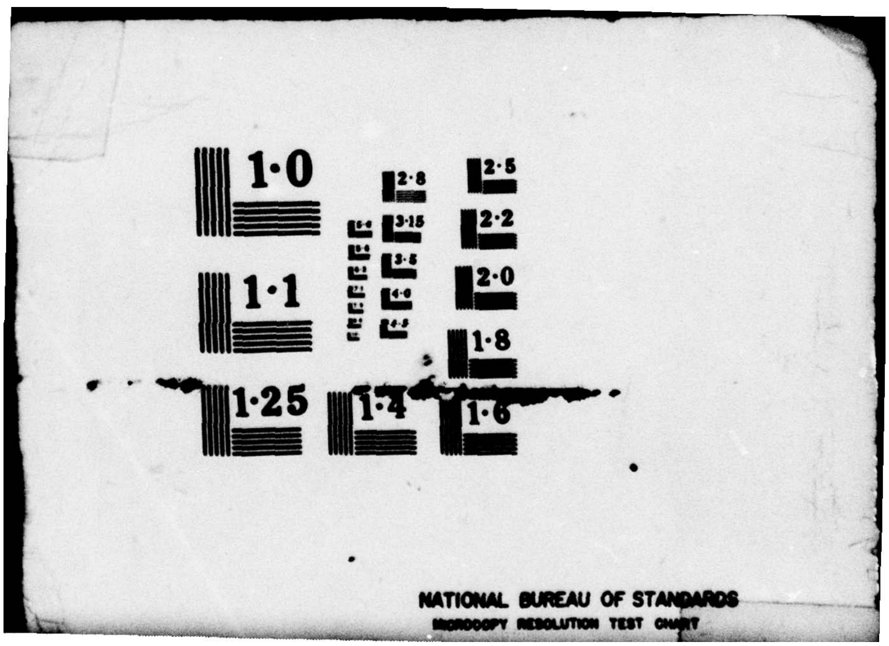
AD-A073 020 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL--ETC F/G 5/1
AN INVESTIGATION OF LEARNING CURVE THEORY APPLICATION TO AIR FO--ETC(U)
JUN 79 K W VINCENT, W C WALKER

UNCLASSIFIED AFIT-LSSR-25-79A NL

1 OF 1
AD
A073020

END
DATE
FILMED
9 79
DDC


1·0
1·1
1·25
1·4
1·6
1·8
2·0
2·2
2·5
2·8
3·15
3·5
4·0
4·5
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

3

AN INVESTIGATION OF LEARNING CURVE THEORY APPLICATION TO AIR FORCE DEPOT LEVEL MAINTENANCE BUDGETING AND PLANNING

Kenneth W. Vincent, GS-12
William C. Walker, GS-09

LSSR 25-79A

The contents of the document are technically accurate, and no sensitive items, detrimental ideas, or deleterious information are contained therein. Furthermore, the views expressed in the document are those of the author(s) and do not necessarily reflect the views of the School of Systems and Logistics, the Air University, the Air Training Command, the United States Air Force, or the Department of Defense.

USAF SCN 75-20B AFIT Control Number ______________

AFIT RESEARCH ASSESSMENT

The purpose of this questionnaire is to determine the potential for current and future applications of AFIT thesis research. Please return completed questionnaires to: AFIT/ LSH (Thesis Feedback), Wright-Patterson AFB, Ohio 45433.

1. Did this research contribute to a current Air Force project?

a. Yes b. No

2. Do you believe this research topic is significant enough that it would have been researched (or contracted) by your organization or another agency if AFIT had not researched it?

a. Yes b. No

3. The benefits of AFIT research can often be expressed by the equivalent value that your agency received by virtue of AFIT performing the research. Can you estimate what this research would have cost if it had been accomplished under contract or if it had been done in-house in terms of manpower and/or dollars?

a. Man-years __________ $ __________ (Contract).

b. Man-years __________ $ __________ (In-house).

4. Often it is not possible to attach equivalent dollar values to research, although the results of the research may, in fact, be important. Whether or not you were able to establish an equivalent value for this research (3 above), what is your estimate of its significance?

a. Highly Significant b. Significant c. Slightly Significant d. Of No Significance

5. Comments:

Accession For
NTIS GRA&I
DDC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or special
A

______________________ Name and Grade ______________________ Position

______________________ Organization ______________________ Location

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE. $300

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL

FIRST CLASS PERMIT NO. 73236 WASHINGTON D.C.

POSTAGE WILL BE PAID BY ADDRESSEE

AFIT/LSH (Thesis Feedback)
Wright-Patterson AFB OH 45433

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 25-79A	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 AN INVESTIGATION OF LEARNING CURVE THEORY APPLICATION TO AIR FORCE DEPOT LEVEL MAINTENANCE BUDGETING AND PLANNING.		5. TYPE OF REPORT & PERIOD COVERED 9 Master's Thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Kenneth W. Vincent William C. Walker		8. CONTRACT OR GRANT NUMBER(s) 12 79
9. PERFORMING ORGANIZATION NAME AND ADDRESS Graduate Education Division School of Systems and Logistics Air Force Institute of Technology, WPAFB OH		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Research and Administrative Management AFIT/LSGR, WPAFB OH 45433		12. REPORT DATE 11 Jun[redacted]79
		13. NUMBER OF PAGES 65
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

14 AFIT-LSSR-25-79A

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited.

18. SUPPLEMENTARY NOTES

JOSEPH P. HIPPS, Major, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Learning Curve
Improvement Curve
Progress Curve
Depot Level Maintenance
Experience Curve

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

012 250 gm

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The objective of this study is to determine if the learning curve can be recommended for depot level maintenance workload budgeting and planning. Historical depot level maintenance data, collected through the Air Force maintenance data collection system, is examined by a computerized learning curve analysis program to determine if the learning curve can both explain and predict maintenance actions. The analysis of the limited data available does not yield results within acceptable limits. On the basis of this study, the authors cannot recommend the use of the learning curve for maintenance operations and conclude that the level of detail within the maintenance data collection system does not lend itself to learning curve analysis studies.

1473.B

LSSR 25-79A

AN INVESTIGATION OF LEARNING CURVE THEORY APPLICATION TO AIR FORCE DEPOT LEVEL MAINTENANCE BUDGETING AND PLANNING

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

Kenneth W. Vincent, BA
GS-12

William C. Walker, BS
GS-09

Approved for public release;
distribution unlimited

This thesis, written by

Mr. Kenneth W. Vincent, GS-12

and

Mr. William C. Walker, GS-09

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 13 June 1979

Larry L. Smith
COMMITTEE CHAIRMAN

ACKNOWLEDGEMENTS

We wish to express our gratitude and appreciation to Lieutenant Colonel Larry L. Smith, our thesis advisor, for his guidance and encouragement throughout this research effort. We would also like to take this opportunity to congratulate him on being selected for the rank of Colonel.

We also acknowledge the assistance of Mr. Bernard Leslie, AFIT-ACDS, for the graphics used in this thesis.

A special acknowledgement is expressed to our wives. Their encouragement throughout the year has been a great help to us. They have sacrificed much in their family and home life so that we could expend our energies on this thesis effort. We therefore dedicate this thesis to them.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
Chapter	
I. INTRODUCTION	1
Statement of the Problem	2
Objective	3
Justification	4
Scope	4
Reseach Questions	5
II. THE LEARNING CURVE	6
Background	6
History	9
III. RESEARCH METHODOLOGY	14
Assumptions and Limitation	15
Variables	16
Data Source and Validity	16
Population and Sample of Interest	18
Computer Program	19
Criteria Test	21

Chapter Page

IV. ANALYSIS AND FINDINGS 24

Data 24

Data Set One 26

Data Set Two 32

Data Set Three 32

Data Set Four 38

Data Set Five 40

Summary 45

V. SUMMARY AND CONCLUSIONS 47

Summary 47

Conclusions 50

APPENDIXES

A. EXCERPT FROM DEFENSE CONTRACT AUDIT MANUAL 54

SELECTED BIBLIOGRAPHY 57

LIST OF TABLES

Table		Page
1.	ICUNIS ANALYSIS--DATA SET ONE	27
2.	PERCENTAGE DIFFERENCE--DATA SET ONE	29
3.	ICUNIS ANALYSIS--DATA SET TWO	34
4.	PERCENTAGE DIFFERENCE--DATA SET TWO	35
5.	ICUNIS ANALYSIS--DATA SET THREE	40
6.	PERCENTAGE DIFFERENCE--DATA SET THREE	41
7.	ICUNIS ANALYSIS--DATA SET FOUR	43
8.	PERCENTAGE DIFFERENCE--DATA SET FOUR	43
9.	ICUNIS ANALYSIS--DATA SET FIVE	44
10.	PERCENTAGE DIFFERENCE--DATA SET FIVE	44

LIST OF FIGURES

Figure		Page
1.	Data Set 1	28
2.	Data Set 2	33
3.	Data Set 3	39
4.	Data Set 4	42
5.	Data Set 5	46

CHAPTER I

INTRODUCTION

Learning curve theory is based on the observation that there is a relationship between an increase in efficiency and the number of times a particular task is performed. This relationship was first observed in airframe production prior to World War II, and is widely used as a manufacturing planning tool throughout industry today. The proposed research is to examine the potential use of the learning curve relationship as a predictive tool for Air Force organic depot level maintenance budgeting and workload planning.

The Air Force does not adequately consider the learning curve effect in its depot level aircraft maintenance operations due to an important difference between a manufacturing operation and a maintenance operation. A manufacturing process produces a homogeneous product, in which the same tasks are performed over and over. In a maintenance operation, however, there is only an approximation of a homogeneous product, since the same tasks are not necessarily performed for each end item. Nevertheless, learning does occur which affects the time required to perform each maintenance action (11:138-139).

If a learning curve could be used to predict man-hour requirements for depot level maintenance operations, considerable benefits would be derived. These include improved maintenance budgeting of Air Force financial resources and more efficient planning of personnel requirements, facility utilization, and aircraft flow time, thereby resulting in a more efficient allocation of total resources to requirements.

Statement of the Problem

The problem is to assess the appropriateness of learning curve theory for maintenance operations budgeting and planning. The present method of projecting maintenance requirements is to forecast a constant value in manhours per aircraft for all of the aircraft in a particular project, such as a modification. The effect of learning on hours per production unit is considered by projecting increases in labor effectiveness over time. In practice, however, the effectiveness projections are sometimes inaccurate and the resulting requirements are either badly overstated or understated (14). Where requirements are understated, cost over-runs are experienced, flow time through the maintenance facility is understated, and queues develop where aircraft arrive that cannot be accommodated. Where requirements are overstated, the maintenance facility is not fully utilized because, given a predetermined input schedule, aircraft process through the facility at a faster than anticipated rate. Labor resources are likely to be under-utilized because output capacity exceeds the rate of input.

