Proto."*

***a. Variable Selection.*** The logic of this variable is not immediately straightforward. If more prototypes are built, the time required for the EMD phase of the program may increase or decrease. More prototypes being built would lengthen the development subphase of EMD, but would shorten the low-rate production subphase. The idea is the longer a development takes (that is, more prototypes), more manufacturing problems will be solved before entering the low-rate production phase of EMD. If fewer prototypes are built, the manufacturing problems must be solved during the low-rate production phase of EMD. This variable should be positively related to all the subphases. Prototyping was previously suggested as a driver by Nelson in 1987, Tyson and others in 1989, Harmon and others in 1989, and Drezner and Smith in 1990.

An alternate approach would be to treat prototyping as an indicator variable (that is, *Proto)*. This is consistent with the understanding that the exact number of prototypes required is unknown as the program approaches EMD. The number of prototypes may be increased if the program is experiencing unforeseen problems, or to explore further enhancements if the program is unexpectedly successful.

***b. Definition.*** This variable is continuous. Generally this variable includes any aircraft not built on the production line. This variable does not include flight-test aircraft produced during the production phase of the program or aircraft built only for fatigue, static, hydrostatic, or other test purposes that do not include flying the aircraft. Only aircraft actually designated as prototypes were included. There are 56 observations for *NrProto*, which range from zero to six, the mean is two with a standard deviation of one.

***c. Relationship to Dependent Variables.*** As discussed above, this variable is expected to be positively related to the early subphases of EMD, but negatively related to the late subphases.

### *5. Wingspan, "Wingspan."*

***a. Variable Selection.*** This variable is included because it is related to the dependent variable by the assumption that a manufacturer will take longer to develop a larger aircraft. Such size variables have successfully been used in regression models constructed to estimate the cost of aircraft. It is not unreasonable to believe some variables that estimate cost will carry over to estimating the schedule of aircraft programs.

***b. Definition.*** The wingspan is measured, in feet, as the longest distance from wingtip to wingtip of an airplane. If an airplane is capable of modifying the geometry of the wings, like for the B-1, this variable is the longest distance with the wings fully extended. There are 56 observations for *WingSpan*, which range from 39.5 feet (the C-21) to 230 feet (the XC-99), with a mean of 120 feet and a standard deviation of 54 feet.

***c. Relationship to Dependent Variables.*** This variable should be positively related, increasing at a decreasing rate. This is the case because for small values of wingspan, an increase in the wingspan will cause a greater increase in the length of the schedule than for higher values of the wingspan. If the manufacturer is already capable of producing a large wing, an increase in the size of the wing will have less of an impact than if the manufacturer is prepared to produce a small wing, and the size of the wing is increased.

### *6. Wing Area, "WingArea."*

***a. Variable Selection.*** This variable was selected for many of the same reasons as for the wingspan. It has been used in past model building exercises and is logically related to the length of time an EMD phase should take. Also, these size variables, of which there are several, are used because they are not subject to great interpretation: there is a standardized way to measure the size variables. In other words, physical variables can be measured using the same measures across all data-points. Some other variables, such as maximum and average speeds, can be measured at maximum altitude, sea level, or at another altitude. Because there is a standard way to measure these variables, their values are more consistent than some other variables. In their 1972 work for NASA, LTV's VMSC found the equivalent of wing area to be a schedule driver.

***b. Definition.*** This variable is measured in square feet. As with wingspan, the wing area is the maximum wing area possible. There are 55 observations for *WingArea,* which range from 241 square feet (the T-1) to 6,297 square feet (the XB-70), with a mean of 2,150 square feet and a standard deviation of 1,766 square feet.

***c. Relationship to Dependent Variables.*** This variable, as with wingspan, should be positively related in an increasing at a decreasing rate.

### 7. *Empty Weight, "EmpWgt."*

***a. Variable Selection.*** This variable was chosen for the same reasons as the above two. There is strong support for using this variable based on past studies. As with the other physical characteristics, the larger the aircraft, the longer the EMD phase will take. Empty weight as a driver was previously identified by VMSC in 1972 and by Harmon and others in 1989.

***b. Definition.*** This variable, measured in pounds, is the weight of the aircraft without any fuel, payload, or crewmembers. The empty weights of aircraft change over time: the empty weight of the prototype aircraft is different from the empty weight of the production aircraft. Also, the empty weight of a particular aircraft will change from model to model. The data collected for this study was the empty weight of the first production aircraft as reported to the Air Force by the manufacturer. There are 56 observations for *EmpWgt,* which range from 1,437 pounds (the C-12) to 374,000 pounds (the C-5B), with a mean of 94,443 pounds and a standard deviation of 87,544 pounds.

***c. Relationship to Dependent Variables.*** As with the other size variables, this variable should be positively related to the dependent variables. The heavier the aircraft, the longer the EMD phase should take. This variable should be linearly related to the length of the EMD phase, because, as the empty weight increases the amount of time should increase at a steady rate.

### 8. *Number of Engines, "NrEng."*

***a. Variable Selection.*** This variable has very few measurement problems. This variable is thought to influence the length of the EMD phase for the same reasons as the other physical characteristics. If there are more engines the development should take longer. In 1972, VMSC previously suggested the number of engines would be a driver.

***b. Definition.*** This variable is the number of engines on the aircraft used to power the airplane. There are 56 observations for *NrEng*, which range from two to eight engines, with a mean of four engines and a standard deviation of two engines.

***c. Relationship to Dependent Variables.*** This variable is positively related to the dependent variables, and should be related in a linear fashion. The range of this variable is from two to eight engines. Bomber and cargo aircraft are designed to carry large loads of items and all have more than one engine. An increase in the number of engines should increase the amount of time it takes to develop an aircraft, but this increase should be constant as the number of engines increases. This variable represents a design approach taken by the manufacturer. As the number of engines increases, the increase in the time required to design the aircraft will not increase at an increasing or decreasing rate; because for a change in the number of engines when there are only two engines, the change in the amount of time required to develop an aircraft will be equal to a change in the amount of time required for aircraft with a larger number of engines.

### *9. Maximum Thrust, "MaxThr."*

***a. Variable Selection.*** This variable was chosen for the same reasons as empty weight. There is strong support for using this variable based on past studies. As with the other physical characteristics, the larger the aircraft, the longer the EMD phase will take. VMSC, in 1972, recommended maximum thrust as a schedule driver.

***b. Definition.*** This variable, measured in pounds, is the maximum amount of thrust all the system's engines can produce, with the use of any augmentation (for example, an afterburner), if so equipped. The horsepower rating for propeller-driving engines was converted to equivalent thrust. There are 56 observations for *MaxThr,* with a range from 2,920 pounds (the XB-42) to 210,000 pounds (the E-4), with a mean of 50,653 pounds and a standard deviation of 52,433 pounds.

***c. Relationship to Dependent Variables.*** As with the other size variables, this variable should be positively related to the dependent variables. The greater the total maximum thrust, the longer the EMD phase should take. This variable should be linearly related to the length of the EMD phase, because--as the thrust increases--the amount of time required should increase at a steady rate.

### *10. Average Speed, "AvgSpd."*

***a. Variable Selection.*** This variable was chosen to represent the performance (that is, the level of technology) for each aircraft. A higher average speed would imply a higher level of performance and technology. The level of technology has long been thought of as an important factor in estimating the costs of aircraft. For the same reasons, the average speed is included in this study. As a surrogate for the level of performance and technology this should be useful in the analysis. Nelson's 1987 research previously suggested average speed as a driver.

***b. Definition.*** This variable, measured in knots, is the speed at which the aircraft will fly when on a mission for which it is designed. There are 55 observations for *AvgSpd,* which range from 117 knots (the C-125) to 1,721 knots (the XB-70), with a mean of 387 knots and a standard deviation of 211 knots.

***c. Relationship to the Dependent Variables.*** At low levels of average speed, an increase in the average speed should have less of an impact on the amount of time required to develop an aircraft than increases above higher levels of average speed. As the average speed of an aircraft reaches a certain level, the amount of time to develop the aircraft will increase at an increasing rate. As the average speed increases, there will be ever-increasing amounts of time required to develop the aircraft.

### *11. Maximum Speed, "MaxSpd."*

***a. Variable Selection.*** This variable was selected for many of the same reasons the average speed variable was chosen. This variable, however, might be a better indicator of the technological level of the aircraft. There were some aircraft programs that were the most advanced aircraft of their time. For example, the XB-70's top speed was faster than the B-1's top speed, which was developed many years later with more modern technology. The maximum speed of an aircraft and a measure of the size of the aircraft should be two variables strongly related to the amount of time the development program will take. In 1987, Nelson suggested maximum speed would be a schedule driver.

***b. Definition.*** This variable, measured in knots, is measured with the aircraft's flight instruments at the optimum altitude for a particular aircraft in its intended mission profile. There are 55 observations for *MaxSpd,* which range from 170 knots (the C-125) to 1,721 knots (the XB-70), with a mean of 510 knots and a standard deviation of 303 knots.

***c. Relationship to the Dependent Variables.*** The maximum speed of an aircraft should be positively related to the amount of time required to develop the airplane, and should increase at an increasing rate. For small values of the maximum speed, an increase in the maximum speed will cause less of an increase in the amount of time required than an increase in the maximum speed at higher levels of maximum speed. It is harder to increase the speed of an aircraft when the speed is already near the highest recorded speed for that type of aircraft, than increasing the speed of an aircraft at lower levels of speed. An analogy can be drawn to sports. When a high-jumper attempts that last tenth of an inch to break the record, that last tenth of an inch is much harder to clear than a tenth of an inch increase at a lower level of the bar. The same phenomenon occurs when the manufacturer of an aircraft tries to squeeze the last bit of speed out of an aircraft.

### *12. Combat Radius, "CmbtRad."*

***a. Variable Selection.*** This variable is another performance and level of technology measure. The combat radius should be a good measure because to increase the combat radius, many other things must change. In this way, the combat radius is a composite measure for the aircraft. To increase the combat radius, the efficiency of the engines must be increased, the weight must be reduced, and the wingspan and wingarea must be balanced to fit all the other changes. An incremental change in the combat radius requires a change in one or all these other measures, therefore, it measures many different aspects of the aircraft development. Mission radius as a driver was earlier identified by Nelson in 1987 and by Harmon and others in 1989.

