INDUSTRIAL TIME REDUCTION CURVES AS TOOLS FOR FORECASTING

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This is to certify that the

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INDUSTRIAL TIME REDUCTION CURVES AS TOOLS FOR FORECASTING

By

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ABSTRACT

INDUSTRIAL TIME REDUCTION CURVES

The purpose of this study is to determine the reliability of the time reduction curve as a tool for forecasting direct man-hours required in manufacturing. The time reduction curve is defined as the relationship in which the cumulative average direct man-hours per unit used in the manufacture of a product tend to decline by a constant percentage as the cumulative quantity produced is doubled. Where this relationship is present, it may be represented by a straight line on double logarithmic scale.

Historical direct man-hour data, consumed at various cumulative quantities of output, were obtained from three manufacturers. The data represents fifty-four products, and five production programs.

The following questions relative to the time reduction curve were investigated:

First, does the time reduction curve phenomenon exist in situations other than those where production is based on a predetermined time reduction curve? It has been suggested that the curve's existence in the airframe industry is a result of acceptance of this phenomenon as a valid relationship.

Analysis of empirical data strongly suggests that the existence of the time reduction curve phenomenon is not predicated on the use of the curve for purposes of planning and control of man-hours required in production. The firms, from which data were obtained, did not employ a preconceived model of time reduction, yet a definite regularity in time

reduction was observed in a majority of cases.

Second, what is the reliability of the linear form of the time reduction curve on log-log scales?

The correlation to the least squares computed line of regression is high. In fifty of fifty-four cases the index is greater than .90. Over 34 per-cent of the time reduction curves computed were found to be reliable, e.g. did not exceed an arbitrarily set standard of reliability of 4 per-cent standard error of estimate.

Third, what is the magnitude of variation in the rate of time reduction among firms manufacturing similar products, non-similar products made by one firm, and various models of a basic product type manufactured by one firm?

In every category of production the variation in slope exceeded 6 per-cent. The variations in curve slope are of such magnitude as to limit seriously the usefulness of slope experienced on past models when determining what slope should be used in forecasting man-hours of future models of a product type.

Fourth, is it possible to estimate the applicable rate of time reduction on the basis of man-hour data observed in the manufacture of an initial quantity of a product?

A mathematical formula which gives the exact number of observations required before slope characteristic of certain confidence may be determined has been proposed. When this approach to the estimating of time reduction curve slope is used, it is recommended that for the quantity required for slope estimating, man-hour data be reported on the basis of units or small lots.

This appears desirable because in cases where the data is reported on a lot basis the quantity produced may have to be so large as to negate most of the usefulness of the time reduction curve.

An attempt was made to estimate the slope on the basis of a minimum of man-hour observations at various quantities. In twenty-two of the twenty-eight cases it was possible to obtain a relatively accurate forecast of the applicable slope from three lot values. Four lot values were used in three cases, and the remaining three cases required five man-hour values. The average error in the slope estimate, based on minimum production quantities, for all twenty-eight cases is 1.8 per-cent.

The estimated rate of time reduction was used to forecast man-hours for various quantities for which actual data were available. Comparison of the estimated and actual man-hours was made, and the error in estimate computed. An error in estimate of less than 7 per-cent was obtained in 72.3 per-cent of the fifty-four cases for which computations were made. In 90.3 per-cent of cases the error in man-hour estimate is less than 13 per-cent. However, in 7.4 per-cent of cases the error in estimate ranges from 20 to 25 per-cent.

Finally, does the time reduction curve have value in forecasting of man-hours required in production?

It is concluded that in spite of the fact that the time reduction curve relationship is highly reliable, it is of limited usefulness in forecasting direct man-hours required in the production of a product before a number of units of that product have been manufactured. This

condition exists because of the inability to estimate the applicable time reduction curve slope before the start of production. However, this study indicates that the time reduction curve is within certain limitations, a useful tool for forecasting direct man-hours required in production after a limited quantity of a product has been manufactured.

The conclusions of this study are limited by the fact that data used in the primary analysis were obtained from only three manufacturers. This was supported, however, by certain other data reported in the airframe industry.

PREFACE

The writer wishes to express appreciation to many for the encouragement and assistance during the preparation of the thesis.

In particular, the guidance and assistance provided by Dr. Rollin H. Simonds, as advisor throughout the thesis, is greatly appreciated. The time and assistance of Dr. Stanley E. Bryan and Dr. John H. Hoagland has also been of great value.

The consultation of the several industrial firms has contributed to the preparation of this study.

I am grateful to Mrs. Amy Coon who so patiently assisted in typing the study.

Without my wife, Irene, who assisted me with editing and was a source of constant inspiration, this study might never have been finished.

Only the writer is responsible for conclusions or inaccuracies that may have crept into this study.

S. Alexander Billon
February 1960

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CHAPTER I

INTRODUCTION

Shortly before World War II the time reduction curve technique was developed and used by the Airframe industry and the United States Air Force for the purpose of planning and controlling the various requirements of defense production programs. For more than two decades the technique has been known by various names. There is, as yet, no agreement as to what term should be applied to the technique. Today this technique is known as the time reduction curve,[1] learning curve,[2] experience curve,[3] improvement curve,[4] and progress curve.[5] Of the various designations used the expression "time reduction curve" seems to represent the relationship more accurately and is less confusing than the other names. This expression is broad enough to include the various factors which have an influence on manufacturing time reduction. Some of the other designations are either too restrictive or have previously been adapted to denote other phenomena than that which

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[1] Douglas Aircraft Company uses this term, see: H. W. Thue, "Time Reduction Curves," Proceedings, Industrial Engineering Institute, University of California, Los Angeles, (1953), p. 28.

[2] The term "learning curve" is used by the U. S . Air Force and a number of contractors. See Air Materiel Command, Air Force Guide for Pricing, (Dayton, Ohio, November, 1959), p. 35.

[3] A. W. Morgan, Experience Curves Applicable to the Aircraft Industry, (Baltimore, Maryland: The Glenn L. Martin Company, 1952).

[4] W. F. Brown, The Improvement Curve, (Wichita, Kansas: Boeing Airplane Company, 1955).

[5] A. Anzanos, et. al., Contract Estimating Progress Curves, and Application, (St. Louis: McDonnell Aircraft Corporation, 1958).

will be presently discussed[6].