Objective

The objective of this study is to determine if the learning curve can be recommended as a useful tool for maintenance budgeting and workload planning. As stated in the previous section, learning is presently accounted for by a projected increase in labor effectiveness over time. However, the inaccuracy of the labor effectiveness is often manifested in shortages or excesses of manpower requirements.

Historical data from Air Force maintenance data collection systems tend to support the existence of learning in that there is a progressive decrease in man-hours expended per unit for most maintenance and modification programs. Therefore, learning curve theory may be a more appropriate means than labor effectiveness projection to budget and plan depot level maintenance resource requirements. This proposition is supported, in theory, in several maintainability studies (10:16; 17:25).[1]

---

[1]An article by Myron A. Wilson, "The Learning Curve in Maintenance Analysis," 5th Reliability and Maintainability Conference, July 18-20, 1966, New York NY, is referenced in these articles, but efforts to obtain it have not been successful.

Selected "samples of convenience" of maintenance data will be subjected to analysis to determine if the data reflect the learning curve effect. Should a learning curve be demonstrated, the researchers would recommend that Air Force Logistics Command (AFLC) personnel consider the use of learning curve as an alternative to present methods in use at AFLC depots.

Justification

A request for investigating the applicability of the learning curve principles to maintenance actions was submitted to the Air Force Institute of Technology by AFLC Directorate of Maintenance (AFLC/MA) personnel. This request asked that the relationship of learning curve theory to maintenance labor requirements be investigated. If the learning curve is appropriate for projecting labor requirements, it may provide a means to more accurately budget funds and plan workloading.

Scope

This study is limited in scope to aircraft maintenance at the organic depot level only. All contractual maintenance and organization or intermediate level maintenance is outside the study's scope.

Research Questions

1. Is the learning curve theory an appropriate explainer of organic depot level maintenance manpower requirements?

2. If the learning curve theory is an appropriate explainer, can the learning curve model be used as a predictive tool for use in maintenance budgeting and workload planning?

CHAPTER II

THE LEARNING CURVE

Learning phenomena have been generally accepted for many years and are based on the observation that when a task is repeated, each successive repetition will require less time. The learning curve can forecast this reduction in time with sufficient accuracy to be used as a predictive tool (7:2). This thesis is not a treatise on learning curve theory. However, the theory and its background will be addressed in this chapter to give the reader a basic understanding of the theory as used in this analysis. The thesis by Brewer (2) and the RAND report by Asher (1) are excellent sources for those interested in learning curve theory.

Background

The term "learning curve" originated because it was thought that worker learning was responsible for the resulting reduction of time. Further research indicated that the reduction was caused by many other factors in addition to worker learning (5:1). Factors that can contribute to time reduction are design changes, improved production planning, improved scheduling, resequencing of work operations, tooling improvement, and improved material ordering (2:7). In an attempt to describe the additional influences, terms such as "improvement curve," "progress curve," and "experience curve" were used. The term "learning curve" will be used because of its common usage within the Air Force and in the history of this subject.

The classical form of the learning curve theory states that as the total quantity of units produced doubles, the cost per unit declines by some constant percentage (1:1). The two basic types of learning curves are the "cumulative average learning curve" and the "unit learning curve." For the cumulative average learning curve, the cumulative average cost for the nth unit is the cumulative total cost for the first through the nth unit divided by n. Learning is based on the cumulative average cost: As the number of units produced doubles, the cumulative average manhours required to produce an item decreases by a constant percentage. The mathematical model of the cumulative average learning curve is $\bar{Y} = AX^B$ where:

- $\bar{Y}$ is the cumulative average direct manhours at unit X,
- A is the direct manhours required for the first unit produced,
- X is the cumulative number of units produced, and

B is an exponent that defines the shape of the learning curve (1:16).

This model can be converted to a linear form through a logarithmic transformation where:

$$\text{Log } \bar{Y} = \text{Log } A + B \text{ Log } X.$$

Transformation to the linear form facilitates visualization of relationships and permits mathematical computation through the use of regression analysis (12:1-5).

The other basic type of learning curve is the "unit learning curve." The unit curve is based on the assumption that the unit manhours required to produce an item decrease by some constant percentage as the quantity of product is doubled. The mathematical model for the unit curve is $Y = AX^B$ where:

Y is the unit manhours required to produce unit X,

A is the direct manhours of the first unit produced,

X is any numbered unit, and

B is an exponent that defines the shape of the learning curve (1:21-24).

The model can also be transformed into a linear form by the formula:

$$\text{Log } Y = \text{Log } A + B \text{ Log } X.$$

The difference between these twc models is only in the way the dependent variable data are edited. $\bar{Y}$ is the cumulative average unit cost in manhours and Y is the unit cost in manhours.

History

The first publication describing the learning curve phenomena in airframe production is credited to T. P. Wright who, in 1936, published an article in the Journal of Aeronautical Science titled "Factors Affecting the Cost of Airplanes" (5:49). After fourteen years of research on aircraft production data, Wright presented the theory that learning followed a log-linear pattern. His mathematical model hypothesized that the cumulative average labor cost for any quantity of airplanes produced decreases by a constant percentage as the quantity of airplanes produced is doubled (5:4). This became known as the cumulative average learning curve as described earlier in this chapter. The Crawford-Strauss study, published in 1947, was based on production data from 118 World War II aircraft. Crawford, in association with the Stanford Research Institute, theorized that as the quantity doubled, direct labor hours per unit decreased at a constant percentage. This is the origin of the unit learning curve theory (2:44; 7:2). The first Stanford study also developed a nominal airframe industry average curve. This was a composite curve for all data included in the study. This curve, 79.7 percent rounded to 80 percent, has sometimes been misapplied by disregarding the fact that individual program curves varied from approximately 70 percent to nearly 100 percent (13:2).

In 1952, W. Z. Hirsch concluded that labor-intensive production has a greater capacity for learning improvement than does capital-intensive production (5:7). This observation recognizes the fact that airframe production is a labor-intensive process.

In a study conducted by P. Guibert, the rate of production was introduced as a variable affecting costs. He also theorized that a horizontal asymptote is approached after a large number of units is produced (5:8).

There are several other sources of literature and studies about the learning curve theory. The RAND Corporation has published several reports on the learning curve theory in the aircraft industry. The report by Asher recommended earlier in this chapter was published in 1956 by the RAND Corporation and is recognized to be a comprehensive treatise on the learning curve theory. In addition, most aircraft manufacturing companies have learning curve manuals that have been developed as a result of the company's historical production data (2:49).

There have been several studies that dispute the log-linear theory of the learning curve. The Stanford

Research Institute concluded that early units of production do not follow a log-linear pattern. Instead, the early units tend to form an upward curve. This is known as the Stanford-B curve but it has not been accepted for widespread use (5:9). Carr, in an article published in Aviation magazine, contended that rate of delivery is important in the governing of costs. His theory is based on the assumption that as rate of production increases, new crews are added to the production process. Since these crews are not experienced and have not had the opportunity to learn, the resultant curve is S-shaped (1:27-28; 3:76-77; 5:6-7). Boeing has also studied a "humped" curve that shows nonlinearity during early production (5:24). Although these studies are well documented and have a definite place in learning curve history, they have not disproved the log-linear curve theory as a useful model for making predictions of production costs (1:129; 2:133; 11:125).

Investigation of available literature in the Defense Documentation Center (DDC) and the Defense Logistics Studies Information Exchange (DLSIE) was conducted to examine the studies of learning curve theory that previously had been accomplished. The predominant number of topics were concerned with the use of the learning curve theory for acquisition of airframes. However, several theoretical articles recommended a potential use of learning curve theory in maintenance activities (10:16; 11:131; 17:5,25). None cited a study that addressed using the learning curve theory for depot level aircraft maintenance. This may be due to the difference between manufacturing and maintenance: The former process produces a homogeneous product with repeated tasks, whereas the latter process may involve variety in the tasks required to return the item to a serviceable condition.

Although it was not documented in DDC or DLSIE studies, the learning curve has been used by Smith (15) in one instance of contractual depot level modification. In this instance, a cumulative average learning curve with a slope of 81 percent was detected early in the program. The resultant curve was used to predict the cost of future units of F-105 aircraft modification (Safety Pack II) process (15). Actual manhours for each aircraft were collected through the end of the contract and compared with the predicted hours. Total actual hours were within 5 percent of total predicted hours. This incident reinforces the observation previously stated that maintenance tasks involve many of the criteria required for the learning curve theory: intensive manual labor, an approximation of a homogeneous product, stable production rate, and task specialization. Hence, as state earlier, the purpose of this study is to investigate whether the learning curve theory is indeed appropriate to depot level maintenance operations. The methodology of this investigation is addressed in the following chapter.

CHAPTER III

RESEARCH METHODOLOGY

As stated earlier, the objective of this study is to ascertain if the learning curve theory can be used as a predictive tool for depot level maintenance operations. To achieve this objective, the research methodology will essentially consist of the following actions:

1. The data required for this study will be solicited from the appropriate Air Logistics Center (ALC) organizations.

2. These data will be analyzed with a computerized learning curve analysis program.

3. A determination will be made whether the above analysis of the data yields results that pass an appropriate criterion test. This will resolve research question number one: Is the learning curve an appropriate explainer?

4. Those data sets that affirmatively answer research question number one will be subjected to an additional criterion test to resolve research question number two: Can it be used as a predictive tool?

A detailed explanation of the methodology is addressed in this section.

Assumptions and Limitation

Assumptions. The assumptions of this study are:

1. The data sets for each project analyzed accurately reflect the actual hours expended on each aircraft.

2. The work to be performed on each aircraft is homogeneous.

3. The log-linear learning curve model, rather than the Stanford-S or the Boeing humped curve, is appropriate to the present study.

4. The unit curve, rather than the cumulative average curve, is appropriate to analyze the data. Analysis may be performed using the unit curve in the event the data set has missing values, whereas analysis using the cumulative average curve requires a complete data set.

Limitation. The limitation of this study is: Only a limited number of appropriate data sets will be available for this study. The small sample size, regardless of the outcome of the analysis, will not allow statistically supportable evidence for the appropriateness or nonappropriateness of learning curve theory to organic depot level maintenance operation. The researchers will rely on judgment whether or not to recommend the use of learning curve theory based on the data analysis.

Variables

The two pertinent variables for this study are the production sequence of each aircraft and the corresponding manhours required to produce that aircraft. The independent variable is the number of opportunities to learn, or the number of units produced (13:1). The aircraft production sequence number is required to identify which opportunity to learn the particular aircraft represents. The dependent variable is the unit cost, in actual manhours, per corresponding unit of production. In this analysis, the cost input will be the actual hours expended to produce each aircraft. The method employed to derive the actual hours is described in the following section.

Data Source and Validity

The actual hour data and corresponding production sequence number required for the proposed analysis have been solicited directly from th ALC/Directorate of Maintenance, Workloading Division (MAW). It is only at the ALC level that data are detailed enough for this study. At Headquarters AFLC level, the data have been consolidated and summarized to the extent they no longer contain the relevant detail needed for analysis.