***b. Definition.*** Although this variable theoretically should be a good measure of the length of the EMD phase of an aircraft program, it is difficult to define for many observations in this study. The *Green Book* reported exact radii, while the *Brown Book* often reported radii in numbers rounded to the thousands. This is consistent with the logic that Strategic Air Command aircraft are not able to land enroute to their target area while Military Airlift Command aircraft are not so constrained. As a result, this parameter is not normal between *Green Book* and *Brown Book* aircraft.

The combat radius is the distance, in nautical miles, which the aircraft could fly while engaged in a combat mission. That is, this variable is the distance an airplane can fly from an airfield, perform its mission, and return to the same airfield. A combat mission involves performing evasive maneuvers, flying full-throttle, and utilizing maximum altitude. There are 45 observations for *CmbtRad,* with a range from 357 nautical miles (the C-125) to 3,550 nautical miles (the B-52G), with a mean of 1,199 nautical miles and a standard deviation of 853 nautical miles.

***c. Relationship to the Dependent Variables.*** The relationship of this variable to the amount of time required for the EMD phase of the program should be a positive one and should increase at an increasing rate. Similar to the analogy of the high jumper clearing the last setting, an increase in the combat radius for low values of the combat radius will increase the time required less than an increase in combat radius for higher values of the combat radius. In fact, to meet requirements of the Air Force, some manufacturers developed special composite materials and manufacturing processes to reduce the weight of the aircraft. Manufacturers also increase the size of the fuel tanks and attempt to develop more efficient engines. By requiring a higher combat radius, the Air Force extends the time manufacturers need to develop, test, and produce (at a low rate) the aircraft.

### *13. Range, "Range."*

***a. Variable Selection.*** This variable, as with the combat radius, should be a good measure of the amount of time required for the EMD phase because to reach a higher range, the manufacturer must make many other factors as efficient as possible. This variable is more easily defined than combat radius. Range was previously identified as a potential driver by Nelson in 1987.

***b. Definition.*** The range is measured in nautical miles, as the distance the aircraft could fly from one airfield to another. The only difficulty in defining this variable comes in ensuring that the range used is for when the aircraft is carrying the intended payload for its intended mission. Furthermore, the early models of a particular aircraft have substantially different ranges than later models due to weight growth during production or increases in engine efficiency. There are 56 observations for *Range,* with a range from 446 nautical miles (the C-23) to 12,500 nautical miles (the B-52A), with a mean of 3,161 nautical miles and a standard deviation of 2,367 nautical miles.

***c. Relationship to the Dependent Variables.*** The range for a particular aircraft should be positively related to the length of the EMD phase in an increasing rate. As the range of the aircraft gets longer and longer, an increase in the range will involve more serious engineering challenges, thus lengthening the EMD phase.

***14. Date EMD Effort Started, "EMD."***

***a. Variable Selection.*** This was collected as a potential independent variable precisely because the literature is so divided about whether the length of the EMD phase is increasing over time.

***b. Definition.*** The date the program entered EMD is used. As with the other dates in the data base, it is transformed into its Julian-date equivalent. For example, 03 July 1993 becomes 93.501. The database covers *EMDs* from 1940 (the B-29) to 1990 (the C-27), with the mean *EMD* in 1960 and a standard deviation of 16 years.

***c. Relationship to Dependent Variables.*** In keeping with the last RAND findings, a modest, positive relationship is expected (Drezner and Smith, 1990:9).

***15. Independent Variables Considered, But Not Included.*** The literature suggested several more parameters as driving schedule. However, some of them are not known with any certainty before entry into EMD. Others simply are not readily available. The data sources focus on providing the performance and physical parameters of the aircraft, programmatic details are often omitted.

***a. Number of Aircraft Accepted.*** This was thought to capture the importance of the particular aircraft to the Air Force. The reasoning was that if the Air Force accepts more aircraft, then the Air Force had a stronger need for the aircraft. If more are needed, then it might be a high priority. If it is a high priority, then maybe schedule will be affected.

There are some problems with measuring Air Force priority with this variable. Before the 1960s, the Air Force bought many more of every type of aircraft, and these aircraft were not as technically complex or capable as later aircraft. There are other recognized problems with this variable, but other studies said a variable which measures priority should be included in schedule models. Harmon and others, in 1989, suggested the cumulative quantity to be a driver.

***b. Funding Stability.*** The more stable the funding is for a particular program, the more of a priority the program is for the Air Force. The more of a priority the program is, the shorter the amount of time that should be required. Unfortunately, funding stability is rarely recorded, let alone mentioned. Funding stability was suggested as a schedule driver by Nelson in 1987 and by Drezner and Smith in 1990, although they did not provide concrete suggestions about how to measure it.

***c. Program Management Directive (PMD) Precedence Rating.*** The precedence rating is just that, a rating based on precedence of all major programs. The higher the precedence rating, the shorter the EMD phase should take. Unfortunately, PMD information was available for only six programs. Such a priority variable was previously identified by Drezner and Smith in 1990.

***d. State of the Art (SOA).*** While this variable would have been a better measure of the level of technology used for the particular aircraft, the techniques used to arrive at an SOA value for each program and the data required would involve a significant effort. SOA as a driver was suggested by VMSC in 1972, by Nelson in 1987, by Harmon and others in 1989, and by Drezner and Smith in 1990.

***e. Number of Engineering Change Proposals (ECPs).*** This variable would measure the stability of the program. The Air Force is unsure of the performance requirements of the program when a program is started. This leads to instability in the program and would lengthen the EMD phase of the program. Although the number of ECPs experienced by a program would be an excellent indicator of EMD length, a program manager entering the beginning of the EMD phase will not know the number ECPs his or her program will experience. Therefore, inclusion of this variable would not be useful. Such a variable measuring the requirements stability was previously identified by Drezner and Smith in 1990.

### *F. Principal Component Analysis*

One of the bigger challenges in regression analysis is culling the potential independent variables into the few significant ones that statistically capture the variance in the dependent variable, yet do not violate the assumptions of linear regression (such as multicollinearity). One statistical aid is principal component analysis.

After considering which categories should explain the amount of time the EMD subphases should take, principal component analysis is used to mathematically assign the independent variables into the categories. Ideally, the results of principal component analysis will support the analyst's intuitive impressions of the independent variables' relationship to the dependent variables.

Anytime multiple independent variable models are constructed, the chance for encountering correlation between the independent variables increases. When this happens, the variances of the coefficients increase, the coefficients become difficult to explain, and the signs for the coefficients may even become contrary to logic.

The term used to refer to correlation between independent variables is multicollinearity. Multicollinearity is a problem when constructing multiple independent variable models chiefly because the variance of the sampling distribution of parameter estimators for each variable is increased and--in cases where the multicollinearity is high--the coefficients may even become nonunique.

One way to lessen the impacts of multicollinearity is to use principal component analysis to create uncorrelated independent variables. This is best explained by Freund and Littell:

> Principal component analysis is a multivariate analysis technique that attempts to describe interrelationships among a set of variables. Starting with a set of observed values on a set of *m* variables, this method uses linear transformations to create a new set of variables, called principal components. (Freund and Littell, 1991:101)

After the principal components are calculated, they can be used in a regression without the risk of being influenced by multicollinearity. Since there is no correlation between the principal components, they can be regressed against the dependent variable to accurately learn which principal components are important without suffering the effects of multicollinearity. This enables the analyst to select among the principal components which meet a given level of importance, measured by the significance of each principal component.

After learning which principal components were significant, one inspects the individual principal components to discover which independent variables contribute the most to the significant principal component. This procedure is performed by analyzing the eigenvectors (that is, the intersection of each independent variable and each principal component). A higher eigenvector for an independent variable suggests the variable measures, at least partly, that principal component. Several values with near-equal eigenvectors are interpreted to measure the same general category. An example of this would be if the eigenvectors for average speed and maximum speed both had high values for the same principal component. This result would support the hypothesis that average speed and maximum speed measure the same characteristic of the dependent variable.

A summary of the steps performed to this point should be helpful to the reader. This summary, in numbered step form, appears in Figure 7 below.

Steps

1. Logically determine the *categories* which explain the length of each subphase of EMD.

2. Identify independent variables which measure each of these categories.

3. Collect data for each independent variable from reliable sources for as many observations as possible.

4. Perform the mathematical calculations to determine the principal components.

5. Regress all of the principal components against each subphase of EMD (the dependent variables).

6. Choose the principal components, which meet the decision rule for p-values, for further exploration.

Figure 7. Steps Through Principal Component Analysis

The result of performing these steps should meaningfully reduce the number of independent variables by excluding from further consideration the variables that measure the principal components that do not meet one's predetermined decision rule (for example, the p-value for the t-statistic). At this point, an inspection of the remaining variables--keeping in mind the previous expectations of each independent variable--should be performed. The analyst needs to decide if some variables had been dropped by the principal component analysis, which--for some logical reason--should not be. For example, based on an analysis of the correlations between the independent and dependent variables and the independent variable having been cited in the literature, the modification and prototype indicator variables should not be dropped.

### *G. R-Square Selection Method*

In Freund and Littell's methodology, the R-square selection technique is used to find the variables in the best-fit model. The R-square selection method regresses all possible combinations of the independent variables and ranks each based on its R-square value. For example, if one included seven variables in the model, the R-square selection technique would provide the best, in terms of R-square, seven-variable model, best six-variable model, best five-variable model, and so on. This technique does not consider the significance of the model or of the coefficients nor does it address considerations associated with degrees of freedom.

It is important to note that the R-square selection technique may not select variables that are common between models for the same dependent variable. For example, while $X_1$, $X_3$, $X_6$, and $X_9$ may be the best variables in a four-variable model, the best three-variable model includes $X_1$, $X_6$, and $X_7$. That is, the variables may be added or dropped depending on the $R^2$ of the model.

The result of performing this step with the remaining variables provides best-fit models. However, because of the "noise" (that is, seemingly random variance that defies being captured by available parameters) endemic to DOD acquisition research, the models may not be as statistically significant as is necessary for a robust model. As a result, the thesis' methodology goes a step beyond Freund and Littell and the models' and the coefficients' significance levels are analyzed via the backward selection technique.

### *H. Backward Selection*

Many variables provided by the R-square selection technique have very low significance when regressed in a full model. Because of this, a manual backward selection technique--based on the p-values from the t- and F-tests (for the significance of the coefficients and of the model, respectively)--should also be used.