Because the time reduction curve represents the production progress in dynamic terms, it has become one of the most important tools in airframe production analysis as well as cost estimating and pricing of defense contracts. In the past the use of the time reduction curve technique has been confined to the airframe industry, its suppliers, and the Air Force. During the past few years companies engaged in civilian production are increasing the use of this technique in the solution of their problems.

The conventional time reduction curve theory, the one most widely accepted, states that as the quantity produced doubles, the direct man-hour time per unit declines by a constant percentage[7]. The term "time per unit" is often used interchangeably to mean either the average time of a given number of units or the time of a specific unit. The former may be called the cumulative average time reduction curve and the latter the unit time reduction curve. Both values, when plotted, represent a hyperbolic function on arithmetic scales. When the same data is plotted on logarithmic scales a linear function is obtained. Figures 1.1 and 1.2 show a unit curve of eighty per cent slope, which shows a cumulative average per unit time reduction of 20 per cent everytime the total quantity produced is doubled. The time reduction curve theory is based on the hypothesis that the time of producing an item will decrease as successive units are produced, and

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[6] For the origin of the "learning curve," see Chapter 2.

[7] T. P. Wright, "Factors Affecting the Cost of Airplanes," Journal of Aeronautical Sciences, (Feb., 1936) p. 124.

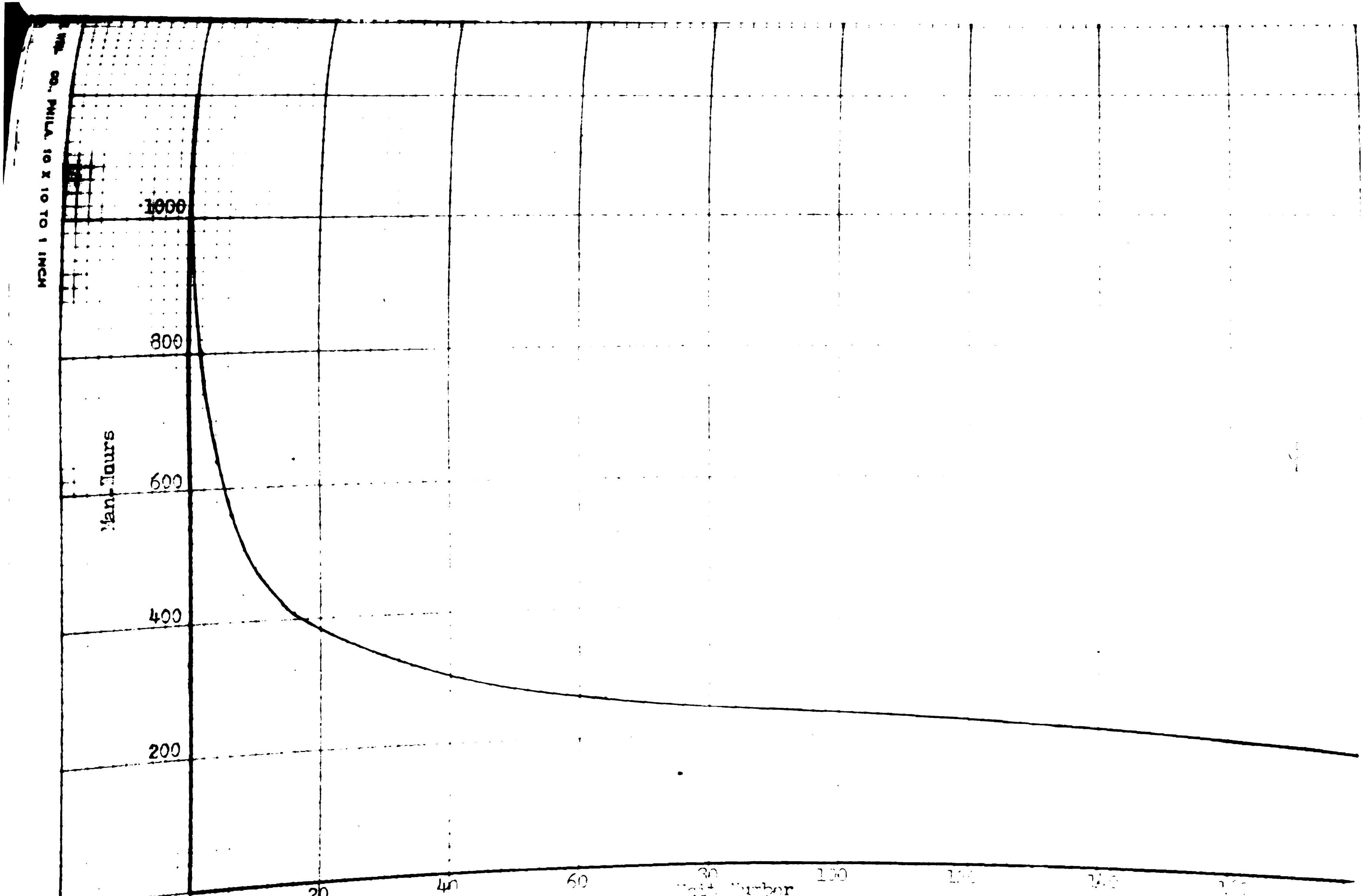

Figure 1.1 The 80 per cent cumulative average time reduction curve on arithmetic scale