There are three terms used in defining manhour requirements: standard hours, actual hours, and effectiveness. Standard hours are the task times as determined by a labor standard study and are generally considered to be the gross time it would take an average operator working at an average pace to accomplish a task (4:12.2). Actual hours are the number of manhours expended to accomplish a task or project. Effectiveness is a measure of production's accomplishment of a task or group of tasks in relation to the standard hours. These three terms are related and if any two quantities are known the third can be mathematically determined. The formula is:

$$\frac{\text{standard hours}}{\text{actual hours}} = \text{effectiveness}$$

Since effectiveness is a measurement tool, at 100 percent effectiveness, standard hours would equal actual hours. However, 100 percent effectiveness is not an upper limit. If production were capable of producing an item in fewer hours than the standard hours, effectiveness would be greater than 100 percent.

Effectiveness is the present means to account for learning as a project progresses from start to finish. For example, for a new project, the work flow schedule and manpower requirements might be based on an initial effectiveness of 65 percent. The planned or projected effectiveness is gradually increased until it reaches the targeted effectiveness.

Only a limited number of projects will be appropriate for this study due to the method by which the data are collected at the ALCs. In most instances there are several projects in progress in the ALC Resource Control Center (RCC) or Section where the projects are accomplished. The standard hours can be identified to each project. However, the actual hours or the effectiveness for each project cannot be identified because the actual hours data are not collected and the effectiveness is an overall effectiveness for the RCC. Therefore, the only projects that are appropriate for learning curve analysis in this study are those that are the sole project within an RCC or Section. Where this situation exists, the effectiveness of the RCC or Section can be applied to the standard hours to determine actual hours.

There is a significant difference between this study and Smith's study (15) in the method of data collection. Smith collected actual hours daily for each aircraft. In the present study, the standard hours for each aircraft were collected daily, but the means by which they were converted to actual hours is a monthly effectiveness factor. Collection of actual hour data is a preferred method, but lacking the time and resources to collect actual hour data, this study must rely on using standard hours and effectiveness to obtain actual hours.

Population and Sample of Interest

The population of interest for this study is all aircraft maintenance actions or projects that fit the criteria for being appropriate to learning curve theory. However, the sample of data sets selected for analysis is not a random sample of these maintenance actions. The sets constitute, instead, a "sample of convenience," and have been identified by either the AFLC/MA study sponsor or by ALC/MAW maintenance personnel as being appropriate for the intended analysis. These data sets represent discrete project workloads within an RCC, wherein the actual hours can be identified to the project.

Due to the limited number of samples to be analyzed, no generalizations regarding specific learning curve parameters can be made. It is assumed, however, that if a learning curve effect can be demonstrated by this study, then maintenance actions in general may be subject to some degree of learning curve effect. The learning curve approach could then provide maintenance operations personnel with an alternative with which to account for the effects of learning. This may be preferable to the present method of using labor effectiveness projections.

Computer Program

The ICUNIS learning curve analysis program will be employed to fit a weighted least-squares line to the historical data (program documentation is included in Appendix A). This program is part of a family of learning curve analysis programs available at AFLC and the ALCs on the Air Force "Copper Impact" system (9). ICUNIS is designed for the unit curve, wherein the labor hours can be identified to discrete, specific units of production. The following formulas are employed:

Regression slope coefficient B =

$$\frac{\Sigma(xy) - \Sigma(x)\Sigma(y)/N}{\Sigma(x^2) - [\Sigma(x)]^2/N}$$

Computed value of first unit A = antilog

$$\left(\frac{\Sigma(y) - B\Sigma(x)}{N}\right)$$

Improvement curve percentage = $100 \cdot 2^B$

Coefficient of Correlation R =

$$\frac{\Sigma(xy) - \Sigma x\Sigma y/N}{\sqrt{[\Sigma(x^2) - (\Sigma x)^2/N]\ [\Sigma(y^2) - (\Sigma y)^2/N}}$$

Where

x = log of unit number

y = log of unit labor hours

N = total number of units (8:217).

The ICUNIS program outputs the following values:

Computed value of first unit...A =

Regression slope coefficient...B =

Improvement curve percentage =

Coefficient of correlation.....R =

Coefficient of determination...R^2 =

In addition the program provides percentage differences between values on fitted regression line and the actual historical hours.

Criteria Test

The criterion to be examined for the resolution of research question number one will be the "coefficient of determination" (R^2) provided by the ICUNIS computer program. A data set should yield an R^2 value of at least 0.8 to be considered valid for the purposes of this study. The coefficient of determination is a measure of the strength of the relationship betwen the independent variable (number of aircraft produced) and the dependent variable (manhours per aircraft). Mathematically, R^2 is the ratio obtained by dividing the explained variance of the observed Y values from the fitted regression line (the "predicted values") by the total variance of the Y values from the fitted regression line. The R^2 value, therefore, is the ratio of the explained variance of Y divided by the total variance of Y (2:96). R^2 has a range from 0 to +1. If all the data points (observed values) are close to the regression line (predicted values), R^2 will approach unity. However, as the scatter of data points becomes greater, R^2 will approach zero. The selected value of 0.8

is arbitrarily considered by the authors to be the minimum acceptable value for a strong relationship.

Those data sets with an acceptable R^2 will be subjected to further analysis to resolve research question number two, which concerns the use of the model as a predictive tool for maintenance budgeting and workload planning. This resolution will therefore focus on the predictive ability of the model. Since only historical data are available, the model will be tested to determine if it can predict individual data points. This role of the model as a self predictor has been used in other studies (6:41; 16:56). Predictions will be simulated by omitting a sequential number of the last values from a data set. The analysis program will be run with this incomplete data set. If the model is a valid predictor it will be able to predict the deleted data values within an arbitrarily chosen ± 5 percent.

As regards the data meeting the above criteria, the limitations on the degree to which we can validly generalize this study to maintenance operations should be reiterated. For a particular data set with an R^2 equal to or greater than 0.8, an affirmative answer for that data set is derived for research question number one: Is the learning curve theory an explainer of organic depot level maintenance manpower requirements? Similarly, should the same data set also pass the predictive validity criterion, then one can conclude that the data set shows one example of where the learning curve is both an explainer and a predictor of maintenance manpower requirements. Should all of the data sets pass both criteria, the researchers would recommend that maintenance planners consider the learning curve theory as an alternative to the present methods in use. However, caution is necessary as to the validity of generalizing the findings to all maintenance operations. Due to the small sample size used in the study, an affirmative answer to both criteria for all data sets will not statistically support any such generalization. For the same reason, small sample size, failure of one of more of the data sets to pass the arbitrarily selected criteria will not invalidate or discredit the premise that learning curve theory can be generalized to the entire population. However, the position as regards this latter instance (one or more failures), is that the researchers would not be in a position to recommend the use of the learning curve theory for maintenance activities.

CHAPTER IV

ANALYSIS AND FINDINGS

This chapter is arranged in seven sections. The first section discusses the data and the method by which the data are portrayed. The subsequent five sections address the individual data sets examined. Each includes a discussion of the raw data, variables, analysis of the data, results of the criteria tests, resolution of the research questions, and comments on the findings. A summary of the findings is the last section and closes the chapter.

Data

In the discussion of data analysis, none of the data sets identify the maintenance project name or the type of aircraft. This masking was done to facilitate cooperation of contributing ALCs.

It was anticipated that there would be limited data appropriate for this analysis. Only five of the data sets contributed meet the criterion of being the only workload within an RCC. This condition, as explained earlier, is necessary to identify the actual hours expended to an individual aircraft. It is reiterated here that this limited sample does not allow for any statistically supportable conclusions.

One additional data set was received but not analyzed. This data was from a modification project. However, neither the actual hours nor the effectiveness for this project can be identified. In addition, the Programmed Depot Maintenance (PDM) portion of the work package was not separated from the modification effort. This data set represented the sole contribution from one ALC. It is mentioned here because it highlights one of the problems the researchers faced, mainly the scarcity of appropriate data.

The number of aircraft involved in the maintenance actions ranges from 19 on one project to 269 on another project. The project with 19 aircraft is the only complete data set. The others are incomplete due to such factors as RCC changes, work package changes, and the inability of the ALCs to separate modification work from PDM work for some aircraft. Where the ALCs are uncertain of the actual hours for an aircraft, the values for these aircraft are omitted. An incomplete data set does not invalidate the analysis. The ICUNIS program does not require a complete data set if the remaining values are identified to their appropriate sequence number in the production run.

The results from each data set are portrayed in three exhibits. First, the ICUNIS analysis output for each data set is shown, reflecting the calculated learning curve percentage (as an "improvement curve percentage"), and the R^2 value derived. A second exhibit is the "percentage difference" for each data value. This shows the percentage difference between the calculated value on the regression line compared to the actual value of the input data. This percentge is calculated as follows:

$$\frac{\text{actual hours - projected hours}}{\text{actual hours}} = \text{percentage difference.}$$

The final exhibit for each data set is a computerized graphics display showing the actual data values and the fitted regression line. The values of both axes have been converted to logarithmic scales.

Data Set One

This project is for eighty-six aircraft for which an avionics modification program was performed concurrently with Programmed Depot Maintenance (PDM). The man-hour information for the first twenty aircraft is not available since the PDM portion of the work package initially could not be identified. For the subsequent sixty-six aircraft, a special skills code was assigned. This allowed the identification of the modification portion of the work. All of the data values for modifying the final sixty-six aircraft have been included in the data.

The INCUNIS computer analysis (Table 1) computed a learning curve of 93.2 percent. However, it reflects an R^2 value of 0.17. Since this value does not meet the criterion (≥ 0.8) to resolve research question one, no further analysis on this data is performed to resolve research question number two. The percentage difference, shown in Table 2, ranges from -22.4 percent to +34.2 percent. The graphic presentation of the data is shown in Figure 1.