First, regress the full model, that is, the model with all of the R-square selected independent variables. Examine the p-value for each variable; a significance level of $p<.05$ is a recognized criterion in the literature (for example, Harmon and others, 1989:271). Remove the most insignificant variable from the model and rerun the now-reduced model. Continue this process of removing the least significant variable until all variables meet the $p<.05$ significance criteria.

The next few paragraphs explain some modeling decisions and some diagnostics to ensure the models do not violate the assumptions critical to linear regression.

### *I. Dummy-Adjusted Slopes and Interaction Effects*

The final models may contain categorical variables. Categorical variables can be added to affect either the slope or the intercept of models. One should examine the scatter plots to figure out if the categorical variables should be used to adjust for differing slopes beyond, or instead of, the dummy-adjusted intercept.

Also, anytime an analyst uses a multivariate model, he or she must consider the interaction effects between the variables. That is, in a univariate model, the usual interpretation of parameters is--holding everything else constant--the parameter has this effect on the dependent variable. However, in multivariate models one usually cannot hold everything else constant, that is, the parameters have some common cause or effect such that they move together in some fashion. To counter such effects, one must consider the inclusion of an interaction-effect variable such that the two (or more) parameters are multiplied together.

## *J. Diagnostics*

***1. Specification and Homoscedasticity.*** The residual plots for each model must be visually examined to decide if the model is linear as specified or if any transformations of the independent (and sometimes the dependent) variables are appropriate. That is, to transform, for example, an increasing at a decreasing rate into a linear relationship.

Similarly, the residual plots should be visually examined to ensure the models do not violate the assumption that all random errors have the same variance. That is, they not be heteroscedastic. Remedial measures for heteroscedasticity also include transformation.

***2. Outliers.*** One then examines the residual plots to figure out if any outliers exist. The visual inspection should be augmented by reviewing the Y-hat matrix to find outliers with respect to X, the studentized residuals to determine outliers with respect to Y, and the Cook's D score to find outliers in overall influence. Outliers may suggest misspecification of the model. Otherwise, extreme outliers may be dropped if there is a logical reason for not including them.

In considering the Y-hat matrix, those observations for whom the individual value, $h_i$, exceeds $2p/n$ (where p is the number of parameters and $n$ is the number of observations), may be considered as exhibiting high leverage (Neter and others, 1989:396). Observations whose studentized-residual value exceeds 2.5 are clearly influential (Freund and Littell, 1991:62). As for the Cook's distance measure, those observations whose Cook's D percentile value exceeds 50 percent has substantial influence (Neter and others, 1989:403).

*3.* ***Autocorrelation.*** The models should be examined to ensure they do not violate the assumption of independence underlying the distribution of the random errors. Autocorrelation is common in time-series data. That schedules would fall victim to autocorrelation is not unexpected, given the common belief that schedules are getting longer over time. Such autocorrelation is detected via the Durbin-Watson statistic.

A Durbin-Watson statistic greater than 1.60 suggests that the possibility of autocorrelation (Freund and Littell, 1991:87). The sample correlation of adjacent residuals that accompanies the Durbin-Watson statistic indicates the degree of association between adjacent residuals. If the correlation exceeds .30, remedial measures should be considered. Unfortunately, the remedial measures for autocorrelation can be complex (see Kennedy, 1992:247-267).

*4.* ***Multicollinearity.*** As discussed earlier, multicollinearity is a problem common to multivariate models. The variance inflation factor (VIF) can be used to assure multicollinearity is not a problem. As a heuristic, VIF values which exceed 10 should be addressed (Freund and Littell, 1991:97). However, principal component analysis should prevent multicollinearity from becoming a problem.

### *K. Summary*

While the specific steps are explained above, an additional summary--depicted in Figure 8 below--should prove helpful. The next chapter explains the results achieved by following the methodology contained in this chapter, and will describe how we analyzed the results.

Steps

1. Logically determine the *categories* of measures which explain the length of each subphase of EMD.

2. Identify independent variables which measure each of these categories.

3. Collect data for each independent variable from reliable sources for as many observations as possible.

4. Perform the mathematical calculations to determine the principal components.

5. Regress all of the principal components against each subphase of EMD (the dependent variables).

6. Choose the principal components, which meet the decision rule for p-value, for further exploration.

7. Examine each principal component's eigenvectors to determine which independent variables measure that particular principal component.

8. Consider, for inclusion, logical parameters which principal component analysis did not recommend.

9. Include each of these variables in the R-square selection process, and keep the variables which are included in the best five-variable through two-variable models.

10. Employ each of the remaining variables in a manual backward selection process based on a significance level of .05.

11. Diagnose the models.

Figure 8. Steps of Methodology

# *IV. Analysis*

## *A. Introduction*

This chapter describes the results of performing the methodology outlined in Chapter III on the data collected. The variables are selected through a process which moves from principal component analysis through R-square selection technique to the backward selection technique. The most significant models are then diagnosed and presented.

## *B. Principal Component Analysis*

As described in Chapter III, a principal component analysis of the collected variables was performed. The results match--somewhat--the initial logic, but there are some differences. Several figures follow which present the results of the principal component analyses.

At this point, the reader should be reminded four separate explanatory models are being built, one for each duration described in Chapter III. Therefore, the following figures are identified with the specific dependent variable being explained. Figures 9 through 12 present the results of the regression of all the principal components against each of the four dependent variables.

Figures 13 and 15 present the calculated principal components' eigenvectors. In Figures 13 and 15, each column headed by Prin# represents a category that explains the duration for the model. For a given Prin# column, large (negative or positive) values suggest the independent variable to the left is the variable that measures the category.

Another fact the reader should recognize is the principal component analysis needs to be accomplished twice. The first principal component analysis, depicted in Figure 9, does not include the prototype indicator variable, after all, *Proto* will always equal one for the duration to the first prototype flight *(DurProF)*. If *Proto* is included in the regression for the duration to first prototype flight, the result is a perfect linear combination, therefore, Figure 9 has one fewer variable than Figures 10 through 12.

Dependent Variable: Duration to First Prototype Flight

| Variable | Prob > \|T\| |
|---|---|
| INTERCEP | 0.0001 |
| PRIN1 | **0.0077** |
| PRIN2 | 0.6546 |
| PRIN3 | **0.2266** |
| PRIN4 | **0.0772** |
| PRIN5 | **0.1951** |
| PRIN6 | 0.9003 |
| PRIN7 | **0.4847** |
| PRIN8 | 0.6899 |
| PRIN9 | **0.2998** |
| PRIN10 | **0.1947** |
| PRIN11 | **0.0143** |
| PRIN12 | **0.1635** |

Figure 9. PrinComp for *DurProF*

Dependent Variable: Duration to First Production Flight

| Variable | Prob > \|T\| |
|---|---|
| INTERCEP | 0.0001 |
| PRIN1 | **0.4139** |
| PRIN2 | **0.0017** |
| PRIN3 | 0.5983 |
| PRIN4 | **0.4573** |
| PRIN5 | 0.5808 |
| PRIN6 | 0.7242 |
| PRIN7 | 0.7533 |
| PRIN8 | 0.9050 |
| PRIN9 | 0.8209 |
| PRIN10 | **0.2948** |
| PRIN11 | 0.9980 |
| PRIN12 | 0.7326 |
| PRIN13 | **0.1000** |

Figure 10. PrinComp for *DurPdnF*

Dependent Variable: Duration to First Production Delivery

| Variable | Prob > \|T\| |
|---|---|
| INTERCEP | 0.0001 |
| PRIN1 | **0.3734** |
| PRIN2 | **0.0039** |
| PRIN3 | 0.5382 |
| PRIN4 | **0.3051** |
| PRIN5 | 0.6331 |
| PRIN6 | 0.7926 |
| PRIN7 | 0.6283 |
| PRIN8 | 0.7887 |
| PRIN9 | 0.9329 |
| PRIN10 | **0.3626** |
| PRIN11 | 0.8400 |
| PRIN12 | 0.7413 |
| PRIN13 | **0.1956** |

Figure 11. PrinComp for *DurPdnD*

Dependent Variable: Duration to First
User Delivery

| Variable | Prob > \|T\| |
|---|---|
| INTERCEP | 0.0001 |
| PRIN1 | **0.1336** |
| PRIN2 | **0.0070** |
| PRIN3 | 0.8669 |
| PRIN4 | **0.1183** |
| PRIN5 | 0.8632 |
| PRIN6 | 0.7587 |
| PRIN7 | 0.7720 |
| PRIN8 | 0.6372 |
| PRIN9 | 0.8832 |
| PRIN10 | 0.8909 |
| PRIN11 | **0.2857** |
| PRIN12 | **0.2248** |
| PRIN13 | 0.8608 |

Figure 12. PrinComp for *DurUsrD*

In Figures 9 through 12, the most-important principal components are in bold print. Unfortunately, perhaps due to not having collected the most-explanatory parameters, significance levels for the principal components are less than ideal. According to Freund and Littell, "[you] should not use the *p* values literally, but the magnitudes of the *p* values can be used to indicate relative importance of the coefficients" (Freund and Littell, 1991:105). Therefore, one must use the most important ones. As a rough decision rule, principal components whose $p<.5$ were pursued as potential categories.

Figure 9 shows for the duration to first prototype flight, principal components 1, 3, 4, 5, 7, 9, 10, 11, and 12 are most significant. For the duration to the first production flight, Figure 10 shows principal components 1, 2, 4, 10, and 13 are important. Figure 11 shows the same principal components that are important in the duration-to-first-production-flight model are also important in the duration to first production delivery model. This may be so because these two durations are, for many observations, the same date. Different principal components are significant (see Figure 12) for the remaining model, duration to the first user delivery: principal components 1, 2, 4, 11, and 12. As can be seen from the figures above, there were several principal components that recurred in two or more of the models. This leads one to believe the variables that measured these principal components may be more useful in subsequent analysis.

Figures 13 and 15 show the eigenvectors for each principal component, and the variables of which they are comprised. Remember, Figure 13 does not contain the prototype indicator variable for reasons already stated.