Source: Hypothetical data

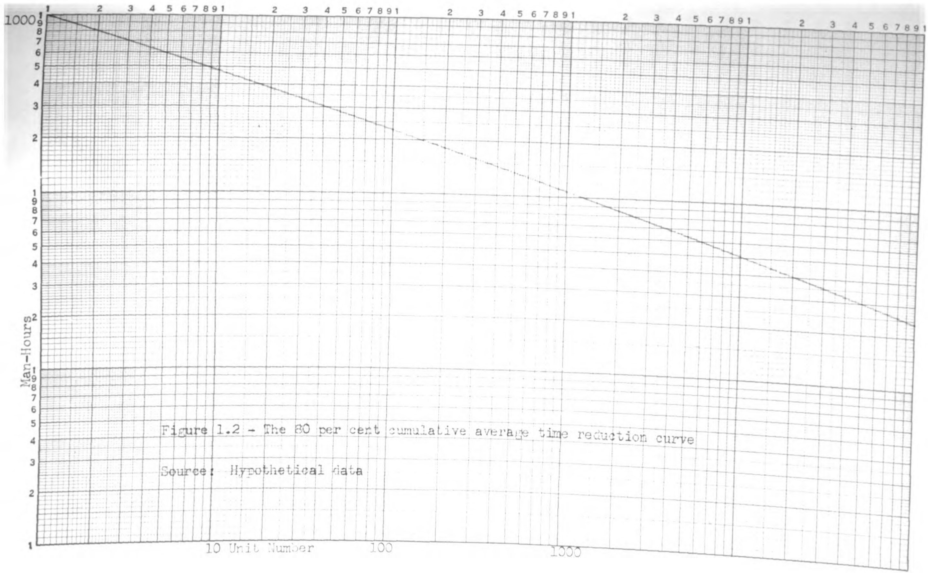

Figure 1.2 - The 80 per cent cumulative average time reduction curve

Source: Hypothetical data

that the amount of the decrease will be less with each consecutive unit. The slope of the curve is usually expressed as a percentage, e.g., 80 per-cent, 90 per-cent, etc. The slope of the time reduction curve is simply an expression of the ratio between the man-hours at any unit and the man-hours at twice the quantity of that unit. The curve indicates a relatively high rate of decrease at the beginning of the sequence, but as output is continued, it approaches stability, at least for all practical purposes.[8] In theory the decrease in man-hours continues indefinitely, but as large quantities are produced, the decrease per unit becomes very small and insignificant.

There are many variables that may contribute to the decrease in man-hours required in production. It should not be assumed that all factors are known or have been isolated. Although this could conceivably be accomplished in an individual case, the measuring of the effect of each factor would probably be of little use in other situations. Preliminary evidence indicates that the factors responsible for the decrease in man-hours as the quantity of output is increased may be grouped under the following categories: (1) Manpower attributes, including learning on the part of the organization in the early stages of the program, morale, employee suggestion system, and influence of incentives. (2) Engineering efforts, including more effective communication, clarification of drawings, elimination of errors, and simplification of design. Industrial engineering activities have a

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[8]It should be noted that at no time during the production of six thousand B-17 bombers at Boeing did the curve cease to decrease. There is no proof at this time, whether the time reduction curve will become horizontal as output is continued.

direct bearing on time and methods. (3) Organization and effectiveness of the production control functions will affect the decrease in time. (4) The type of tooling coordination, and the extent of automated machine tools has an influence on man-hour requirements. Development of a more efficient materials management system will also tend to decrease costs.[9] While it is certain that some learning on the part of the workers accounts for the sizeable decrease in time at the early stages of a production program it seems clear that beyond this initial stage the burden of continued decreases must be on management. It is necessary that management provide the leadership and the stimulus to further improvement. The importance of effective organization and coordination of all departments cannot be overemphasized.

Use of the Time Reduction Curve

The time reduction curve was put to use by the aircraft industry in late 1939, when mass production of trainer aircraft got underway.[10] At this stage, the time reduction curve served primarily as a tool of forecasting flow time.[11] This is reasonable to expect since there was an extreme urgency to get as many aircraft completed as possible in a short time. Also, existing production facilities were either

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[9] For a more detailed discussion of factors which affect time reduction see Chapter 7.

[10] E. J. Blume and R. E. Morris, Improve Your Pay, (Columbus, Ohio: North American Aviation, n.d.), p. 2.

[11] Flow time may be defined as the interval between the first production hour and the last hour expended in the manufacture of a product.

inadequate or in short supply. Military agencies which were charged with the procurement responsibility had to keep close score on manpower, facility, and materials utilization. As a result, the Army Air Forces, Air Materiel Command began a mandatory production data reporting system which would enable it to control production to a greater extent[12].

By the end of the war hundreds of aircraft producing facilities made use of the time reduction curve technique. When aircraft production declined at war's end, there seemed to be also a decline of interest in the time reduction curve, except for the large airframe manufacturers, who continued to apply it to an ever greater variety of problems. The post-war period has witnessed the introduction and application of the time reduction curve technique to civilian production. The beginning was made by the civilian subsidiaries of the airframe companies.

The Bureau of Labor Statistics has examined man-hour cost data of a number of ship manufacturers. It is reported that there was an average decline of sixteen to twenty-two per cent in the man-hours required as the quantity produced doubled[13]. Professor Bryan in a study of a shoe manufacturing situation found that direct man-hour cost per unit declines even after cumulative production of a pair of

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[12] Source Book of World War II Basic Data; Airframe Industry, Vol. 1, A. A. F. Materiel Command, Wright Field, Dayton, Ohio, (n. d.)

[13] F. J. Montgomery, "Increased Productivity in the Construction of Liberty Vessels", Monthly Labor Review, (November, 1943), pp. 861-864.

boots has passed the ten thousand mark.[14] Recently it is reported that the time reduction curve applies also to the production of machine tools,[15] and electronics.[16] Andress states that the time reduction curve, "Holds true whether the industry is aircraft, metal working, textile or candy making. What was not known until a decade ago is that the rate of improvement is regular enough to be predictable. It is this fact that makes what would otherwise be a rather common-place observation the clue to a broader and more practicable concept for business."[17]

Today the time reduction curve is used as a tool to provide the solution to many manufacturing management problems, not only in the aircraft industry, but in a number of other industries as well. An indication of the importance of the time reduction curve to industry may be inferred from the following facts:

(1) Manufacturers use the curve to estimate the cost of defense contracts, which are then negotiated with the Air Force.

(2) The Air Materiel Command uses the curve to establish the mobilization potential of production facilities.

(3) The Air Materiel Command uses the curve to appraise contractors' performance efficiency and to check the progress of

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[14] Stanley E. Bryan, "Value and the Learning Curve," Purchasing, (September, 1954).

[15] W. Z. Hirsch, "Manufacturing Progress Functions," The Review of Economics and Statistics, Vol. 34, (May, 1952), pp. 143-145.

[16] Reno R. Cole, "Increasing Utilization of the Cost-Quantity Relationship in Manufacturing," The Journal of Industrial Engineering, (May-June, 1953), pp. 173-177.

[17] Frank J. Andress, "The Learning Curve as a Production Tool," Harvard Business Review, (January-February, 1954), p. 87.

current contracts, as well as production dependability.

(4) The Air Materiel Command and manufacturers use the curve in planning, predicting, and testing the feasibility of schedules.

(5) Manufacturers use the curve to develop man-hour requirements for specific production programs.

(6) The Air Force uses the curve in negotiating prices of defense material. The prime contractors are using the curve to price subcontractor furnished materials and parts. In other cases, where prices are negotiated, there is a tendency to use the curve to arrive at a realistic price.