TABLE 1

ICUNIS ANALYSIS--DATA SET ONE

Computed Value of First Unit	A =	1,942.25
Regression Slope Coefficient	B =	-0.10067
Improvement Curve Percentage	=	93.26
Coefficient of Correlation	R =	-0.409917
Coefficient of Determination	R^2 =	0.168032

The low R^2 value indicates a wide scatter of actual values from the predicted line. One factor that may have contributed to this scatter is that, according to the information received from the ALC, many of the aircraft arrived with unserviceable avionics equipment. This equipment required repair since it interfaces with the modified avionics equipment. Not all of the aircraft with unserviceable equipment had the same equipment

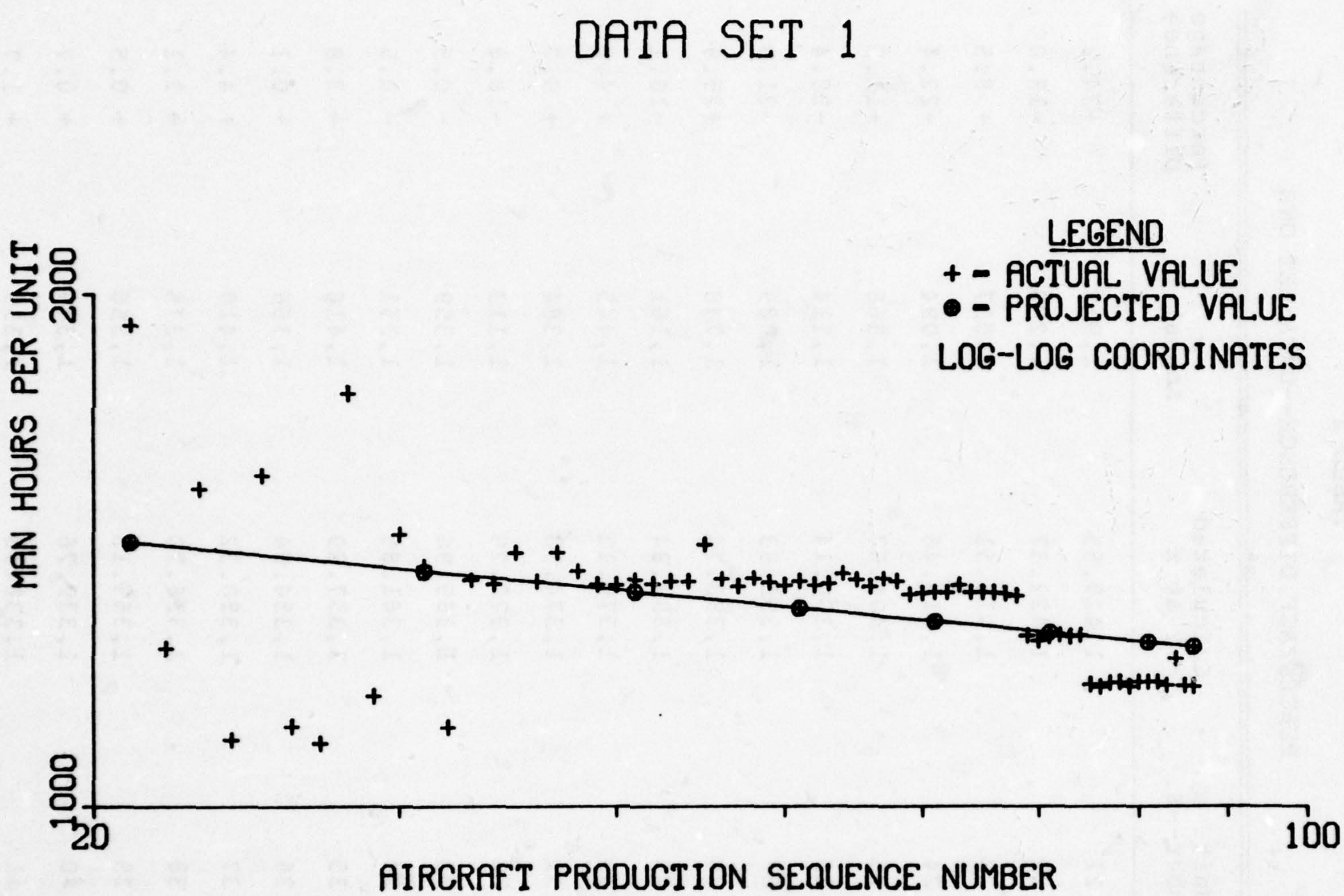

DATA SET 1
LEGEND
+ - ACTUAL VALUE
● - PROJECTED VALUE
LOG-LOG COORDINATES
MAN HOURS PER UNIT
2000
1000
20
100
AIRCRAFT PRODUCTION SEQUENCE NUMBER

Figure 1

TABLE 2

PERCENTAGE DIFFERENCE--DATA SET ONE

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
21	1,429.55	1,918	+34.2
22	1,422.87	1,283	-13.0
23	1,416.51	1,537	+ 8.5
24	1,410.46	1,094	-22.4
25	1,404.67	1,566	+11.5
26	1,399.14	1,114	-20.4
27	1,393.83	1,089	-21.9
28	1,388.74	1,748	+25.9
29	1,383.84	1,161	-16.1
30	1,379.13	1,445	+ 4.8
31	1,374.58	1,384	+ 0.7
32	1,370.20	1,113	-18.8
33	1,365.96	1,359	- 0.5
34	1,361.86	1,351	- 0.8
35	1,357.89	1,410	+ 3.8
36	1,354.04	1,356	+ 0.1
37	1,350.32	1,410	+ 4.4
38	1,356.70	1,375	+ 2.1
39	1,353.18	1,350	+ 0.5
40	1,339.76	1,349	+ 0.7
41	1,336.43	1,359	+ 1.7

TABLE 2--Continued

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
42	1,333.19	1,351	+ 1.3
43	1,330.04	1,356	+ 2.0
44	1,326.97	1,356	+ 2.2
45	1,323.97	1,425	+ 7.6
46	1,321.04	1,360	+ 2.9
47	1,318.18	1,356	+ 2.1
48	1,315.39	1,361	+ 3.5
49	1,312.67	1,354	+ 3.1
50	1,310.00	1,348	+ 2.9
51	1,307.39	1,356	+ 3.7
52	1,304.84	1,348	+ 3.3
53	1,302.34	1,352	+ 3.8
54	1,299.89	1,370	+ 5.4
55	1,297.49	1,359	+ 4.7
56	1,295.14	1,346	+ 3.9
57	1,292.83	1,361	+ 5.3
58	1,290.57	1,356	+ 5.1
59	1,288.35	1,332	+ 3.4
60	1,286.17	1,334	+ 3.7
61	1,284.04	1,336	+ 4.0
62	1,281.93	1,335	+ 4.1
63	1,279.87	1,349	+ 5.4
64	1,277.84	1,335	+ 4.5

TABLE 2--Continued

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
65	1,275.84	1,335	+ 4.6
66	1,273.89	1,334	+ 4.7
67	1,271.96	1,333	+ 4.8
68	1,270.07	1,329	+ 4.6
69	1,268.20	1,259	- 0.7
70	1,266.37	1,250	- 1.3
71	1,264.56	1,258	- 0.5
72	1,262.8	1,260	- 0.2
73	1,261.03	1,258	- 0.2
74	1,259.30	1,260	+ 0.1
75	1,257.60	1,179	- 6.3
76	1,255.93	1,175	- 6.4
77	1,254.28	1,181	- 5.8
78	1,252.65	1,182	- 5.6
79	1,251.04	1,176	- 6.0
80	1,249.46	1,183	- 5.3
81	1,247.90	1,183	- 5.1
82	1,246.36	1,183	- 5.1
83	1,244.84	1,178	- 5.4
84	1,243.34	1,221	- 1.8
85	1,241.86	1,177	- 5.2
86	1,240.40	1,176	- 5.2

unserviceable. This could be a source of variability in the hours on each aircraft if the repair were charged to the modification and not to other depot tasks.

Data Set Two

These data were derived from a modification project for 269 aircraft. However, the data for all of the first 112 aircraft and several of the subsequent remaining aircraft are not available due to RCC and work package changes. The changes prevent the isolation of the modification hours from other depot tasks for the omitted aircraft.

As reported in Table 3, the computed learning curve is 97 percent. The percentage difference between predicted and actual values range from -3.2 percent to +8.4 percent. The resulting R^2 value was only 0.21, which precludes further analysis regarding research question number two. The data and the plot of the results are presented in Table 4 and Figure 2.

Data Set Three

Data set three is an Analytical Condition Inspection (ACI) project. ACI is performed on a sample of aircraft from the fleet in an attempt to ascertain the condition of the fleet in general. In this project, the aircraft is partially disassembled, measured and visually

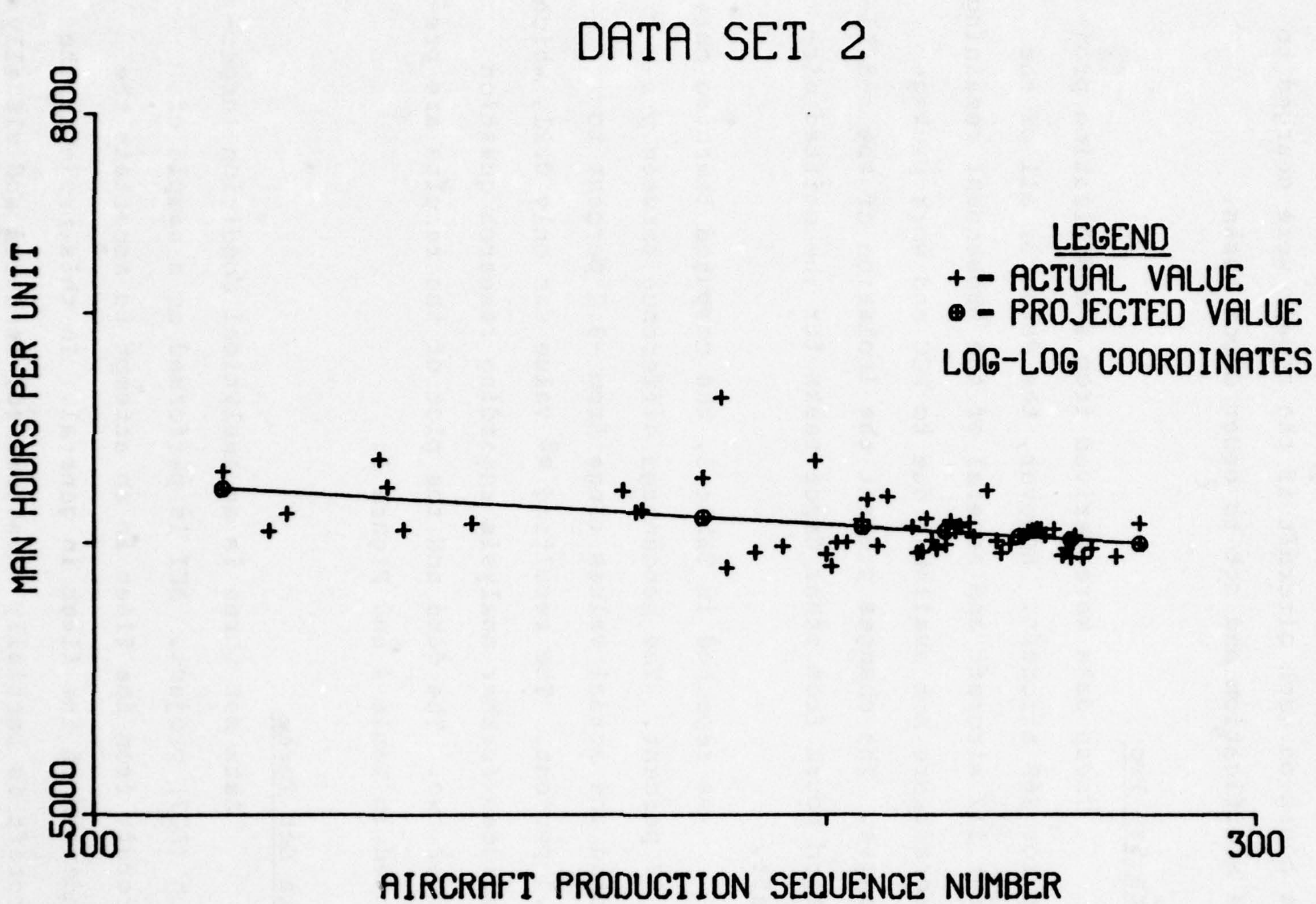

DATA SET 2
8000
5000
MAN HOURS PER UNIT
100
300
AIRCRAFT PRODUCTION SEQUENCE NUMBER
LEGEND
+ - ACTUAL VALUE
⊕ - PROJECTED VALUE
LOG-LOG COORDINATES

Figure 2

inspected to determine the condition of the aircraft. The aircraft is also subjected to a series of nondestructive tests.