Eigenvectors for the Duration to First Prototype Flight

|  | PRIN1 | PRIN2 | PRIN3 | PRIN4 | PRIN5 | PRIN6 | PRIN7 | PRIN8 | PRIN9 | PRIN10 | PRIN11 | PRIN12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MCDAC | -.082638 | 0.000980 | -.032095 | **0.833852** | 0.404295 | -.084530 | 0.305875 | 0.133929 | 0.099353 | -.003585 | -.057864 | 0.038772 |
| MOD | -.101757 | 0.390520 | -.015691 | -.234065 | **0.668478** | 0.566931 | -.092378 | -.049768 | 0.003000 | -.037905 | 0.036874 | 0.004191 |
| NONOFF | -.079165 | **0.590657** | -.065754 | 0.006451 | -.387553 | 0.064663 | 0.316718 | -.077820 | **0.582395** | -.172451 | 0.022941 | 0.101479 |
| WINGSPAN | 0.373400 | 0.087222 | -.395551 | 0.074828 | 0.015568 | 0.007140 | -.130031 | 0.056272 | 0.228954 | 0.481634 | 0.309285 | **-.538970** |
| WINGAREA | **0.434245** | 0.077474 | -.145534 | 0.091393 | -.085963 | 0.201187 | -.010923 | -.243268 | -.067704 | 0.354427 | **-.660874** | 0.319022 |
| EMPWGT | **0.418422** | 0.218346 | -.004440 | 0.198350 | -.047864 | -.028613 | -.261381 | -.020586 | -.207875 | -.116494 | 0.559766 | **0.543977** |
| NRENG | 0.339331 | -.215319 | -.252473 | -.221643 | -.007188 | 0.236134 | **0.468419** | 0.627551 | -.043543 | -.209369 | -.000806 | 0.104138 |
| MAXTHR | **0.404115** | 0.220313 | 0.164096 | 0.149975 | -.019739 | -.045933 | -.272136 | 0.064149 | -.090905 | **-.601534** | -.286795 | -.453544 |
| AVSPD | 0.224867 | -.159511 | **0.510913** | 0.101151 | -.152242 | 0.415406 | **0.434633** | -.365738 | -.133415 | 0.069132 | 0.245436 | -.226936 |
| MAXSPD | 0.197298 | -.186117 | **0.579848** | -.054445 | 0.130896 | -.001745 | -.265740 | 0.318226 | **0.583693** | 0.177700 | -.047968 | 0.153776 |
| RANGE | 0.322971 | -.100919 | -.058828 | -.301506 | 0.430811 | -.507454 | 0.311561 | -.424885 | 0.201261 | -.160599 | 0.032432 | 0.055524 |
| EMD | 0.034930 | **0.521694** | 0.354052 | -.144391 | 0.056680 | -.371447 | 0.249361 | 0.311873 | -.376242 | 0.360309 | -.056328 | -.072313 |

Figure 13. Eigenvectors for *DurProF*

Figure 13 shows for principal component number one, the variables wing area, empty weight, and maximum thrust represent the category. Having these three variables contained in one principal component does not follow the initial logic. The wing area and empty weight variables were initially thought to measure the physical characteristic, and the maximum thrust variable was thought to measure the technological aspects of a weapon system. It appears that instead of measuring the technological characteristic, the maximum thrust variable measures the physical category. This is consistent with the thought that the larger an aircraft is, the more thrust it will likely require. If an aircraft is larger and requires more thrust, then the thrust also measures the size of the aircraft.

Principal component number two is measured by the nonoffensive indicator variable and the date of EMD contract award variable. These two variables do not seem at all related. Principal component number three appears to be measured by the average speed and maximum speed variables. Of course, these two variables are highly correlated. Further analysis of the principal components for the duration to first prototype flight would result in some logical associations between variables, and some illogical ones. A summary of each of the important principal components and the variables that represent them follows in Figure 14.

Duration to First Prototype Flight

| Principal Component | Variables | Category |
|---|---|---|
| Prin1 | Wing area<br>Empty weight<br>Maximum thrust | Physical |
| Prin2 | Nonoff<br>EMD | Unknown |
| Prin3 | Average speed<br>Maximum speed | Technology |
| Prin4 | McDAC | Programmatic |
| Prin5 | Mod | Programmatic |
| Prin7 | Number of engines<br>Average speed | Unknown |
| Prin9 | Nonoffensive<br>Maximum speed | Unknown |
| Prin10 | Maximum thrust | Technology |
| Prin11 | Wing area | Physical |
| Prin12 | Wingspan<br>Empty Weight | Physical |

Figure 14. Variables for *DurProF*

Again, one must perform two principal component regressions so the prototype indicator variable could be included as a potential parameter for post-prototype-flight durations (that is, for those durations for which *Proto* may be something other than 1). Figure 15 shows the principal component calculation with the prototype indicator variable included.

|  | **PRIN1** | **PRIN2** | PRIN3 | **PRIN4** | PRIN5 |
|---|---|---|---|---|---|
| MCDAC | -.0816 | -.0164 | -.0343 | **0.7725** | 0.5076 |
| MOD | -.1144 | 0.3781 | -.0525 | -.2392 | 0.4491 |
| NONOFF | -.0911 | **0.4856** | -.1334 | 0.1243 | -.4927 |
| PROTO | 0.0859 | -.4469 | -.0384 | 0.1642 | -.3659 |
| WINGSPAN | 0.3712 | 0.0664 | -.4012 | 0.0678 | 0.0313 |
| WINGAREA | **0.4311** | 0.0818 | -.1516 | 0.0924 | -.0444 |
| EMPWGT | **0.4119** | 0.2093 | -.0278 | 0.2196 | -.0452 |
| NRENG | 0.3440 | -.1850 | -.2251 | -.2515 | 0.0177 |
| MAXTHR | **0.3974** | 0.2197 | 0.1389 | 0.1807 | -.0547 |
| AVSPD | 0.2257 | -.0846 | 0.5257 | 0.0907 | -.0584 |
| MAXSPD | 0.2003 | -.1168 | 0.5960 | -.0601 | 0.0792 |
| RANGE | 0.3214 | -.0383 | -.0409 | -.3573 | 0.3733 |
| EMD | 0.0186 | **0.5112** | 0.2977 | -.0805 | -.0798 |

|  | PRIN6 | PRIN7 | PRIN8 | PRIN9 | **PRIN10** |
|---|---|---|---|---|---|
| MCDAC | -.0776 | 0.0570 | 0.3272 | -.0903 | 0.0869 |
| MOD | 0.6119 | 0.4385 | -.0268 | 0.0797 | -.0803 |
| NONOFF | 0.0699 | 0.0794 | 0.3881 | 0.2345 | 0.4440 |
| PROTO | 0.0642 | 0.7291 | 0.1566 | 0.0917 | -.2130 |
| WINGSPAN | 0.0078 | 0.0128 | -.1205 | -.0358 | 0.3511 |
| WINGAREA | 0.1902 | -.1318 | -.0559 | 0.2081 | -.0407 |
| EMPWGT | -.0269 | 0.0285 | -.2712 | -.0309 | -.2092 |
| NRENG | 0.2279 | -.1074 | 0.5008 | -.5954 | 0.0099 |
| MAXTHR | -.0357 | 0.1289 | -.2425 | -.0704 | -.1802 |
| AVSPD | 0.3884 | -.3349 | 0.3496 | 0.3326 | -.1746 |
| MAXSPD | 0.0179 | 0.2371 | -.1673 | -.2008 | **0.6500** |
| RANGE | -.4919 | 0.1572 | 0.3109 | 0.4860 | 0.0405 |
| EMD | -.3564 | 0.1634 | 0.2629 | -.3602 | -.2954 |

|  | **PRIN11** | **PRIN12** | **PRIN13** |
|---|---|---|---|
| MCDAC | -.0136 | -.0575 | -.0411 |
| MOD | 0.0026 | 0.0419 | 0.0041 |
| NONOFF | -.2314 | 0.0195 | -.1086 |
| PROTO | 0.1235 | 0.0179 | 0.0265 |
| WINGSPAN | 0.4043 | 0.2970 | **0.5477** |
| WINGAREA | 0.3837 | **-.6464** | -.3271 |
| EMPWGT | -.0818 | **0.5740** | **-.5284** |
| NRENG | -.2273 | -.0036 | -.1115 |
| MAXTHR | **-.5833** | -.3048 | 0.4374 |
| AVSPD | 0.1030 | 0.2441 | 0.2390 |
| MAXSPD | 0.0549 | -.0524 | -.1667 |
| RANGE | -.1448 | 0.0339 | -.0541 |
| EMD | 0.4323 | -.0453 | 0.0885 |

Figure 15. Eigenvectors for *DurPdnF*, *DurPdnD*, and *DurUsrD*

The above principal components are measured by several different variables. The best way to portray an analysis of the above table is to summarize the results for each of the three remaining models--the duration to the first production flight, duration to the first production delivery, and the duration to the first user delivery--in Figures 16 through 18.

Duration to First Production Flight

| Principal Component | Variables | Category |
|---|---|---|
| Prin1 | Wing Area<br>Empty weight<br>Maximum Thrust | Physical |
| Prin2 | Nonoffensive<br>EMD | Unknown |
| Prin4 | McDAC | Programmatic |
| Prin10 | Maximum Speed | Technology |
| Prin13 | Wingspan<br>Empty Weight | Physical |

Figure 16. Variables for *DurPdnF*

Duration to First Production Delivery

| Principal Component | Variables | Category |
|---|---|---|
| Prin1 | Wing area<br>Empty Weight<br>Maximum Thrust | Physical |
| Prin2 | Nonoffensive<br>EMD | Unknown |
| Prin4 | McDAC | Programmatic |
| Prin10 | Maximum Speed | Technology |
| Prin13 | Wingspan<br>Empty Weight | Physical |

Figure 17. Variables for *DurPdnD*

It is apparent the same principal components that measure the duration to the first production flight match those of the duration to the first production delivery. This result should be expected. Normally the first production aircraft is delivered very soon after its first flight.

Duration to First Delivery to the User

| Principal Component | Variables | Category |
|---|---|---|
| Prin1 | Wing Area<br>Empty Weight<br>Maximum Thrust | Physical |
| Prin2 | Nonoffensive<br>EMD | Unknown |
| Prin4 | McDAC | Programmatic |
| Prin11 | Maximum Thrust | Technology |
| Prin12 | Wing Area<br>Empty Weight | Physical |

Figure 18. Variables for *DurUsrD*

The next step in the methodology was to decide whether to include any variables in the R-square selection technique that the principal component analysis did not select. It was felt the modification and prototype indicator variables should be included in the R-square process. These variables were shown to be significant in previous SER research by Harmon and others.

### *C. R-Square Selection Technique*

The methodology led next to the R-square selection technique. As explained in Chapter III, this technique selects multiple independent variable models based on each model's best R-square value. All of the variables listed above were used for each model, and for the duration to first prototype flight, duration to first production delivery, and duration to user delivery models, the modification and prototype indicator variables were added. The results of the R-square selection technique follow in Figures 19 through 22.