(7) Manufacturers use the curve to determine floor space requirements, assuming that a standard average number of square feet of space are required per worker.

(8) Using this technique it is also possible to determine the assembly tool requirements.

(9) The curve is employed in computing the working capital required during the manufacturing period because, the area of greatest financial drain is at the beginning of a program. The cost of producing the early units of a new product exceed the revenues.

The above list of uses is by no means complete. Cost control, for example, is another area where the time reduction curve may be used. It does not appear that possibilities for additional applications have been exhausted.[18]

Purpose of the Study

The time reduction curve is one of the instruments which is used by the U.S. Air Force and the airframe industry in forecasting production requirements. Recently it has found increasing acceptance in other industries.[19]

The purpose of this study is to determine the reliability of the time reduction curve as a tool of forecasting direct man-hours in certain manufacturing situations. For the purpose of this study, the time reduction curve is defined as the relationship in which the cumulative average direct man-hours per unit used in the manufacture of a product tend to decline by a constant percentage as the cumulative quantity produced is doubled. Where this relationship is present, it may be represented by a straight line on double logarithmic scales.

The following questions relative to the time reduction curve will be investigated: First, does the time reduction curve phenomenon exist in manufacturing situations other than those where production activities are based on a planned time reduction function? No assumptions are made relative to the effect that such use of a preconceived time reduction model will have on observed man-hour data. However, it appears

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[18] The following publications contain discussion of the uses of the time reduction curve: R. Brenneck, "The Learning Curve for Labor Hours - for Pricing," NAA Bulletin, (June, 1958), pp. 77-78; Rolfe Wyer, "Industrial Accounting with the Learning Curve," The California Certified Public Accountant, Vol. 33, No. 3, (February, 1956), pp. 24-34; E. J. Blume, and Donald Peitzke, Purchasing with the Learning Curve, North American Aviation, Columbus, Ohio, (August, 1953); W. F. Brown, The Improvement Curve, Boeing Airplane Company, (Wichita, Kansas, (March, 1955).

[19] Reno R. Cole, "Increasing Utilization and the Cost-Quantity Relationship in Manufacturing," The Journal of Industrial Engineering, (May-June, 1958), pp. 173-177.

desirable to analyze empirical data observed in situations where the curve is not used in planning and controlling production requirements.

Second, what is the reliability of the linear function of the time reduction curve on log-log scale? What are the reasons for deviations from a straight line on double logarithmic scale?

Third, what is the magnitude of variation in the rate of time reduction among firms manufacturing similar products, non-similar products manufactured by one firm, and also various models of a basic product type manufactured by one firm?

Fourth, if the variation in the previously experienced rate of time reduction is large, is it possible to estimate the applicable rate on the basis of man-hour data experienced in the manufacture of an initial quantity of units?

Fifth, in view of the findings relative to the above questions, does the time reduction curve have value in forecasting direct man-hour requirements?

This study is concerned only with the direct portion of the man-hours expended and chargeable to a specific product. Where this rule is violated, a note to this effect will be included. Because a change in characteristics of a product usually affects the man-hours required, accurate forecasting necessitates adjustment for the change in order that a comparable basis be maintained. Accordingly, a method of time reduction curve adjustment for design changes will be proposed. Finally, certain relevant problems will be indicated for future investigations to develop better man-hour forecasting techniques.

Most of the empirical data used in this study were obtained directly from three mid-western manufacturers through extensive personal visits to the man-hour generating, as well as all other departments concerned with man-hour data accumulation. Because of the time, scope, and otherlimitations it was necessary to confine this investigation to three manufacturers, and some data gathered by the Air Force.

Chapter 2 contains a review of the historical development of the time reduction curve, as well as a summary of the more important contributions to the curve literature. Chapter 3 contains an analysis of the time reduction curve theory, assumptions, and variations. In Chapter 4, historical man-hour data is presented. Chapters 5 and 6 are devoted to analysis of data with specific reference to the above hypotheses. Factors which are judged to have an effect on time reduction slope are discussed in Chapter 7. Methods of adjustment for changes in the product unit are considered in Chapter 8. Summary of conclusions may be found in Chapter 9.

CHAPTER II

HISTORY AND DEVELOPMENT OF THE TIME REDUCTION CURVE

Introduction

Many have described learning as the source of all human progress and improvement. Whether or not the above statement is accepted, there is little doubt that learning in its broadest meaning has been responsible, to a large extent, for the relatively high standard of living enjoyed by Americans. The short-term and the long-term success of every manufacturing enterprise depends on continuous improvement of its service to society. One aspect of this improvement is that the cost which is required to produce the products demanded be reduced in terms of effort expended on their acquisition.

THE INDIVIDUAL LEARNER'S CURVE

The fact that as an individual repeats a physical task his performance improves has been known for a long time.[1] It is probably this fact more than anything else that is responsible for the (early) mistaken notion that the time reduction curve phenomenon is attributed to learning on the part of the individual, in its entirety. The time reduction curve was originally known as the learning curve, and the latter term is still being used by some companies, although the misnomer is quite apparent from the fact that the term learning curve

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[1] Ralph C. Davis, Industrial Organization and Management, (New York: Harper and Brothers, 1940), p. 338.

has been used by psychologists for many decades.[2] This is not to argue that an individual worker's learning, through repetition or otherwise, is not reflected in the time reduction curve. On the contrary, evidence seems to indicate that the high rate of improvement at the early stage of a program is in large part due to workers' learning.[3] The inadequacy of the explanation of the time reduction curve in terms of workers' learning alone becomes quite apparent when the time reduction curve continued to register decreases in man-hours even after thousands of units were produced over an extended period of time.