TABLE 3

ICUNIS ANALYSIS--DATA SET TWO

Computed Value of First Unit	A =	7,624.88
Regression Slope Coefficient	B =	-0.042982
Improvement Curve Percentage	=	97.0647
Coefficient of Correlation	R =	-0.456176
Coefficient of Determination	R^2 =	0.208297

The data received from the ALC begins with the first aircraft of the project and is continuous through the nineteenth aircraft. This was the total number of aircraft that had been completed at the time of data collection for this study. The project is comprised of two series of aircraft. The data from the two series are referred to as series A and series B.

The contributing ALC pointed out that there is a difference in the work accomplished on each series aircraft. This difference was investigated and it was determined that it amounted to an additional 249 standard hours for each series A aircraft. The 249 standard hours were removed from the total standard hours for each

TABLE 4

PERCENTAGE DIFFERENCE--DATA SET TWO

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
113	6,222.83	6,297	+ 1.2
118	6,211.26	6,046	- 2.6
120	6,206.77	6,119	- 1.4
131	6,183.42	6,343	+ 2.6
132	6,181.40	6,229	+ 0.8
134	6,177.40	6,052	- 2.0
143	6,160.17	6,078	- 1.3
165	6,122.39	6,213	+ 1.5
167	6,119.22	6,125	+ 0.1
168	6,117.65	6,133	+ 0.3
178	6,102.47	6,266	+ 2.7
181	6,098.09	6,613	+ 8.4
182	6,096.64	5,899	- 3.2
187	6,089.54	5,960	- 2.1
192	6,082.64	5,985	- 1.6
198	6,074.60	6,339	+ 4.4
200	6,071.98	5,953	- 2.0
201	6,070.68	5,905	- 2.7
202	6,069.38	5,998	- 1.2
204	6,066.81	6,002	- 1.1
207	6,063.01	6,090	+ 0.4

TABLE 4--Continued

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
208	6,061.74	6,179	+ 1.9
210	6,059.26	5,987	- 1.2
212	6,056.79	6,191	+ 2.2
217	6,050.72	6,065	+ 0.2
218	6,049.53	5,961	- 1.5
219	6,048.34	5,966	- 1.4
220	6,047.15	6,099	+ 0.9
221	6,045.98	6,009	- 0.6
222	6,044.80	5,976	- 1.1
224	6,042.47	5,992	- 0.8
225	6,041.32	6,088	+ 0.8
226	6,040.16	6,047	+ 0.1
227	6,039.02	6,066	+ 0.4
229	6,036.74	6,079	+ 0.7
230	6,035.61	6,023	- 0.2
233	6,032.25	6,214	+ 3.0
235	6,030.04	6,007	- 0.4
236	6,028.93	5,958	- 1.2
238	6,026.75	5,993	- 0.6
240	6,024.58	6,029	+ 0.1
241	6,023.50	6,025	0.0
242	6,022.43	6,042	+ 0.3

TABLE 4--Continued

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
243	6,021.36	6,050	+ 0.5
244	6,020.30	6,053	+ 0.5
245	6,019.24	6,054	+ 0.6
246	6,018.19	6,029	+ 0.2
248	6,016.10	6,052	+ 0.6
252	6,011.96	5,939	- 1.2
253	6,008.90	5,937	- 1.2
257	6,006.89	5,972	- 0.6
263	6,000.93	5,943	- 1.0
269	5,995.11	6,077	+ 1.4

series A aircraft. The resulting standard hour figure was divided by the effectiveness to determine the actual hours for that aircraft. The purpose of this action was to try to get the actual hours on the series A aircraft for the comparable workload accomplished on the series B aircraft.

The data set was input to the ICUNIS analysis and the resulting output is portrayed in Table 5. While a learning curve of 92.1 percent is portrayed, the reader must consider the R^2 factor of 0.16. This is far below the criterion established for an affirmative answer to research question one. Therefore, further analysis for resolving research question two is not warranted for this data set. Table 6 is the percentage differences observed during ICUNIS analysis. Of special interest is the vast range of differences in the data set. The difference ranges from -29.9 percent to +44.4 percent. These data are pictorially exhibited in Figure 3. The positive differences are above the projection line and the negative differences are below the projection line. The large variances in the data differences may be observed easily in the graph.

Data Set Four

As explained in the narrative for data set three, data set four is the series A aircraft extracted from the production sequence of nineteen aircraft. This consists of production sequence numbers 1, 2, 7, 8,10, 12, 14, 16,

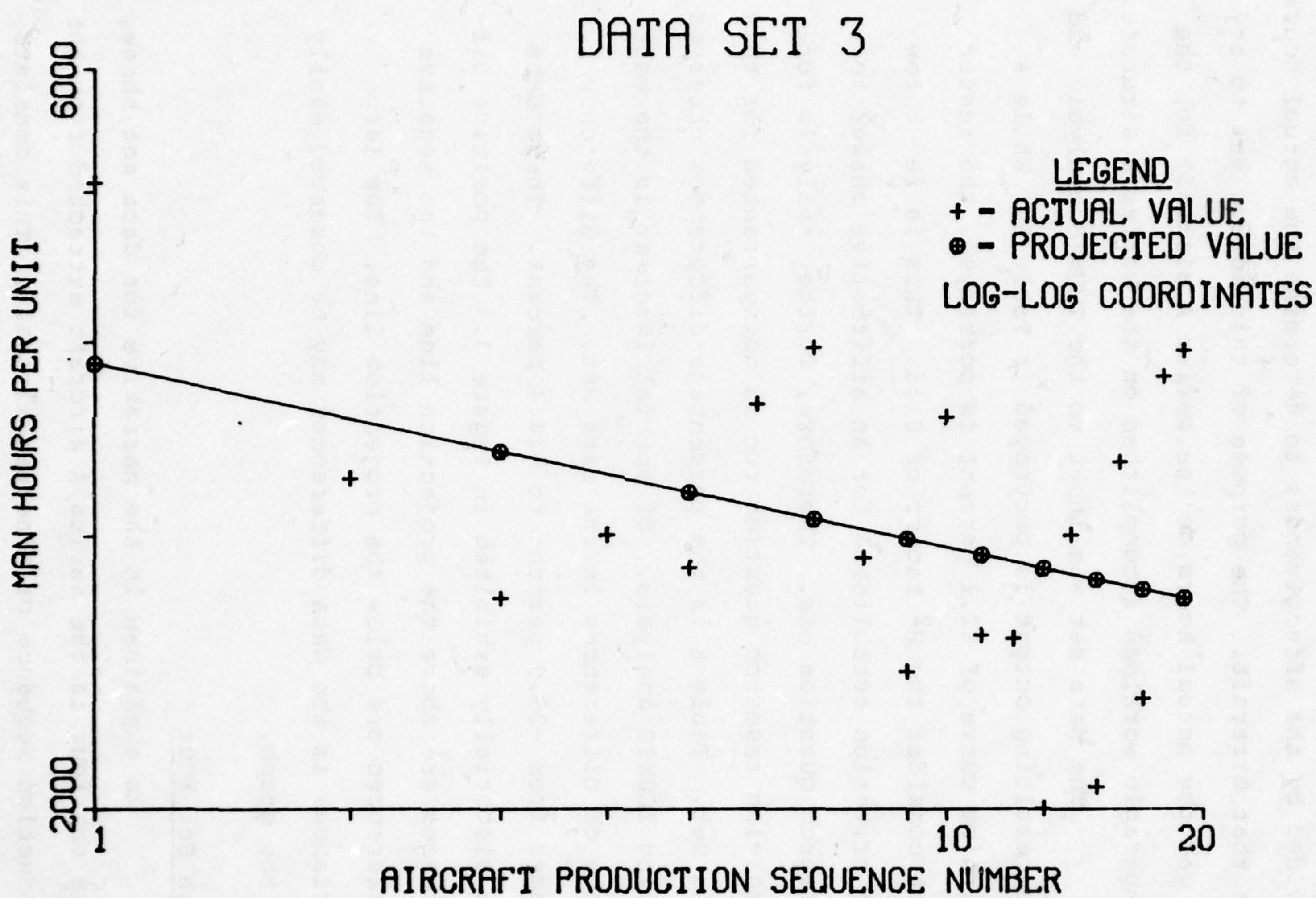

DATA SET 3
LEGEND
+ - ACTUAL VALUE
⊕ - PROJECTED VALUE
LOG-LOG COORDINATES
MAN HOURS PER UNIT
6000
2000
1
10
20
AIRCRAFT PRODUCTION SEQUENCE NUMBER

Figure 3

TABLE 5

ICUNIS ANALYSIS--DATA SET THREE

Computed Value of First Unit	A =	3,874.00
Regression Slope Coefficient	B =	-0.118652
Improvement Curve Percentage	=	92.1048
Coefficient of Correlation	R =	-0.40057
Coefficient of Determination	R^2 =	0.160456

18, and 19. Table 7 is the ICUNIS analysis. The R^2, or coefficient of determination, for this data set is 0.20. This is still below the criterion test limit for research question one. The range of the percentage difference is -23.5 percent to +22.0 percent as portrayed in Table 8. Figure 4 portrays the data on logarithmic grids.