Dependent Variable: Duration to Prototype Flight

| Number of Variables | R-Square | |
|---|---|---|
| 2 | 0.325786 | WINGAREA MOD |
| 3 | 0.393533 | WINGAREA NONOFF NRENG |
| 4 | 0.444058 | WINGAREA MOD NONOFF NRENG |
| 5 | 0.462465 | WINGAREA MOD MAXSPD NONOFF NRENG |

Figure 19. R-Square Selection for *DurProF*

Dependent Variable: Duration to First Production Flight

| Number of Variables | R-Square | |
|---|---|---|
| 2 | 0.420811 | MOD PROTO |
| 3 | 0.456456 | MCDAC MOD PROTO |
| 4 | 0.479843 | EMPWGT MCDAC MOD PROTO |
| 5 | 0.495398 | NONOFF EMPWGT MCDAC MOD PROTO |

Figure 20. R-Square Selection for *DurPdnF*

Dependent Variable: Duration to First Production Delivery

| Number of Variables | R-Square | |
|---|---|---|
| 2 | 0.461655 | MOD PROTO |
| 3 | 0.501537 | EMPWGT MOD PROTO |
| 4 | 0.529481 | WINGAREA MCDAC MOD PROTO |
| 5 | 0.538869 | EMD MAXTHR MCDAC MOD PROTO |

Figure 21. R-Square Selection for *DurPdnD*

Dependent Variable: Duration to First User Delivery

| Number of Variables | R-Square | |
|---|---|---|
| 2 | 0.3696240 | EMD MAXTHR |
| 3 | 0.4581144 | EMD MAXTHR PROTO |
| 4 | 0.5185441 | EMD WINGAREA MAXTHR MOD |
| 5 | 0.5423576 | EMD EMPWGT MAXTHR MOD PROTO |

Figure 22. R-Square Selection for *DurUsrD*

Using the results from the R-square selection process, the methodology moves on to the manual backward selection based on the p-value for each variable.

### *D. Backward Selection*

The object of reducing the variables remaining in each model was to make each model and each variable significant. The significance of the model was measured by the value of the F-score and the significance of each individual variable was measured by the p-value of each variable, as measured by the coefficients' t-tests. Figures 23 through 26 below present the F-score, R-square value, and p-values for each successive model to the final model. The criterion for inclusion of each variable in the final model was a p-value of .05.

The development of the duration to user delivery *(DurUsrD)* model represents one reason manual backward selection technique was used and not the automatic backward selection technique available in SAS application software. Further inspection of the Figure 26 will shed light on the issue. The first three iterations of the algorithm which takes the least significant variable out seems to have arrived at a model with the variables date of EMD contract award, maximum thrust, modification indicator variable, and empty weight of the aircraft as all being significant. However, because two of the variables, wing area, and the prototype indicator variable, which dropped in previous iterations had been successful in the first three models it was decided to attempt to improve the model by adding these back. The fourth line of the table shows the result of adding the wing area variable back to the model and dropping the empty weight variable (only because it is slightly less significant than the modification indicator variable -- .03 versus .02). The result shows this effort was without success. The next bit of tweaking--which was consistent with the models the R-square selection technique suggested in Figure 22--was to add the prototype indicator variable back (it is included in two of the other three models) and drop the modification indicator variable. Either the third or the fifth line could be the final model, but due to the higher F-score, the fifth-line model was chosen as the final model.

Model:
Duration to First Prototype Flight

| Step | Wingarea | Mod | NonOff | NrEng | MaxSpd | F | Rsqr |
|---|---|---|---|---|---|---|---|
| 1 | .00 | .10 | .24 | .04 | .31 | 5 | .46 |
| 2 | .00 | .09 | .04 | .01 | drop | 9 | .53 |
| 3 | .00 | drop | .01 | .01 | drop | 11 | .48 |

Final Model:
$DurProF = 3.0034 + .00094(WingArea) - 1.201(NonOff) - .519(NrEng)$

Figure 23. Backward Selection for *DurProF*

Model:
Duration to First Production Flight

| Step | Mod | Proto | McDAC | EMD | MaxThr | F | Rsqr |
|---|---|---|---|---|---|---|---|
| 1 | .03 | .02 | .19 | .19 | .33 | 7 | .51 |
| 2 | .01 | .01 | .17 | .23 | drop | 8 | .50 |
| 3 | .01 | .02 | .14 | drop | drop | 10 | .47 |
| 4 | .01 | .03 | drop | drop | drop | 13 | .44 |

Final Model:
$DurPdnF = 3.0530 - 1.5636(Mod) + 1.213(Proto)$

Figure 24. Backward Selection for *DurPdnF*

Model:
Duration to First Production Delivery

| Step | Mod | Proto | McD | EMD | MThr | WArea | EWgt | F | Rsqr |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .03 | .06 | .29 | .48 | .68 | .92 | .89 | 5 | .54 |
| 2 | .02 | .04 | .22 | .44 | .66 | drop | .89 | 6 | .54 |
| 3 | .02 | .03 | .22 | .39 | .09 | drop | drop | 7 | .54 |
| 4 | .01 | .01 | .18 | drop | .14 | drop | drop | 9 | .53 |
| 5 | .01 | .01 | drop | drop | .12 | drop | drop | 11 | .50 |
| 6 | .01 | .02 | drop | drop | drop | drop | drop | 15 | .46 |

Final Model:

$$\mathit{DurPdnD} = 3.0530 - 1.5636(\mathit{Mod}) + 1.213(\mathit{Proto})$$

Figure 25. Backward Selection for *DurPdnD*

Model:
Duration to First Delivery to the User

| Step | EMD | MThr | Proto | Mod | EmWgt | WArea | F | Rsqr |
|---|---|---|---|---|---|---|---|---|
| 1 | .02 | .01 | .25 | .06 | .44 | .61 | 6 | .55 |
| 2 | .01 | .0 | .18 | .06 | .06 | drop | 9 | .57 |
| 3 | .00 | .00 | drop | .02 | .03 | drop | 10 | .54 |
| 4 | .00 | .00 | drop | .01 | drop | .03 | 9 | .52 |
| 5 | .00 | .00 | .02 | drop | drop | drop | 11 | .49 |

Final Model:

$$\mathit{DurUsrD} = 5.379 - .0517(\mathit{EMD}) + .00001535(\mathit{MaxThrust}) + 1.2822(\mathit{Proto})$$

Figure 26. Backward Selection for *DurUsrD*

## *E. Modeling Decisions and Diagnosis*

***1. Dummy-Adjusted Slopes and Interaction Effects.*** An examination of the scatter plots did not reveal the need to use dummy-adjusted slopes. As a crosscheck, the models were rerun using dummy slopes and the significance of the models and of the coefficients worsened. The same was accomplished for the possibility of interaction effects with the same results.

2. ***Specification and Homoscedasticity.*** An examination of the residual plots for each model revealed the models linear as specified and reasonably homoscedastic. Mild heteroscedasticity is a concern, however, with the *DurProF* model. A log-log transformation failed to resolve this problem and only worsened the significance statistics. Changing *NrEng* as a categorical variable has similar results, only with slightly worse significance statistics.

3. ***Outliers.*** Reviewing the scatter plots and the studentized residuals revealed the following significant outliers with respect to Y: the C-17 for *DurProF,* the C-97 and the C-17 for *DurPdnF* and for *DurPdnD,* and none for *DurUsrD.* This is consistent with logic since the C-97 was delayed by World War II and since the C-17 represents the development stretchouts common in the 1980s and 1990s.

Reviewing the scatter plots and the hat matrix revealed the following significant outliers with respect to X: the C-5A and the C-5B for *DurProF,* none for *DurPdnF* and *DurPdnD,* and the E-4 for *DurUsrD.* This is consistent with the extreme *WingArea* for the C-5A and the C-5B, and the extreme *MaxThrust* for the E-4.

Reviewing the Cook's D statistic revealed no significant overall outliers. Given (1) the Cook's D statistics, (2) the overall importance and trend representativeness of the C-97, the C-17, and the E-4, and (3) the intuitiveness of the explanations for why these observations are outliers, it was decided not to discard these observations.

***4. Autocorrelation.*** A review of the Durbin-Watson statistics failed to identify a major autocorrelation or time-phase problem.

***5. Multicollinearity.*** A review of the Variance Inflation Factors (VIFs) found no issues with multicollinearity. This is consistent with the intent of the principal-component-analysis technique.

## *F. Final Models*

### *1. SER for DurProF.*

$$\begin{aligned} DurProF = 3.0034 + 0.0009 * WingArea - 1.2014 * NonOff \\ - 0.5188 * NrEng \end{aligned} \tag{19}$$

where

*DurProF = duration from EMD start to the first prototype flight* (years)

*WingArea = wing area* (square feet)

*NonOff = indicator variable for noncombatant aircraft*

*NrEng = number of engines*

The intercept is significant at $p < .0001$, *WingArea* is significant at $p < .0001$, *NonOff* is significant at $p < .01$, *NrEng* is significant at $p < .007$, and the model is significant at $p < .0001$. The adjusted $R^2$ is .44, the F-value is 10.56, and the sample size was 38 aircraft.

The mean duration from start of EMD to the first prototype flight is 3.00 years, plus .0009 times the wing area in square feet, minus .52 times the number of engines. For example, a typical system, with a wing area of 2,000 square feet and four engines, would have an estimated duration to first prototype flight of 2.73 years.

If the system is not a bomber (that is, it is nonoffensive), take another 1.20 years off that, for 1.53 years.

This is intuitive. *WingArea* is a size parameter: the larger the aircraft is, the longer it will take to develop it. *NonOff* measures the time savings one has when one does not have to design the system to withstand the rigors of combat. *WingArea* and *NonOff* were previously identified as potential drivers by VMSC and by TASC, respectively.

However, *NrEng* is counterintuitive to the initial logic: it was expected to be a size parameter. Rather, *NrEng* appears to measure--for a needed amount of thrust--that it takes less time to design the aircraft with more less-thrust-efficient engines than with fewer more-thrust-efficient engines. This is consistent with one of VMSC's TER for NASA (see Equation 3), where *NrEng* had a negative estimating relationship with development schedule.