Industrial psychologists generally agree that as a worker repeats a manual task, the time required to perform this task will decline. This may be illustrated by a learner's curve. Figure 2.1, relates productivity to the number of weeks the employee is on the job. Plotting the number of units produced per day on the vertical axis and the time in days on the horizontal, results in a typical learner's curve. The normal shape for this curve is a rapid rise at first, then less rapid until it flattens out. At this point, the learner has reached what is often called standard or a 100 per-cent normal efficiency.[4] Hadley proposes that this curve be used to estimate the required training time for new employees, and also computing

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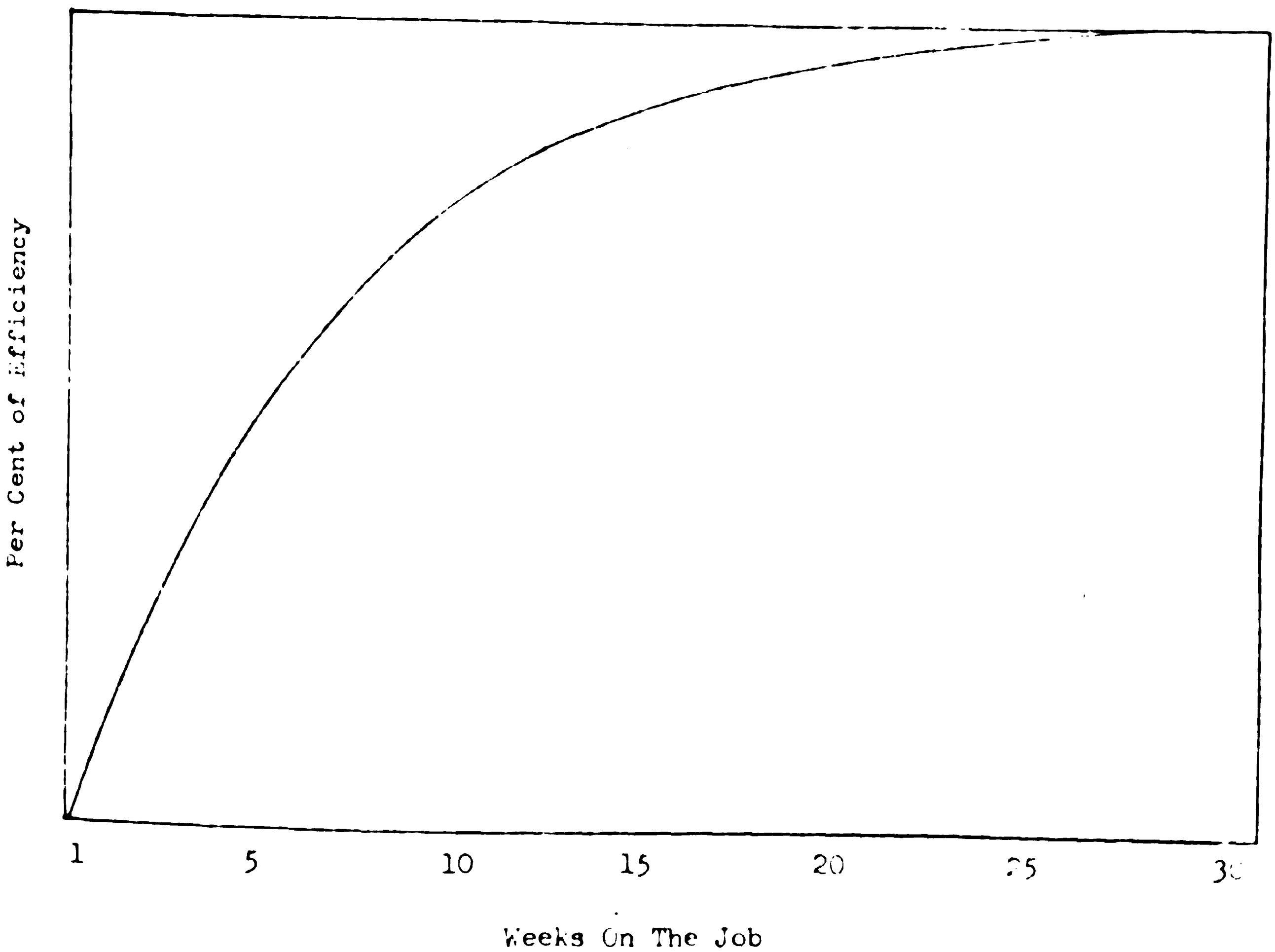
[2] Donald A. Laird, and Eleanor C. Laird, Practical Business Psychology, (New York: McGraw-Hill Book Company, 1956), p. 376.

[3] Ibid, p. 377.

[4] Franklin G. Moore, Production Control, (New York: McGraw-Hill Book Company, 1953), Chapter 9.

FIGURE 2.1

A TYPICAL LEARNERS CURVE



Source: Hypothetical Data

learners' allowances.[5] It may be stated that the learning period is a function of the complexity of a given task. Some tasks require little time and ability to master while others take a relatively long time. Psychologists agree that ability, incentive, and attitude are some other variables that enter into a learning situation.

The discovery of learning curves has been attributed to Dr. William L. Bryan. His studies of telegraph code learning were a most significant contribution to applied psychology, and were published first in 1897, at the psychological laboratory, which he started nine years earlier at the University of Indiana.[6] Bryan was the first to find that learning does not progress smoothly, that learning is most rapid at the beginning, then it slows down as the ultimate in skill is approached; and that there is a plateau in the learning curve, a time when the learner does not seem to improve, and the curve may actually turn downward.[7]

Since this pioneering effort on the part of Bryan, many industrial psychologists have studied the learning curve for different industrial situations.[8] Regardless of the task involved, a clear similarity in the learning curve is in existence. Tiffin reports

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[5] J. R. Hadley, "Learning Curves on Log-Log Paper; Technique for Determining Learners Allowances," <u>Advanced Management</u>, (April, 1950), pp. 16-17.

[6] Dr. Bryan later became president of the University and held that post for 35 years.

[7] W. L. Bryan, and N. Hartern, "Studies in the Telegraphic Language," <u>Psychological Review</u>, (1899, Vol. 6), pp. 346-376.

[8] Milton L. Blum, <u>Industrial Psychology and its Social Foundations</u>, (New York: Harper and Brothers, 1956), p. 213.

learning curve of "normal" shape, i.e. similar to that described in above paragraphs, has been found to exist in hosiery production.[9] A study to determine the shape of learning curves for industrial motor tasks is one of the most recent contributions to learning curve knowledge.[10] In this study learning curves were obtained for persons on twelve different sewing tasks. These tasks ranged in length of learning time from seven to twenty-seven weeks for individual learners. There was considerable variation in job characteristics ranging from simple automatic tasks to those requiring a good deal of adjustment in behavior. All jobs observed were on a similar wage incentive system, and in all cases output was not counted until at least one satisfactory unit was produced. Not only were all the average learning curves similar, but when they were equated for different learning times, and the different levels of potential efficiency, they approximated closely the identical shape throughout the period. The rate of change was similar and comparable for the different tasks, and therefore, it was possible to determine a typical curve for learners in this particular situation.