Data Set Five

Data set five consists of the series B aircraft in data set three. The production sequence is aircraft 3, 4, 5, 6, 9, 11, 13, 15, and 17. The coefficient of determination shows a much stronger relationship in the variables but the R^2 of 0.49 is still a negative answer to research question one (Table 9). Of particular interest is the percentage differences listed in Table 10. Although the R^2 is much higher for this data set in comparison to data set four, the range of differences was approximately the

TABLE 6

PERCENTAGE DIFFERENCE--DATA SET THREE

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
1	3,874.00	5,069	+30.8
2	3,568.14	3,269	- 8.4
3	3,400.54	2,736	-19.5
4	3,286.43	3,004	- 8.6
5	3,200.56	2,863	-10.5
6	3,132.06	3,649	+16.5
7	3,075.30	3,968	-29.0
8	3,026.96	2,904	- 4.1
9	2,984.95	2,451	-17.9
10	2,957.87	3,579	+21.4
11	2,914.72	2,587	-11.2
12	2,883.78	2,574	-10.8
13	2,857.51	2,002	-29.9
14	2,832.50	3,004	+ 6.1
15	2,809.40	2,067	-26.4
16	2,787.97	3,346	+20.0
17	2,767.99	2,355	-14.9
18	2,749.28	3,799	+38.2
19	2,731.70	3,944	+44.4

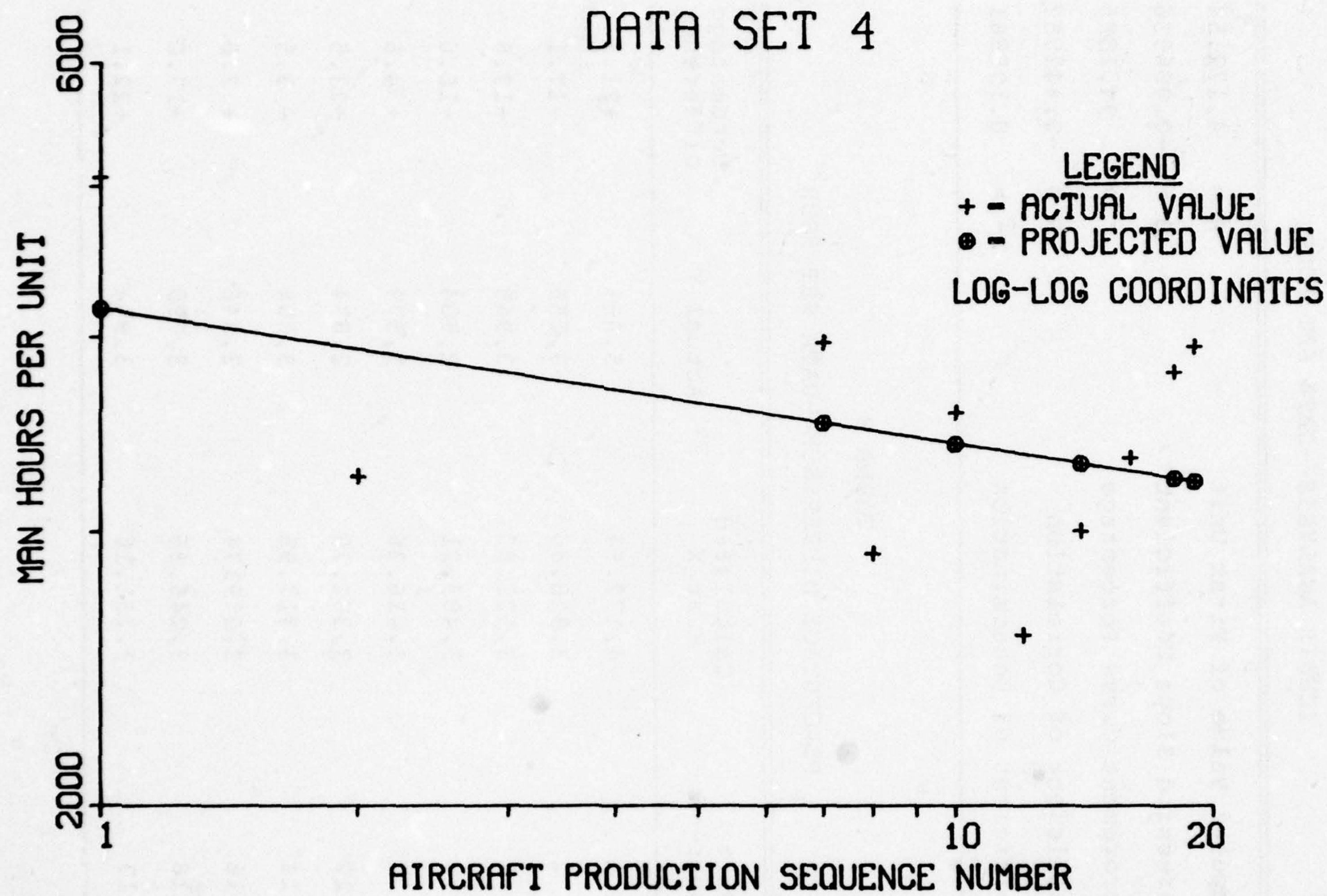

DATA SET 4
LEGEND
+ - ACTUAL VALUE
⊕ - PROJECTED VALUE
LOG-LOG COORDINATES
MAN HOURS PER UNIT
6000
2000
1
10
20
AIRCRAFT PRODUCTION SEQUENCE NUMBER

Figure 4

TABLE 7

ICUNIS ANALYSIS--DATA SET FOUR

Computed Value of First Unit	A =	4,172.54
Regression Slope Coefficient	B =	-0.086836
Improvement Curve Percentage	=	94.1585
Coefficient of Correlation	R =	-0.442562
Coefficient of Determination	R^2 =	0.195861

TABLE 8

PERCENTAGE DIFFERENCE--DATA SET FOUR

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
1	4,172.54	5,069	+21.5
2	3,928.80	3,256	-17.1
7	3,523.83	3,968	+12.6
8	3,483.21	2,904	-16.6
10	3,416.36	3,579	+ 4.8
12	3,362.70	2,574	-23.5
14	3,317.99	3,004	- 9.5
16	3,279174	3,346	+ 2.0
18	3,246.36	3,799	+17.0
19	3,231.16	3,944	+22.1

TABLE 9

ICUNIS ANALYSIS--DATA SET FIVE

Computed Value of First Unit	A =	4,015.48
Regression Slope Coefficient	B =	-0.211695
Improvement Curve Percentage	=	86.3522
Coefficient of Correlation	R =	-0.69741
Coefficient of Determination	R^2 =	0.486394

TABLE 10

PERCENTAGE DIFFERENCE--DATA SET FIVE

Unit Number--X	Calculated Y at X	Actual Y	Percentage Difference
3	3,182.24	2,736	-14.0
4	2,994.22	3,004	+ 0.3
5	2,856.07	2,863	+ 0.2
6	2,747.94	3,649	+32.8
9	2,521.91	2,451	- 2.8
11	2,417.02	2,587	+ 7.0
13	2,333.03	2,002	-14.2
15	2,263.42	2,067	- 8.7
17	2,204.23	2,355	+ 6.8

same (-14 percent to +33 percent). Figure 5 portrays the results.

Summary

Five data sets were available for this analysis. Two of the five were extracted from one of the data sets. Some data sets had missing values. These omissions are examined in the discussion section of this chapter. The computerized ICUNIS analysis program was employed to calculate the learning curve percentage and coefficient of determination (R^2) of each data set. The range of learning curves was from 86.5 percent to 97.1 percent. The R^2 values ranged from 0.16 to 0.49. Therefore, none of the data sets passed the criterion test ($R^2 \geq 0.8$) required for an affirmative answer to research question number one: Is the learning curve theory an explainer of maintenance budgeting and workload planning operations. Because of the negative answer to research question one, no further analysis was performed regarding the predictive ability of the model to resolve research question two: Can the learning curve model be used as a predictive tool for maintenance budgeting and workload planning.

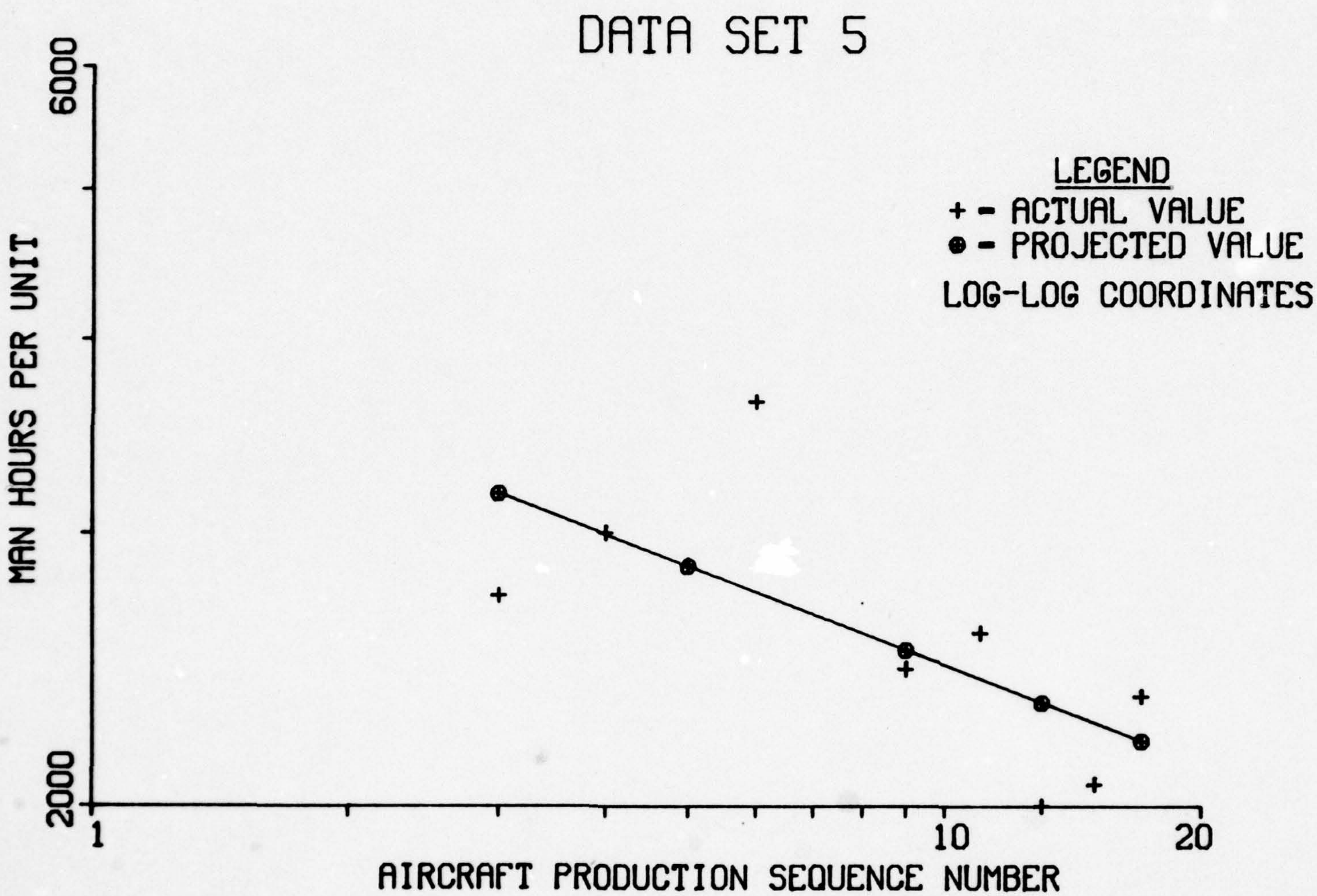

DATA SET 5
LEGEND
+ - ACTUAL VALUE
⊗ - PROJECTED VALUE
LOG-LOG COORDINATES
MAN HOURS PER UNIT
6000
2000
1
10
20
AIRCRAFT PRODUCTION SEQUENCE NUMBER

Figure 5

CHAPTER V

SUMMARY AND CONCLUSIONS

This chapter provides a summary of the research problem addressed, the related literature, the model examined, and the procedures employed to resolve the problem. The research results are presented and the conclusions of this study close the chapter.