### *2. SER for DurPdnF.*

$$DurPdnF = 3.0530 - 1.5636 * Mod + 1.2130 * Proto \tag{20}$$

where

*DurPdnF = duration from EMD start to the first production-article flight* (years)

*Mod = indicator variable for those programs that are modifications of existing systems*

*Proto = indicator for those programs where prototyping is used as an acquisition strategy*

The intercept is significant at $p<.0001$, *Mod* is significant at $p<.006$, *Proto* is significant at $p<.03$, and the model is significant at $p<.0001$. The adjusted $R^2$ is .41, the F-value is 13.25, and the sample size included 37 aircraft.

The mean duration to first production flight is 3.05 years. If the system is a modification of an existing system, it will be 1.56 years shorter. If the system was prototyped, it will take 1.21 years longer. So the model estimated a range from 1.49 years to 4.27 years. This is consistent with the initial logic and with the previous findings of RAND and IDA (for *Proto)* and of IDA (for *Mod)*.

### *3. SER for DurPdnD.*

$$DurPdnD = 3.5104 - 1.5828 * Mod + 1.3466 * Proto \tag{21}$$

where

*DurPdnD = duration from EMD start to the first production-article delivery to the acquiring agency* (years)

*Mod = indicator variable for those programs that are modifications of existing systems*

*Proto = indicator for those programs where prototyping is used as an acquisition strategy*

The intercept is significant at $p<.0001$, *Mod* is significant at $p<.005$, *Proto* is significant at $p<.02$, and the model is significant at $p<.0001$. The adjusted $R^2$ is .43, the F-value is 14.58, and the model was built on a sample of 37 aircraft.

Not surprisingly--since after the first production unit is signed over to the Air Force soon after the first production flight--this SER estimates a duration near that of

Equation 20. Here the model estimates a duration range from 1.93 years to 4.96 years.

### *4. SER for DurUsrD.*

$$\mathit{DurUsrD} = 5.3794 - 0.0517 * \mathit{EMD} + 0.00002 * \mathit{MaxThr} + 1.2822 * \mathit{Proto} \tag{22}$$

where

*DurUsrD = duration from EMD start to the first production-article delivery to the using command* (years)

*EMD = decimalized Julian date of the start of EMD*

*MaxThr = total maximum thrust* (pounds)

*Proto = indicator variable for those programs where prototyping is used as an acquisition strategy*

The intercept is significant at $p < .0002$, *EMD* is significant at $p < .009$, *MaxThr* is significant at $p < .002$, *Proto* is significant at $p < .02$, and the model is significant at $p < .0001$. The adjusted $R^2$ is .45, the F-value is 11.22, and the sample size was 39 aircraft.

This model estimates a mean duration of 5.38 years, minus .05 times the date the program enters EMD, plus .00002 times the system's maximum thrust. For example, a typical system, which entered EMD on 4 April 1960 (that is, 60.271) with 51,000 pounds of maximum thrust, could expect a duration of 3.28 years to the first delivery to the using command. If the system was prototyped, it would take 1.28 years longer.

It was expected that *MaxThr* and *Proto* would be parameters, since they were previously identified by VMSC and by RAND and IDA, respectively. However, *EMD* is a surprise parameter given RAND's findings that it is not a significant schedule driver. Furthermore, that *EMD* is a negative coefficient (that is, *DurPdnD* decreases as *EMD* increases) is especially surprising; but these models are explanatory. So while they do an elegant job of explaining the data set, caution must be used in estimating outside the model's relevant range. The range of this model's data set for entry into EMD was from 1940 to 1990, with a mean year of 1960.

Of all the SERs developed in this thesis, Equation 4 is the one that would most need recalibration as time passes. It is hard to imagine future nontactical aircraft beyond the ranges of the models' other continuous parameters (that is, *WingArea, NrEng,* and *MaxThr).*

# *V. Recommendations*

## *A. Review*

The program manager for a nontactical-aircraft program now has a schedule estimate which allows him or her to consider the EMD schedule when analyzing program tradeoffs. Without an estimate of the schedule, the program manager could not realistically decide if performance and/or cost of the system needs to be scaled back to meet the user's need. By having this information, he or she can more accurately decide between alternatives. This and future research in parametric schedule estimating will provide the program manager, and his or her superiors, a better understanding of what effect their decisions have on the schedule of a program.

This thesis attempted to develop models to estimate the duration of time from the award of the EMD contract award to four other program milestones. These models can be useful to program managers in many ways. Each duration chosen represents important lengths of time for a program manager. These durations estimates can indicate to a program manager whether the program is going to be on time or more managerial oversight or pressure on the contractor to perform is needed. These models can also be used to crosscheck a contractor's proposed schedule during the source selection process. Without the use of such models, the source selection team can only guess at a possible duration for each period or take the contractor's estimate at face value. This statement is not intended to discredit contractor estimates, but often contractor estimates are optimistic.

It was shown that parametric schedule estimating can be accomplished. Significant variables and models were developed: all four models were significant at $p<.0002$, seven of the 10 nonintercept parameters were significant at $p<.01$, and the other three nonintercept parameters were significant at $p<.05$. All four SER models were built from sample sizes of 37 or more data sets. It was found that the independent variables normally used to perform parametric cost estimates are not useful for estimating schedules and that more qualitative-type variables are better estimators: of the 10 nonintercept parameters, six were indicators. It was also found that the EMD phase of major weapon systems is not lengthening. In fact, EMD appears to be getting shorter--at least in this database.

### *B. Caveats*

Although these models can be used to estimate program durations, caution must be used when one employs these or any models to predict future durations. For example, these SERs do not even capture most of the variance in the data base: all the coefficients of determination (that is, the adjusted $R^2$s) were less than .50. As such, one needs to stay within the models' relevant ranges, decision makers should not interpret the estimated duration as "set in stone," and the estimated duration is only a mean value with--often--wide variation.

Estimating within the relevant range of the data should not be too much of a problem with the first three models. However, any future programs will fall outside the range of the EMD contract award date variable *(EMD)* in the duration to user delivery date *(DurUsrD)* model. Nevertheless, the rest of the database covers the full range of physical and performance characteristics for bombers, transports, tankers, and surveillance aircraft, so for the variables other than *EMD* this should not be a problem. Most of the parameters are indicators, so the relevant range is not an issue. As for the *DurUsrD* model, its relevant range for *EMD* would require that the model be recalibrated if one wishes to use it to estimate for future systems. This certainly limits its application.

The people who are most familiar with the program should perform the schedule estimate. These people, frequently, are the contractor's employees. For example, the shop floor manager who adds the hours his or her job takes has a much better idea of how long his or her micro-project will take. Parametrically-developed models provide a probabilistic window within which the actual duration will lie; therefore, the predicted duration should not be used as a rigid performance-control criterion. Rather, the intent of parametrically-developed models is to provide rough initial estimates, to crosscheck estimates developed using a bottoms-up technique, to provide a quick way to get an idea of the program's duration, and for use in tradeoff analyses.

As alluded to above, the estimated duration is simply the expected value, that is, the mean. This mean is only the balancing point of the distribution. As with any distribution, there is variance. This variance may provide a large range around the mean. Thus, using the estimated value of the duration without respect for the variance will guarantee 100 percent inaccuracy. A decision-maker should be provided not only the point estimate, but also the range estimates for a variety of confidence levels.

### *C. Recommendations for Future SER Research*

Caveats aside, there is much potential for further SER research. The following are recommendations and suggestions to future SER researchers.

The primary constraint to most research in the DOD acquisition field is limited data. A historic database of program milestones is desperately needed. While such a database has evolved for CER research, successful SER research hinges on the availability of historic actual program milestone dates. The culmination of this database would evolve into "one-stop shopping" for future schedule research. Not only would a historical schedule database permit larger and more representative data sets, which could be used to fine-tune the SERs to smaller subsets of systems, but critical scheduling dates, such as critical design review (CDR) and functional configuration audit (FCA), would be available to estimate the dates program managers need.

Such a database should also include the acquisition strategies and other categorical factors theorized to drive schedules. Some of these independent variables are available, but would require considerable normalization for inclusion in schedule research. Many of these variables are identified by other authors in the articles reviewed in chapter two. As can be seen in the models' coefficients of determination, these SERs do not capture even most of the variance in EMD schedules. As RAND and IDA theorized, there are many categorical parameters known before EMD which impact the schedule. These variables should be harnessed in future research.

Programs not selected to progress beyond EMD were included in the database (for example, the XB-49). It would be interesting to expand the database to include all unsuccessful programs to see if there is a significant difference between those programs destined to failure and those that go on into production. Perhaps some factor could be identified to estimate which programs are risky, from a continuation perspective.

Similarly, the database could be expanded to include more Navy aircraft, foreign aircraft, and commercial aircraft. This would allow a larger sample size with its attendant flexibility. A larger database would also adapt to trends in mission needs. That is, the first 20 years of this thesis' database is dominated by bombers, while transports are more prominent in the last 20 years. Perhaps this shift in mission needs confounded the models.

Of course, expanding SER research outside aircraft systems is appropriate. Especially so, given the emphasis on space and electronic systems over aircraft systems. Similarly, the literature and this thesis suggest that programmatic parameters--not physical or performance characteristics--drive EMD schedule durations. If this is so, then SERs could possibly be built to estimate development schedules for a wide range of products.

### [illegible] *Conclusions*

It was shown that statistically-significant SERs can be built using parameters known before EMD. Program managers and decision makers can now analyze tradeoffs among alternatives based, not only between cost and performance, but also the proposed system's schedule. It supported the literature's assertions that categorical variables--not continuous ones--are what drive schedules. It showed the potential for future SER research into other categorical parameters that would capture even more schedule variance.