Industiral psychologists agree that two changes take place when a worker learns on the job. The first category of changes may be called qualitative changes. These include all the improvements that the individual acquires in his behavior either consciously

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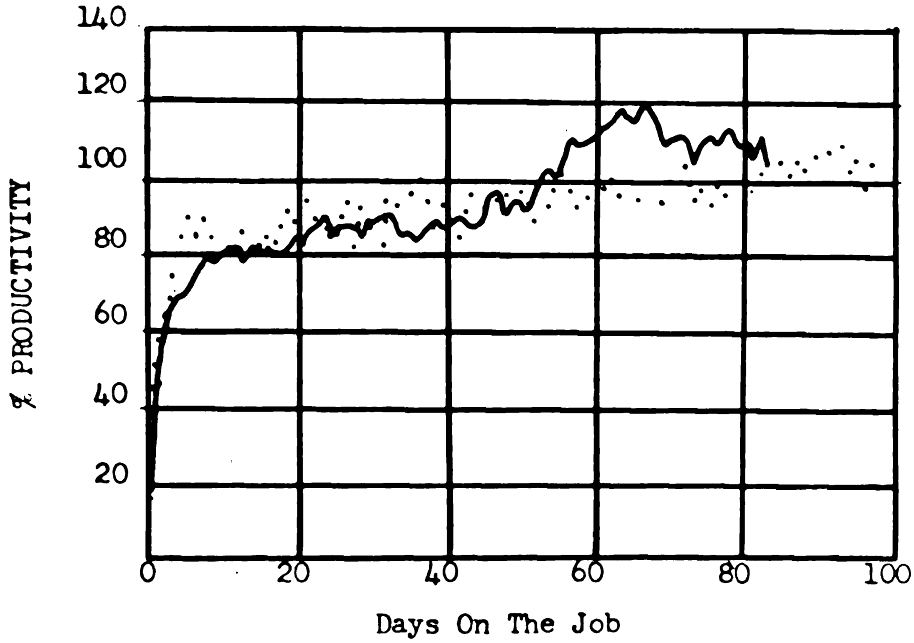
[9] Joseph Tiffin, Industrial Psychology, (New York: Prentice-Hall, Inc., 1952), p. 17?.

[10] J. G. Taylor, "An Investigation of the Shape of Learning Curves for Industrial Motor Tasks," (Unpublished Master's Thesis, Cornell University, 1951), p. 160.

FIGURE 2.2

TWO INDUSTRIAL LEARNING CURVES



Source:

Taylor, J. G., "An Investigation of the Shape of Learning Curves For Industrial Motor Tasks" unplublished Master's thesis, Cornell University, 1951 or unconsciously, and consists primarily of modifications of the form of movements as the task is repeated. A study by de Montpelier of France, attempted to determine movement pattern changes as the cycle was repeated. The motions of the subjects were recorded photographically for each cycle. A steady increase in speed was observed throughout the thousand trials. There was also a clear improvement in the form of movements. The most important change was the elimination of most corners and angles.[11]

In addition to analysis and research of qualitative changes, psychologists have studied the factors influencing the shape and the length of individual learning curves for various tasks. From the management point of view, the individual learning curve is of interest for a number of reasons. First, learning curves are valuable in diagnosing problems of learning, indicating difficulties and reasons for delays in learning by the individuals and groups. Next, learning curves may be used in evaluating methods of teaching and other changes in working conditions and methods. Finally, they give the individual learner an immediate goal to work toward. In one situation the workers are told what the reasonable rate of progress should be, so that the worker will not be unduly discouraged.[12]

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[11] T. A. Ryan, and D. C. Smith, Principles of Industrial Psychology, (New York: Ronald Press Company, 1954), p. 431.

[12] Melrose Hosiery Company, reported in Joseph Tiffin, Industrial Psychology, (New York: Prentice-Hall, Inc., 1952), p. 310.

In some cases the workers' motivation can be kept up by tying a wage incentive plan to the learning curve, given the learning curve for his job.[13]

The existing evidence is virtually in agreement that there is a horizontal level which the learner reaches after a specified time on the job. The agreement is far from unanimous. Blum states that:

> Too often the concept plateau appears in connection with the learning curve. This is an overstated and overworked idea. Sometimes there is a flatness in the learning curve which is eventually followed by a spurt. This flattening indicates a period of no apparent progress and is referred to as a plateau. There are many reasons for the appearance of a plateau in the learning process. It may be the result of lack of motivation, inefficient methods, or, very often, ineffective teaching and poor training. However, a plateau is not an integral part of the learning process; hence one should not be concerned by its absence.[14]

Blum argues that learning and productivity should continue to increase indefinitely. If so, the possibility of existence of a continuous time reduction curve which is solely due to learning is obvious. Another authority states that the plateau is peculiar to industrial situation learning, and that a plateau need not be a permanent position, and that it is possible to progress from there to a new plateau.[15] The possibility of this happening has been demonstrated in many cases where a new method or motion is discovered and adopted by employees, presuming that they had incentive to do so. As a practical matter there is, in most plants, a standard level of performance, which when reached by an employee, satisfies supervision.

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[13]J. R. Hadley, op. cit., p. 16.

[14]Milton L. Blum, Industrial Psychology and Its Social Foundations, (New York: Harper and Brothers, 1956), p. 480.

[15]Ryan and Smith, op. cit., p. 438.

Furthermore, any additional progress is probably discouraged by the union, thus learning or improvement may be absorbed by the worker through certain well developed techniques. Ryan and Smith attribute plateaus in learning as being primarily due to changes in motivation of the learner.[16] Another important reason given by the above authors is that level periods exist because the workers practice incorrect responses, which are not conducive to improvement.

When there is a change in method there appears to be what might be called a plateau. Actually, it is the end of a learning curve for the old method and the beginning of a new learning curve for the new method. In some industrial learning situations the learning of new methods cannot be undertaken until the previous method has been mastered. There are some practical implications of individual learning curves. Taylor reports that many of the learners have quit their jobs while they were on a learning plateau. Careful observation showed that the experienced workers were using a different method, which unfortunately for the learners, was not easily mastered.[17]

We have seen that authorities are not in agreement as to the shape of the learners' curve. Most of the writers, whose work was reviewed, appear to be in favor of the more popular hypothesis that after a certain period of time there is a tendency for output, as a result of learning, to reach a plateau. A break-through is probably possible providing the worker has sufficient incentive and perhaps

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[16] Ibid, p. 441

[17] Taylor, op. cit., p. 23.

some help in mastering a better method. Thus, we may conclude that after a certain standard proficiency is reached, no significant progress should be expected without the efforts of management.[18] Performance must level off at some point, because of workers' limited ability, even if other limitations do not exist.