Summary

Depot level maintenance operations contain many of the elements of the learning curve theory, such as labor intensiveness, stable production rate, task specialization, and an approximation of a homogeneous product. This may lead one to believe that learning may take place in maintenance operations, and that the learning curve theory may be appropriate for accounting for the effects of such learning. If learning does exist, and its effect on the maintenance man-hours required could accurately be accounted for, maintenance personnel could improve their budgeting and workload planning techniques. However, no accurate, systematic means of assessing or predicting the rate of learning in maintenance actions is currently used. The objective of this study is to determine if the learning curve theory is appropriate for maintenance and if the authors can recommend its use for maintenance budgeting and workload planning.

The literature on the subject, for the most part, addresses the use of the learning curve for airframe production. Few studies, however, address its use for maintenance operations. Although not documented in a published study, there is at least one actual instance where the learning curve was observed and used in contractual depot level maintenance (15).

This study investigates the use of the unit curve model of the learning curve theory as an explainer and predictor of organic maintenance actions. The model employed is $Y=AX^B$ where:

Y is the unit man-hours required to produce unit X,

A is the direct man-hours of the first unit produced,

X is any numbered unit, and

B is an exponent that defines the shape of the learning curve.

The independent variable (X) is the sequence number in which an aircraft is produced. The dependent variable (Y) is the man-hours required per aircraft.

One indicator of the learning curve model as an effective explainer of variation is the coefficient of determination (R^2). The R^2 value measures the strength of the relationship between the independent variable and the dependent variable. The authors subjectively considered an R^2 of 0.8 to be the minimum acceptable level for this relationship, since the learning curve model would then explain at least 80 percent of the total variation between the predicted values and the actual values observed. The predictive ability of the model is examined through a procedure that truncates the data, then uses the truncated data in the model to predict the omitted values. The ability of the model to predict the omitted data values with ± 5 percent is subjectively considered adequate by the authors.

Due to the method by which maintenance data are collected, the ALCs could contribute only five data sets from organic aircraft depot level maintenance or modification projects that are appropriate for this study. Some of these data sets, however, are incomplete due to such factors as RCC changes, work package change, and instances where the PDM portion of the work could not be distinguished from the modification portion. The authors recognize that no statistically significant generalizations can be made, regardless of the outcome of the analysis, due to this small sample size.

The five data sets are examined by the ICUNIS learning curve analysis program. The learning curve percentages, calculated on a unit curve, range from 86.4 percent to 97.1 percent. However, the R^2 value range is from 0.16 to 0.49. Since all of these values are below the selected R^2 value of 0.8, none of the data sets pass the criterion test to determine if the learning curve is an explainer of maintenance actions. Therefore, no further analysis is performed to determine if the learning curve model is a good predictor of maintenance man-hour requirements.

Conclusions

In this study, none of the five data sets analyzed provide an affirmative answer to the question of whether the learning curve is an appropriate explainer of depot level maintenance man-hour requirements. Therefore, the researchers, on the basis of this study, cannot recommend the use of learning curve theory for Air Force depot level maintenance budgeting and workload planning. However, the small sample size precludes using the results of this study to statistically support or reject the application of learning curve theory to maintenance actions in general, and hence the authors' decision is based on judgement.

There may be at least two reasons why no acceptable learning curve was found if, in fact, learning did occur in the projects for which the data were examined. First, the researchers feel that the maintenance data collection system does not lend itself to studies where actual hour data are required. Thus the assumption that the data are accurate may be incorrect. Second, the assumption of an approximation of homogeneity of work may have been violated in the data sets examined.

As regards the maintenance data collection system, the limitation of only five data sets, from the total aircraft maintenance projects AFLC wide, seems to support the view that the data available are not detailed enough for studies of this nature. Moreover, in at least one of the data sets examined, values were omitted from the analysis because the man-hours expended on the modification portion of the work package could not be discretely identified from the man-hours spent on other depot maintenance tasks. In addition, values were omitted from other data sets due to RCC reorganization, which could affect the collection of historical data. Furthermore, using the efficiency indicator to indirectly determine manhours may have introduced some error. In retrospect, it appears that the data may have been inaccurate.

A second reason that no learning was found may be that the assumption of homogeneity of tasks among the aircraft produced was violated. In the learning curve theory, one of the assumptions is that a homogeneous product is produced. For this study, we have assumed that at least an approximation of a homogeneous product is produced by maintenance. The low R^2 values suggest that if learning did occur, the assumption of an approximation of homogeneity was violated. One factor that may have contributed to this possible violation, for example, is minor work package changes. These changes tend to make the maintenance tasks more heterogeneous among the aircraft produced. The maintenance data analyzed, however, are not detailed enough to identify where these changes, if any, took place in the production sequence. In addition, an examination of the graphs (Figures 1, 2, 3, 4, and 5) reflect great variation in man-hours throughout the duration of some of the maintenance projects. This would seem to reinforce the observation that the assumption of homogeneity may have been violated.

Due to the potential benefits that could accrue to improved maintenance budgeting and workload planning, further study in this area may be warranted. However, the authors recommend that a more detailed and timely method of collecting actual hour data for studies of this type be employed, since the method employed in this research appears to be inadequate for this purpose. A data collection method such as that employed by Smith (15) may be needed wherein the actual hours are collected independently of the established data collection system. The cost of such data collection would have to be weighed against the potential benefits to be gained.

APPENDIXES

APPENDIX A

EXCERPT FROM <u>DEFENSE CONTRACT AUDIT MANUAL</u>

K-402 ICUNI Fitting Least Squares Line Under Unit Curve Theory to Unit Hours or Cost

K-402.1 Purpose.

(a) This program fits a weighted least-squares line under the unit curve theory to unit labor hours or costs. If the historical data include lot hours or costs, the ICLOT program, described in K-401.1 must be used. The machine output from both programs includes percentage differences between values on the line and historical hours or costs.

(b) It is always advisable to plot the line and the historical data on log-log graph paper. This is particularly important when there are one or more large percentage differences. A graphic presentation may disclose changes in the trend which are not apparent from the computer printout.

K-402.2 Data Input. The format of the input is illustrated in Figure K-6. Lines 1 to 699 are available for use as data statements. Enter first the number of continuous sequences of units to be included in the analysis. Then enter for each sequence the number of the first *and* last units followed by the hours of cost for each unit.

K-402.3 Example.

(a) In this hypothetical example, the contractor has been awarded contracts for the production of 35 units, but only the first 20 have been completed. The auditor has been requested to evaluate the contractor's price proposal for an additional quantity of 15 units.

(b) The following data on completed units are available from the contractor's records:

Unit	Hours	Unit	Hours
1	420,841	11	268,362
2	352,709	12	257,209
3	316,853	13	162,008
4	291,091	14	150,931
5	280,832	15	154,602
6	241,136	16	152,333
7	222,520	17	148,256
8	213,655	18	143,901
9	215,322	19	138,250
10	194,683	20	136,908

(c) The auditor plots this information on log-log paper and sees that a marked change in the pattern of improvement occurred after production of the 5th unit and the hours for units 11 and 12 are far out of line. Further review discloses that methods used to produce the first 5 units and special features built into the 11th and 12th make these units unsuitable for projection.

K-402.4 Technical Information.

(a) The following formulas are used to fit a least-squares line to historical data:

Regression slope coefficient b =

$$\frac{\Sigma(xy) - \Sigma(x)\Sigma(y)/N}{\Sigma(x^2) - [\Sigma(x)]^2/N}$$

Computed value of first unit a = antilog

$$\left(\frac{\Sigma(y) - b\Sigma(x)}{N}\right)$$

Improvement curve percentage = $100 \cdot 2^b$

Coefficient of Correlation r =

$$\frac{\Sigma(xy) - \Sigma x \Sigma y/N}{\sqrt{[\Sigma(x^2) - (\Sigma x)^2/N][\Sigma(y^2) - (\Sigma y)^2/N]}}$$

where x = Log of unit number

y = Log of unit labor hours or cost

N = Total number of units.

SELECTED BIBLIOGRAPHY

A. REFERENCES CITED

1. Asher, Harold. "Cost Quantity Relationships in the Airframe Industry." Unpublished research report No. R-291. The RAND Corporation, Santa Monica, CA, July 1956.

2. Brewer, Glenn M. "The Learning Curve in the Airframe Industry." Unpublished master's thesis, SLSR 18-65, AFIT/SL, Wright-Patterson AFB OH, August 1965. AD480042.

3. Carr, Gordon W. "Peacetime Cost Estimating Requires New Learning Curves." Aviation, Vol. 45, No. 4, April 1946, pp. 76-77.

4. Carson, Gordon B., ed. Production Handbook. New York: The Ronald Press Company, 1958.

5. Colasuonno, Major Vincent, USAF. "An Analysis of Progress Curve Conceptual Advances and Progress Curve Uses, Since 1956." Unpublished master's thesis, GSM/SM/67-S, AFIT/SE, Wright-Patterson AFB OH 1967. AD664952.

6. Congleton, Captain Duane E., USAF, and Major David W. Kinton, USAF. "An Empirical Study of the Impact of a Production Rate Change on the Direct Labor Requirements for an Airframe Manufacturing Program." Unpublished master's thesis, LSSR 23-77B, AFIT/LSG, Wright-Patterson AFB OH. ADA052720.

7. Dahlhaus, Frank J. "Learning Curve Methodology for Cost Analysts." Unpublished report, unnumbered, U.S. Army Material Command, Alexandria VA, October 1967. AD661052. LD 17479.

8. Department of Defense. Defense Contract Audit Manual. Washington: Government Printing Office, May 1970.

9. General Electric Information Services. "Analysis Using Learning Curves." Unpublished technical manual, unnumbered, General Electric Company, USA, April 1972.

10. Hill, J. Allen. "The Effect of Turnover Rate on Group Task Time When Task Time Is Governed by the Learning Curve." Unpublished research report, unnumbered, Texas A&M University, College Station TX, March 1970. AD739003.

11. Hirschmann, Winfred B. "Profit from the Learning Curve," Harvard Business Review, Vol. 42, No. 1, January/February 1964, pp. 125-139.

12. Ilderton, Robert Blair. "Methods of Fitting Learning Curves to Lot Data Based on Assumptions and Techniques of Regression Analysis." Unpublished master's thesis, School of Arts and Sciences, George Washington University, Washington, 1970. ADA011583.