## *Appendix: Database*

### *Part I: Categorical Independent Variables*

| Manufacturer | Aircraft | Name | *McDAC* | *Mod* | *Proto* | *NonOff* |
|---|---|---|---|---|---|---|
| Boeing | B-29 | Stratofortress | 0 | 0 | 1 | 0 |
| Douglas | B-26 | Invader | 1 | 1 | 1 | 0 |
| Convair | B-36 | Peacemaker | 0 | 0 | 1 | 0 |
| Northrup | XB-35 | Flying Wing | 0 | 0 | 1 | 0 |
| Convair | XC-99 |  | 0 | 1 | 1 | 1 |
| Boeing | C-97 | Stratofreighter | 0 | 1 | 1 | 1 |
| Douglas | XB-42 | Mixmaster | 1 | 0 | 1 | 0 |
| Douglas | XB-43 | Mixmaster II | 1 | 1 | 1 | 0 |
| North Am | B-45 | Tornado | 0 | 0 | 1 | 0 |
| Martin | XB-48 |  | 0 | 0 | 1 | 0 |
| Convair | XB-46 |  | 0 | 0 | 1 | 0 |
| Northrup | YB-49 | Flying Wing II | 0 | 1 | 1 | 0 |
| Boeing | B-50 | Superfortress | 0 | 1 | 0 | 0 |
| Boeing | B-47 | Stratojet | 0 | 0 | 1 | 0 |
| Martin | XB-51 |  | 0 | 0 | 1 | 0 |
| Northrup | C-125 | Raider | 0 | 1 | 1 | 1 |
| Douglas | C-124 | Globemaster | 1 | 1 | 1 | 1 |
| Fairchild | C-123 | Provider | 0 | 1 | 1 | 1 |
| Douglas | A-3 | Skywarrior | 1 | 0 | 1 | 0 |
| Boeing | B-52A | Stratofortress | 0 | 0 | 1 | 0 |
| Martin | B-57 | Canberra | 0 | 1 | 0 | 0 |
| Convair | YB-60 |  | 0 | 1 | 1 | 0 |
| Convair | C-131 |  | 0 | 1 | 0 | 1 |
| Douglas | B-66 | Destroyer | 1 | 1 | 1 | 0 |
| Lockheed | C-130 | Hercules | 0 | 0 | 1 | 1 |
| Convair | B-58 | Hustler | 0 | 0 | 1 | 0 |
| Douglas | C-133 | Cargomaster | 1 | 0 | 0 | 1 |
| Boeing | KC-135 | Stratotanker | 0 | 0 | 1 | 1 |
| Lockheed | C-140 | Jetstar | 0 | 0 | 1 | 1 |
| Boeing | B-52G | Stratofortress | 0 | 1 | 0 | 0 |
| North Am | XB-70 | Valkyrie | 0 | 0 | 1 | 0 |
| Lockheed | P-3A | Orion | 0 | 1 | 1 | 1 |
| Rockwell | T-39 | Sabreliner | 0 | 1 | 1 | 1 |
| Lockheed | C-141 | Starlifter | 0 | 0 | 1 | 1 |
| General Dyn | FB-111 |  | 0 | 1 | 1 | 0 |
| Lockheed | C-5A | Galaxy | 0 | 0 | 1 | 1 |
| Douglas | C-9 | Nightengale | 1 | 1 | 0 | 1 |
| Lockheed | P-3A | Orion | 0 | 1 | 1 | 1 |

| Manufacturer | Aircraft | Name | McDAC | Mod | Proto | NonOff |
|---|---|---|---|---|---|---|
| Lockheed | S-3 | Viking | 0 | 0 | 1 | 1 |
| Rockwell | B-1A |  | 0 | 0 | 1 | 0 |
| Boeing | T-43 |  | 0 | 1 | 0 | 1 |
| Boeing | E-3 | Sentry | 0 | 1 | 1 | 1 |
| Boeing | E-4 |  | 0 | 1 | 0 | 1 |
| Beech | C-12 | Huron | 0 | 1 | 0 | 1 |
| Douglas | KC-10 | Extender | 1 | 1 | 0 | 1 |
| Northrup | B-2 |  | 0 | 0 | 1 | 0 |
| Rockwell | B-1B | Lancer | 0 | 1 | 1 | 0 |
| Lockheed | C-5B | Galaxy | 0 | 1 | 0 | 1 |
| Gulfstream | C-20 |  | 0 | 1 | 0 | 1 |
| Learjet | C-21 |  | 0 | 1 | 0 | 1 |
| Shorts | C-23 | Sherpa | 0 | 1 | 0 | 1 |
| Douglas | C-17 | Globemaster | 1 | 0 | 1 | 1 |
| Boeing | E-8 |  | 0 | 1 | 1 | 1 |
| Fairchild | C-26 | Metro III | 0 | 1 | 0 | 1 |
| Beech | T-1 | Jayhawk | 0 | 1 | 0 | 1 |
| Chrysler | C-27 | Spartan | 0 | 1 | 0 | 1 |

## *Appendix, Part II: Continuous Independent Variables*

| Aircraft | *NrAccpd* | *NrProto* | *WingSpan* | *WingArea* | *EmpWgt* |
|---|---|---|---|---|---|
| B-29 | 4,221 | 3 | 141.3 | 1,739 | 71,500 |
| B-26 | 2,451 | 3 | 70 | 540 | 22,362 |
| B-36 | 284 | 2 | 230 | 4,772 | 133,820 |
| XB-35 | 0 | 2 | 172 | 4,000 | 82,807 |
| XC-99 | 0 | 1 | 230 | 4,772 | 135,914 |
| C-97 | 888 | 3 | 141.3 | 1,769 | 74,962 |
| XB-42 | 0 | 2 | 70.6 | 555 | 20,888 |
| XB-43 | 0 | 2 | 71.2 | 563 | 22,890 |
| B-45 | 139 | 3 | 89 | 1,175 | 44,854 |
| XB-48 | 0 | 2 | 108.3 | 1,330 | 92,600 |
| XB-46 | 0 | 1 | 113 | 1,285 | 48,000 |
| YB-49 | 0 | 2 | 172 | 4,000 | 89,112 |
| B-50 | 370 | 0 | 141.2 | 1,720 | 77,456 |
| B-47 | 2,028 | 2 | 116 | 1,428 | 77,830 |
| XB-51 | 0 | 2 | 53.1 | 548 | 29,584 |
| C-125 | 23 | 1 | 86.5 | 1,132 | 26,718 |
| C-124 | 448 | 1 | 174.1 | 2,510 | 95,707 |
| C-123 | 300 | 5 | 110 | 1,223 | 35,366 |
| A-3 | 280 | 2 | 72.5 | 680 | 41,192 |
| B-52A | 742 | 2 | 185 | 4,000 | 164,081 |
| B-57 | 403 | 0 | 64 | 960 | 28,793 |
| YB-60 | 0 | 2 | 206 | 4,772 | 150,000 |
| C-131 | 518 | 0 | 91.7 | 817 | 27,893 |
| B-66 | 289 | 1 | 72.5 | 780 | 42,549 |
| C-130 | 2,039 | 2 | 132.6 | 1,745.5 | 59,328 |
| B-58 | 116 | 3 | 56.8 | 1,542.5 | 56,358 |
| C-133 | 45 | 0 | 179.6 | 2,673 | 115,719 |
| KC-135 | 877 | 1 | 130.8 | 2,433 | 97,030 |
| C-140 | 16 | 2 | 53.7 | 542.5 | 21,455 |
| B-52G | 193 | 0 | 185 | 4,000 | 168,445 |
| XB-70 | 0 | 2 | 105 | 6,297 | 231,215 |
| P-3A | 483 | 2 | 99.7 | 1,300 | 59,201 |
| T-39 | 210 | 1 | 44.5 | 342.1 | 9,753 |
| C-141 | 285 | 1 | 160 | 3,228 | 134,203 |
| FB-111 | 76 | 1 | 70 | 550 | 47,481 |
| C-5A | 81 | 5 | 222.7 | 6,200 | 363,195 |
| C-9 | 39 | 0 | 93.3 | 1,001 | 61,790 |
| P-3C | 421 | 1 | 99.7 | 1,300 | 61,491 |
| S-3 | 187 | 1 | 68.7 | 598 | 26,650 |
| B-1A | 0 | 4 | 136.7 | 1,946 | 143,000 |

| Aircraft | NrAccpd | NrProto | WingSpan | WingArea | EmpWgt |
|---|---|---|---|---|---|
| T-43 | 19 | 0 | 93 | 980 | 60,550 |
| E-3 | 33 | 2 | 145.8 | 2,892 | 170,706 |
| E-4 | 4 | 0 | 195.7 | 5,550 | 307,265 |
| C-12 | 215 | 0 | 54.5 | 303 | 1,437 |
| KC-10 | 60 | 0 | 165.4 | 3,647 | 236,474 |
| B-2 | . | 6 | 172 | 5,000 | 110,000 |
| B-1B | 100 | 4 | 136.7 | 1,946 | 182,162 |
| C-5B | 50 | 0 | 222.7 | 6,200 | 374,000 |
| C-20 | 10 | 0 | 77.8 | 934 | 38,000 |
| C-21 | 83 | 0 | 39.5 | 253.3 | 10,022 |
| C-23 | 18 | 0 | 74.7 | 453 | 16,040 |
| C-17 | . | 1 | 165 | 3,800 | 261,579 |
| E-8 | . | 2 | 145.8 | 3,050 | 172,795 |
| C-26 | 33 | 0 | 57 | 309 | 9,007 |
| T-1 | . | 0 | 43.7 | 241.4 | 10,072 |
| C-27 | . | 0 | 94.2 | . | 35,500 |