We have discussed the industrial psychologist's views on the shape of an industrial learners' curve. It is evident that there is a definite relationship between the learning curve as discovered by William Bryan, and the time reduction curve which is the subject of this study. The basic difference seems to be in that the former is concerned with a production unit consisting of a single individual, whereas the latter is concerned with the progress of a productive organization which may consist of many thousands of individuals.

THE DEVELOPMENT OF THE TIME REDUCTION CURVE THEORY

In deciding whether or not to review an author's work in the following pages, the criteria of contribution to theoretical or empirical knowledge of the time reduction curve was used. First, the two main approaches to the time reduction curve theory will be discussed; next follows a chronological review of what appeared to be work which contained original material at the date of publication.

The Orthodox Formulations of the Time Reduction Curve Theory

The original formulation of the time reduction curve theory is attributed to T. P. Wright. However, two authorities believe that Leslie McDill should get the credit for the original formulation.

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[18] Depending of course on the effectiveness of incentives and the imagination of the individual worker, there will be exceptions.

Thus, Reguero states that:

> Credit for the original investigation of airframe production data which led to the formulation of the learning curve theory is given to Leslie McDill, who was commanding officer at McCook Field[19] in 1925.[20]

Another writer who attributed the theory to McDill, is Max Stupar who says:

> About 1932, Leslie McDill, studied costs of airplanes in various quantities and arrived at the conclusion that doubling of the quantity resulted in an average man-hour consumption of 80 per-cent of the original value.[21]

Neither of the two authors give the source of their information. The subject of cost of airplanes was of interest in the middle twenties in connection with discussions of economical mass production of airplanes for private use. It is this subject that led T. P. Wright to publish the article to which the origination of the time reduction curve theory is attributed.[22]

Whether or not Wright originated the time reduction curve cannot be stated with certainty. Since McDill did not publish his findings, we will probably never know exactly what his contribution is. We do know that Wright was the first to make the theory known.

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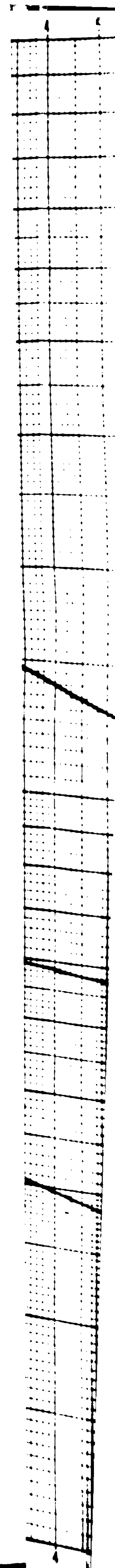
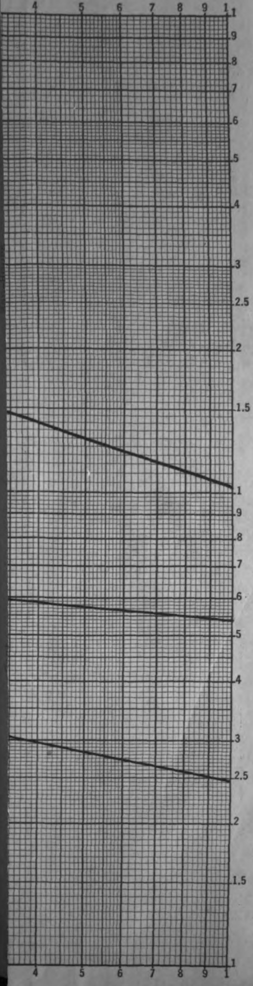
[19] McCook Field was the predecessor of Wright-Patterson Air Force Base, near Dayton, Ohio.

[20] M. A. Reguero, "An Economic Study of the Airframe Industry," (Unpublished Ph.D. dissertation, Department of Economics, New York University, October, 1957), p. 213.

[21] Max Stupar, "Forecasting of Airplane Man-Hours," Unpublished manuscript, Headquarters Air Materiel Command, (1942), p. 7.

[22] T. P. Wright, "Factors Affecting the Cost of Airplanes," Journal of Aeronautical Sciences, (February, 1936), pp. 122-128.





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To quote Wright on the time of his work:

> The present writer started his studies of the variation of cost with quantity in 1922. A curve depicting such variation was worked up empirically from two or three points which previous production experience of the same model in differing quantities made possible. Through the succeeding years, this original curve, which at first showed the variation in labor only, was used for estimating purposes and was corrected as more data became available.[23]

According to Wright, the most important determinants of aircraft production cost are design factors, tooling, engineering changes, size and quantity produced. The design factors include the type of construction material costs, simplicity of design, and reduction of parts. The tooling factor of production cost depends on the quantity produced and on the susceptibility of the design type to be produced on available tooling. Changes require many expenditures besides the direct cost of incorporating them, e.g. shop delays, are another item of costs. Size of product has the effect of favoring decreased costs because the number of parts does not increase at the same rate as size increases. Also, in a large airplane, the parts need not be in miniature size and gauge, and therefore, are easier to handle.

It is the effect of quantity on production cost that was of greatest interest to Wright, and the one area where his contribution has been the most fruitful. Wright holds that the three major costs of production vary with the cumulative quantity of production. It may be noted here that although it has been a widely acknowledged fact that labor and overhead vary as the quantity of unit produced

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[23]<u>Ibid</u>, p. 122.

is increased, there has been a surprising lack of development on the direct material curve which Wright has originally suggested.

Wright attributed the reduction of labor time as production quantity is increased to four factors: (1) The improvement in proficiency of a workman. (2) The greater spread of machine and fixture set up time in large quantity production. (3) The economy in labor which greater tooling can give as the quantity increases. And finally, (4) as more and more tooling and standardization of procedure is introduced, it is possible to use less skilled labor.[24]

In his analysis of empirical data, Wright found that the function between cumulative average direct man-hours and cumulative number of airframes produced could be represented by the following function:

$$Y = ax^b \qquad (2.1)$$

Where:

Y is the direct average man-hours

x is the cumulative output

a is the parameter which indicates the direct man-hour cost for unit number one

b is the second parameter which defines the slope of the time reduction curve.[25]

S is the slope

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[24]Ibid, p. 124.