13. Kroeker, Herbert R., and Robert Peterson. "A Handbook of Learning Curve Techniques." Unpublished research report unnumbered, Ohio State University, Columbus OH, 1961.

14. Mildon, Keith B. Chief, Financial Management and Analysis Division, HQ AFLC, Wright-Patterson AFB OH, personal interview. 7 December 1978.

15. Smith, Lieutenant Colonel Larry L., USAF. Chief, Department of Functional Management, AFIT/LSGM, Wright-Patterson AFB OH, personal interviews conducted intermittently from September 1978 to May 1979.

16. Smith, Lieutenant Colonel Larry L., USAF. "An Investigation of Changes in Direct Labor Requirements Resulting from Changes in Airframe Production Rate." Unpublished doctoral dissertation, unnumbered, University of Oregon, Eugene OR, June 1976. ADA926112.

17. Smith, William Mitchell, "Learning Curve Theory Application to Maintainability Demonstration." Unpublished report, unnumbered, Texas A&M University, College Station TX, May 1968. AD738954.

B. RELATED SOURCES

Arditti, Fred D. "On the Separation of Production from the Developer." Unpublished research report, unnumbered, RAND Corporation, Santa Monica CA, February 1967. AD648136.

Baker, W. W. and J. Silver. "An Expansion of the Improvement Curve to Allow Its Use with a Common/Peculiar Production Mix." Unpublished report, unnumber, 2nd Annual DOD Research Symposium, Washington, October 1967. AD820274. LDL6932, A-T.

Barret, Charles Francis. "An Empirical Analysis of Learning Curves." Unpublished technical report, TR 70-7, AFIT/EN, Wright-Patterson AFB OH, November 1970. AD877042. LD25829.

Batchelder, C. A., and others, "An Introduction to Equipment Cost Estimating." Unpublished research No. RM-6103-SA, RAND Corporation, Santa Monica CA, December 1969. AD702424. LD24682.

Beier, D. C. "Learning Curves for Operators of Stereoscopic Rangefinders." Unpublished report No. 12, University of Wisconsin, Madison WI, November 1944. AD895253.

Boren, H.E. Learning-Curve Tables: Vol. I, 55-69 Percent Slopes. Santa Monica CA: The RAND Corporation, April 1970. AD708713. LD 25209.

Brockman, Major William F., USAF, and Major Freddie D. Dickens, USAF. "Investigation of Learning Curve and Cost Estimation Methods for Cargo Aircraft." Unpublished master's thesis, GSM/SM/67-2/7, AFIT/EN, Wright-Patterson AFB OH, December 1967, AD665464. LD 18215.

Burford, Milton K., and Robert Gritton. "General Principles and Mathematics of Cost Reduction." Unpublished technical report No. NWC TP 5489, Naval Weapons Center, China Lake CA, June 1973. AD911836.

Cheney, William Fitch. "Strategic Implications of the Experience Curve Effect for Avionics Acquisitions by the Department of Defense." Unpublished doctoral thesis, Purdue University, West Lafayette IN, August 1977. ADA046006.

Cochran, E.B. Planning Production Costs: Using the Improvement Curve. San Francisco CA. Chandler Publishing Co., 1968.

Eliel, F. "Compound Progress Curves--An Approximation to Multi-Element Learning Curves." Unpublished technical report No. TPR-469(5530-01)-2, Aerospace Corporation, El Segundo CA, June 19675. AD484353.

Fazio, Captain Peter F., USAF, and Captain Stephen H. Russell, USAF. "An Analytical Approach to Optimizing Airframe Production Costs as a Function of Production Rate." Unpublished master's thesis. SLSR 30-74A. AFIT/SL, Wright-Patterson AFB OH. January 1974. AD775698.

Finnerty, John D. "A Description of the Internal Planning Processes of the Major U.S. Military Airframe Builders." Unpublished research report, unnumbered, Naval Postgraduate School, Monterey CA, February 1977. ADA041148.

Fisher, Major Douglas H., USAF. "Production Cost Management." Unpublished research report No. 0945-76. Air University, Air Command and Staff College, Maxwell AFB AL, 1976. ADB011898L.

Gannon, Patrick J. "Cost Estimating Relationships for Aircraft Armament Subsystem Manufacturing Labor Cost." Unpublished technical report No. AMSWE-CPE 71-11, U.S. Army Weapons Command, Rock Island IL, 1971. AD888681.

Gossett, James L. "Variations Intercepting Experience." Unpublished research report, Unnumbered, U.S. Army Missile Command, Redstone Arsenal AL, January 1971. AD721666. LD 26464.

Hamilton, John L. "Life Cycle Cost Modeling." Unpublished technical report No. 68-8, U.S. Army Material Command, Washington, December 1968. AD684335. LD 684335.

________ and Captain James T. Wormley, "Application of Regression Analysis to Hardware Cost Estimation." Unpublished technical report No. 680-10, U.S. Army Material Command, Washington, 1968. AD681234.

Hartung, W. G. "Cost Estimate Error Resulting from the Use of Learning Curve Methods." Unpublished technical report No. ESD-TR-69-625, Air Force Systems Command, LG Hanscom Field MA, August 1969. AD859698. LD 23719.

James, Paul Meyer. "Analysis of the Turbulent Regime of the Progress Curve When New Learning Additions Have Variable Slopes," Naval Research Logistics Quarterly, Vol. 15, No. 4 (December, 1969), pp. 595-604. AD680542.

Johnson, George V. "On Predicting Production Costs and Probable Learning Rates from R&D Invstments by S-Curve/Learning Curve Relationships." Unpublished report, unnumbered, U.S. Army Mobility Equipment Command, ST. Lous MO, October 1969. AD750098. LD 24641.

Joint Tactical Communications Office. "Cost Effectiveness Program Plan for Joint Tactical Communications." Unpublished report, unnumbered, Fort Monmouth NJ, April 1978. ADA055147.

Kanne, William, Jr. "The Application of an Absorbing Markov Chain in Predicting Learning." Unpublished report, unnumbered, Texas A&M University, College Station TX, May 1969. AD738947.

Karsch, O. Arthur. "A Least Squares Comparison for Learning Curve and Sizing Slope Problems." Unpublished technical report No. 5101-7503, Aeronautical Systems Division, Wright-Patterson AFB OH, February 1971. AD731175.

Katz, Richard. "Understanding and Applying Learning Curves," Automation. Cleveland OH, 1969. LD 23473.

Kelley, Lieutenant Robert W., USA. "Value Engineering and Experience Curve Predictions." Unpublished research, unnumbered, U.S. Army Missile Command, Redstone Arsenal AL, September 1965. AD625984.

Kenyon, R. E. and R. J. Reid. "Aircraft Cost Estimating Relationship Improvements, Construction and Material Effect and New Data." Unpublished research report No. GDCA-ERR-1633, General Dynamics, Convair Aerospace Division, San Diego CA, March 1974. AD17444L.

Large, J. P. "An Introduction to Equipment Cost Estimating." Unpublished research memorandum No. RM-5470-SA, RAND Corporation, Santa Monica CA, January 1968. AD 665825. LD 1817.

________, K. Hoffmayer, and F. Kontrovich. "Production Rate and Production Cost." Unpublished report No. R-1609-PA&E, RAND Corporation, Santa Monica CA, December 1974. ADA009074.

Lee, Lamar, Jr., and Donald W. Dobler. Purchasing and Materials Management: Text and Cases. 3rd ed. New York: McGraw-Hill, 1977.

Logistics Management Institute. "Multi-Year Procurement and Learning Curve Effects." Unpublished research report Task 67-20, Washington, October 1967. AD662403.

Malone, Mark J. "OH-6A Airframe Production Learning Curves." Unpublished technical report No. 74-8, U.S. Army Aviation Systems Command, St. Louis MO, February 1974. ADB009174.

Martin, Edward T. "Learning Curve Demonstration." Unpublished research report No. USAMC-ITC-1-73-10, U.S. Army Logistics Management Center, Red River Army Depot TX, May 1973. AD768126.

McDonald, Paul R. The Theory and Practical Application of Improvement Curves. Covina CA: Procurement Associates, 1967.

Orsini, Captain Joseph A., USAF. "An Analysis of Theoretical and Empirical Advances in Learning Curve Concepts Since 1966." Unpublished master's thesis, GAS/SM/70-12, AFIT/SE, Wright-Patterson AFB OH 1970. AD 875892. LD 25699.

Pichon, Captain Allen A., USAF, and Captain Charles L. Richardson, USAF. "The Develoment of a Predictive Model for First Unit Costs Following Breaks in Production." Unpublished master's thesis, SLSR 15-74B, AFIT/LSG, Wright-Patterson AFB OH, August 1974. AD785953.

Puryear, Van A. "New Progress Functions with Probability Modifiers." Unpublished report, unnumbered, U.S. Army Troop Support Command, St. Louis MO, May 1973. AD 763830.

________. "The Progress Function Analysis and Application for the Acquisition Process." Unpublished report, unnumbered, U.S. Army Mobility Equipment Command, St. Louis MO, December 1972. AD908621.

RAND Corporation. "Military Equipment Cost Analysis." Unpublished report, unnumbered, Santa Monica CA, June 1971. AD901477.

Smith, Roger M. "An Analysis of First Unit Labor Cost for Fixed Wing Aircraft." Unpublished master's thesis, GSA/SM/70-17, AFIT/SE, Wright-Patterson AFB OH, June 1970. AD874199. LD25457.

Smith, Ronald L., and others. "Maintenance Technicians Performance Curves." Unpublished technical report No. RADC-TR-70-156, American Institute for Research, Pittsburg PA, August 1970. AD875295.

Thompson, David D. "The Determination of Time Dependent Availability when Repair Times are Governed by the Learning Curve." Unpublished report No. 1-73-23, Red River Army Depot, Texarkana TX, March 1973. AD768135.

U.S. Army Aviation Systems Command. "Tables for Approximation of Completion versus Expenditures for Log Learning Curves." Unpublished technical report No. 69-1, St. Louis MO, February 1969. AD848154.

U.S. Army Electronics Command. "Development of Acquisition Cost Model." Unpublished report No. DAAB07-69-D05041-Task5(B-a), Fort Monmouth NJ, December 1969. AD878090. LD 246628.

U.S. Army Material Command. <u>Cost Analysis Handbook</u>. Washington, January 1968. AD682069.

________. <u>AMC Cost Analysis Handbook</u>. Alexandria VA, January 1968. AD 682069. LD L6436A.

U.S. Army Missile Command. <u>Alpha & Omega and the Experience Curve</u>. Redstone Arsenal, AL, April 1965. AD617133.

Waggoner, Larry P. "Army Material Experience Curve Guideline." Unpublished technical report No. 113, Army Material Systems Analysis Agency, Aberdeen Proving Ground MD, July 1971. AD887204. LD 27104.

Wortham, A. W. and R. B. Misra. "A Note on the Theory of Learning Curve Relations." <u>The Logistics and Transportation Review</u>. Vol. 8, No. 1, 1975. LD 27828.