## *Appendix, Part III: Continuous Independent-Variables, Continued*

| Aircraft | NrEng | MaxThr | AvgSpd | MaxSpd | CmbtRad | Range |
|---|---|---|---|---|---|---|
| B-29 | 4 | 22,000 | 220 | 347 | 1,717 | 3,500 |
| B-26 | 2 | 10,000 | 200 | 322 | 839 | 1,400 |
| B-36 | 6 | 45,000 | 191 | 298 | 3,360 | 10,000 |
| XB-35 | 4 | 29,400 | 336 | 367 | 2,660 | 4,990 |
| XC-99 | 6 | 52,500 | 212 | 327 | 500 | 900 |
| C-97 | 4 | 35,000 | 335 | 342 | 1,000 | 1,640 |
| XB-42 | 2 | 2,920 | 335 | 419 | 495 | 2,090 |
| XB-43 | 2 | 7,640 | 365 | 437 | 470 | 1,100 |
| B-45 | 2 | 11,000 | 434 | 495 | 788 | 1,520 |
| XB-48 | 6 | 22,920 | 390 | 449 | 575 | 1,109 |
| XB-46 | 4 | 15,280 | 381 | 425 | 603 | 1,163 |
| YB-49 | 8 | 30,000 | 415 | 451 | 1,410 | 2,800 |
| B-50 | 4 | 14,000 | 352 | 353 | 2,210 | 4,140 |
| B-47 | 6 | 31,200 | 431 | 521 | 1,750 | 3,360 |
| XB-51 | 3 | 15,600 | 463 | 560 | 378 | 934 |
| C-125 | 3 | 9,000 | 117 | 170 | 357 | 652 |
| C-124 | 4 | 14,500 | 180 | 280 | 1,000 | 2,430 |
| C-123 | 2 | 35,000 | 140 | 232 | 650 | 1,080 |
| A-3 | 2 | 24,800 | 457 | 556 | 912 | 2,520 |
| B-52A | 8 | 91,200 | 453 | 546 | 3,110 | 12,500 |
| B-57 | 2 | 14,440 | 414 | 520 | 824 | 2,300 |
| YB-60 | 8 | 72,000 | 440 | 451 | 2,910 | 8,000 |
| C-131 | 2 | 12,500 | 180 | 274 | 792 | 1,636 |
| B-66 | 2 | 20,400 | 456 | 548 | 794 | 2,520 |
| C-130 | 4 | 37,500 | 290 | 332 | 1,000 | 1,900 |
| B-58 | 4 | 60,000 | 498 | 1,147 | 1,065 | 3,789 |
| C-133 | 4 | 23,200 | 269 | 302 | 1,000 | 1,700 |
| KC-135 | 4 | 55,000 | 443 | 527 | 1,000 | 2,988 |
| C-140 | 4 | 12,000 | 445 | 498 | 778 | 1,675 |
| B-52G | 8 | 110,000 | 453 | 551 | 3,550 | 6,513 |
| XB-70 | 6 | 168,000 | 1,721 | 1,721 | 2,969 | 3,726 |
| P-3A | 4 | 45,000 | 310 | 366 | 1,346 | 2,383 |
| T-39 | 2 | 6,000 | 436 | 468 | 1,348 | 1,348 |
| C-141 | 4 | 84,000 | 442 | 496 | 1,000 | 2,069 |
| FB-111 | 2 | 40,700 | 444 | 1,262 | 800 | 4,435 |
| C-5A | 4 | 164,000 | 450 | 496 | 1,000 | 3,259 |
| C-9 | 2 | 29,000 | 437 | 505 | 1,000 | 2,161 |
| P-3C | 4 | 49,100 | 328 | 411 | 1,346 | 2,383 |
| S-3 | 2 | 18,550 | 370 | 450 | 458 | 1,999 |
| B-1A | 4 | 119,400 | 420 | 1,262 | . | 6,103 |
| T-43 | 2 | 29,000 | 470 | 535 | . | 2,730 |
| E-3 | 4 | 84,000 | 423 | 473 | 600 | 4,340 |
| E-4 | 4 | 210,000 | 415 | 536 | . | 5,015 |
| C-12 | 2 | 3,750 | 271 | 289 | . | 2,235 |

| Aircraft | *NrEng* | *MaxThr* | *AvgSpd* | *MaxSpd* | *CmbtRad* | *Range* |
|---|---|---|---|---|---|---|
| KC-10 | 3 | 157,500 | 481 | 529 | 1,000 | 3,797 |
| B-2 | 4 | 76,000 | . | . | . | 6,305 |
| B-1B | 4 | 123,120 | 435 | 1,518 | 1,000 | 5,897 |
| C-5B | 4 | 172,000 | 450 | 496 | . | 5,618 |
| C-20 | 2 | 22,800 | 442 | 501 | . | 4,050 |
| C-21 | 2 | 7,000 | 418 | 471 | . | 2,232 |
| C-23 | 2 | 7,120 | 151 | 194 | . | 446 |
| C-17 | 4 | 160,240 | 446 | 463 | 1,000 | 1,528 |
| E-8 | 4 | 96,000 | 455 | 530 | . | 6,350 |
| C-26 | 2 | 5,500 | 248 | 288 | . | 1,740 |
| T-1 | 2 | 5,800 | 298 | 460 | 620 | 1,348 |
| C-27 | 2 | 17,000 | 250 | 263 | 300 | 680 |

## ***Appendix, Part IV: EMD Date***

| Aircraft | D/V | EMD | ProF | PdnF | PdnD | UsrD | IOC |
|---|---|---|---|---|---|---|---|
| B-29 | 39.285 | 40.644 | 42.721 | 43.704 | 44.186 | 44.452 | 44.871 |
| B-26 | 40.871 | 41.416 | 42.521 | . | 43.786 | 44.452 | 44.871 |
| B-36 | 41.274 | 41.789 | 46.600 | 47.923 | 48.460 | 48.482 | 44.871 |
| XB-35 | 41.400 | 41.890 | 46.479 | . | . | . | . |
| XC-99 | . | 42.452 | 47.893 | . | . | . | . |
| C-97 | 42.452 | 43.060 | 44.871 | 49.074 | 49.786 | 49.786 | . |
| XB-42 | . | 43.479 | 44.342 | . | . | . | . |
| XB-43 | 43.704 | 44.036 | 46.373 | . | . | . | . |
| B-45 | 44.605 | 44.685 | 47.205 | 48.123 | 48.285 | 48.871 | . |
| XB-48 | 44.605 | 44.992 | 47.058 | . | . | . | . |
| XB-46 | 44.605 | 45.044 | 47.249 | . | . | . | . |
| YB-49 | . | 45.414 | 47.803 | . | . | . | . |
| B-50 | 40.123 | 45.953 | . | 47.479 | 47.789 | 48.452 | 48.953 |
| B-47 | 44.605 | 45.959 | 47.959 | 50.479 | 50.953 | 51.619 | 53.038 |
| XB-51 | 46.123 | 46.389 | 49.822 | . | . | . | . |
| C-125 | . | 48.200 | 49.581 | 49.619 | 50.953 | . | . |
| C-124 | 47.871 | 48.904 | 49.904 | . | . | 50.367 | . |
| C-123 | 45.285 | 48.452 | 49.784 | 51.301 | . | 55.534 | . |
| A-3 | . | 49.244 | 52.822 | 53.707 | 55.038 | 56.241 | 56.241 |
| B-52A | 45.285 | 51.022 | 52.285 | 54.592 | 55.490 | 55.871 | 56.192 |
| B-57 | 50.707 | 51.068 | . | 53.548 | 53.633 | 54.200 | 54.534 |
| YB-60 | 45.893 | 51.200 | 52.293 | . | . | . | . |
| C-131 | . | 51.619 | . | 54.123 | 54.200 | 54.247 | 54.953 |
| B-66 | 51.499 | 52.123 | 54.123 | 54.488 | 55.038 | 56.038 | 56.200 |
| C-130 | 51.038 | 52.715 | 54.641 | 55.263 | 55.953 | 56.937 | 57.123 |
| B-58 | 49.200 | 53.115 | 56.860 | 59.704 | 59.871 | 60.200 | 61.367 |
| C-133 | . | 53.123 | . | 56.307 | 57.658 | 57.658 | 58.953 |
| KC-135 | 53.871 | 54.592 | 54.452 | 56.663 | 57.038 | 57.460 | 57.460 |
| C-140 | . | 57.200 | 57.674 | 61.953 | 62.786 | 62.789 | 62.791 |
| B-52G | 56.455 | 57.658 | . | . | . | 59.118 | 59.452 |
| XB-70 | 55.852 | 57.975 | 64.721 | . | . | . | . |
| P-3A | 57.619 | 58.310 | 58.630 | 61.285 | 62.200 | 62.200 | 62.614 |
| T-39 | 56.241 | 58.786 | . | 60.493 | 61.422 | 61.619 | . |
| C-141 | 60.337 | 61.285 | 63.959 | 63.967 | 64.797 | 65.307 | 65.367 |
| FB-111 | 63.871 | 65.416 | 67.578 | 68.529 | 68.660 | 69.767 | 71.038 |
| C-5A | 64.227 | 65.748 | 68.493 | 69.493 | 69.493 | 69.959 | 70.742 |
| C-9 | 67.038 | 67.619 | . | 68.458 | 68.605 | 68.704 | . |
| P-3C | 65.704 | 67.705 | 68.712 | 69.200 | 69.367 | 70.534 | . |
| S-3 | 65.871 | 69.581 | 72.055 | 73.285 | 73.786 | 74.137 | 75.534 |
| B-1A | 64.285 | 70.425 | 74.975 | . | . | . | . |

| Aircraft | D/V | EMD | ProF | PdnF | PdnD | UsrD | IOC |
|---|---|---|---|---|---|---|---|
| T-43 | . | 71.367 | . | 73.271 | 73.710 | 73.710 | 75.534 |
| E-3 | 70.556 | 73.068 | 74.205 | 75.562 | 77.225 | 77.225 | 78.285 |
| E-4 |  | 73.159 | . | 73.447 | 74.953 | 79.970 | 80.200 |
| C-12 | . | 74.619 | . | . | . | 75.534 | . |
| KC-10 | 75.038 | 77.964 | . | 80.526 | 81.205 | 82.619 | . |
| B-2 | . | 81.786 | 89.540 | . | . | . | . |
| B-1B | 81.748 | 82.038 | 83.200 | 84.762 | 85.452 | 85.512 | 86.745 |
| C-5B | 81.704 | 82.786 | . | 85.704 | 85.953 | 86.534 | . |
| C-20 | . | 83.430 | . | . | 83.707 | . | . |
| C-21 | . | 83.715 | . | 84.195 | . | . | 85.786 |
| C-23 | . | 84.200 | . | 84.595 | 84.871 | 84.871 | 85.929 |
| C-17 | 81.655 | 85.038 | 91.704 | 93.348 | 93.449 | . | . |
| E-8 | . | 85.737 | 88.973 | . | . | . | . |
| C-26 | . | 88.200 | . | . | 89.200 | 89.200 | 90.329 |
| T-1 | . | 90.140 | . | 91.044 | 91.786 | 92.038 | 92.704 |
| C-27 | . | 90.633 | . | 91.575 | . | 91.622 | . |

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This study developed parametric schedule estimating relationships (SERs) for the engineering and manufacturing development (EMD) phase for nontactical aircraft systems. The potential value of this nontraditional approach to estimating schedule duration has been established by previous applications to tactical aircraft, air-launched munitions, and office buildings. Prior research suggested acquisition strategy parameters to be significant schedule drivers. For this study, data on EMD milestone dates and potential schedule drivers were collected on 56 bomber, transport, tanker, and surveillance aircraft systems. Several SERs were developed for these systems using linear regression analysis. The EMD phase was divided into subphases based on significant milestone such as first prototype flight, first production-article flight, first production-article delivery, and first delivery to the operating command. The final SERs include explanatory variables that capture the acquisition strategy and physical characteristics of the systems. The SERs can be applied by program managers to estimate the EMD schedule of nontactical aircraft systems before entry into EMD.

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