[25]In time reduction curve terminology, slope is defined as the ratio of the unit (or average) man-hour cost at two points of production. This differs from the mathematical definition of slope, where the slope of a function is defined as the first derivative of the function.

For the empirical data available to him, Wright found that "b" has a value of - .322 an 80 per-cent slope is obtained by substituting - .322 for "b" in the following equation:

$$S = \frac{a(2x)b}{ax^b} \qquad (2.2)$$

or

$$\log S = - .322 \log 2 \qquad (2.3)$$

or

$$S = .80 \qquad (2.4)$$

The above illustrates the customary practice in time reduction curve work of obtaining the slope at double the present cumulative output, or in other words, quantities that vary by a factor of two. When it is assumed that the cumulative average man-hours are related to cumulative output as shown in equation (2.1), the resulting cumulative total curve will be:

$$Y = ax^{1+b} \qquad (2.5)$$

and the unit curve will be:

$$Y = a(1+b)x^b \qquad (2.6)$$

There is some question as to whether Wright meant equation (2.1) to describe the unit curve or the cumulative average curve. The controversy should be settled by the following passage in Wright's article:

> A curve may be plotted which shows directly the relationship between the two variables and when plotted on log-log paper, it becomes a straight line. In Figure 2.3 such a curve appears; there called the 80 per-cent curve which is represented by a value of .322 for the exponent x (Y in this study) in the above formula. This 80 per-cent has a definite meaning in that

> it represents the factor by which the average labor cost in any quantity shall be multiplied in order to determine the average labor cost for a quantity of twice that number of airplanes.[26]

Wright was talking about cumulative total output and cumulative average man-hours per unit.

We have already mentioned above that Wright hypothesized that material also decreases as the quantity increases. He found, for instance, that the amount of usage for the first five units alone amounted to 40 per-cent of the cost of purchased material. "It reduces rapidly as quantity increases, to 25 or 30 per-cent in quantities of twenty-five to fifty units and down to 20 per-cent in a quantity of one hundred units."[27]

In addition to the reduction of waste, Wright maintains that greater cutting efficiency and more economical purchasing partially explain the reduction in material cost. Other possible factors at work are reductions in price of materials because of quantity purchases and greater vendor efficiency. Empirical data available to Wright showed that a raw material cost improvement curve of 95 per-cent and purchased material curve of 88 per-cent, were realized. The ability to obtain a steeper curve in the case of purchased material is explained as being due to a greater proportion of labor in the latter.

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[26] _Ibid_, p. 125.

[27] _Ibid_, p. 125.

James R. Crawford

Crawford is one of the most prolific contributors to the published material on the time reduction curve. Unfortunately, most of the material developed by this author has been in the form of company manuals which are not available at this time. His chief contribution to the time reduction curve theory was a study of two hundred jobs in the airframe production process, which resulted in a new formulation of the time reduction curve. Crawford shows that the relationship between direct man-hours per unit and the cumulative unit number could be described by the function $Y = ax^b$.[28]

The above equation is identical to that developed by Wright, except that in this case it is assumed to hold for the unit curve, whereas Wright used it in connection with the cumulative average curve. A number of Crawford's attempts to develop a time reduction curve of simpler equations and formulae did not yield forms that were adopted either by the industry or the Air Force.[29]

Crawford's most recent contribution are Improvement Curve tables which give values for a set of straight lines on logarithmic scales.[30]

Learning on the part of the individual worker is held to be most important by Crawford. He also emphasizes that learning does not mean

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[28] J. R. Crawford, Learning Curve, Ship Curve, Ratios, Related Data, (Burbank, California: Lockheed Aircraft Corporation, n.d.), p. 52.

[29] J. R. Crawford, Estimating, Budgeting, and Scheduling, (Burbank, California: Lockheed Aircraft Corporation, 1945), p. 51.

[30] J. R. Crawford, "Learning Curves," (Unpublished manuscript, 1958), p. 2.

faster motions, "but the improvement in approach which enables him to eliminate lost motion with no additional effort and oftentimes with less effort."[31] Further, he states that jobs which require the most mental effort improve at the most rapid rate. The mental effort may be due either to complexity of the work or lack of experience of the worker.[32]

Another work by Crawford that is worthy of our attention here, is an article which deals primarily with statistical data requirements of a system of production control, however, there are some direct references to the time reduction curve. The author makes the following remark in speaking of determinants of the time reduction curve:

> The rate of decline of a progress curve is determined by the amount of knowledge the employees - including the service organization - have to gain concerning a particular model. This is found to correlate with the amount of residual experience in the plant at the time the project is started. This experience may be in the form of trained personnel or immediate experience with a previous model. From these two elements, the whole series of man-hours per unit can be determined. A simple follow-up by means of manufacturing accounting records, enables performance to be measured within very close limits.[33]

Unfortunately, Crawford does not go into detail as to how knowledge that the employees have at a particular moment may be measured, and levels of performance on a new program predicted.

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[31] J. R. Crawford, Estimating, Budgeting and Scheduling, (Burbank, California: Lockheed Aircraft Corporation, 1945), p. 24.

[32] Ibid, p. 26.

[33] J. R. Crawford, "Statistical Accounting Procedures In Aircraft Production," Aero Digest, (March 15, 1944), pp. 1-8.

OTHER CONTRIBUTIONS

A. B. Berghell

An excellent mathematical treatment of the time reduction curve may be found in Berghell's book entitled Production Engineering in the Aircraft Industry,[34] which contains a chapter on "Learning Curves." Those who prefer the exactness of mathematics should find the chapter interesting.

I. M. Laddon

Laddon was Executive Vice-President of Consolidated Vultee Aircraft Corporation. The article he presents is of interest because it contains a description of change in the production function as the total quantity to be produced by a company is increased. The company was engaged in the manufacture of the "B-24 Liberator" bombers.

> Despite a tremendous labor turnover due to selective service demands, plus the complication of hiring and training thousands of unskilled women, the company today is producing 2.5 planes for every one produced in April, 1942, while employment of production workers has increased by 10 per-cent. Employment of women has risen from less than 1 per-cent in December, 1941, to more than 43 per-cent at this writing, a great majority of women being hired to replace men going into the armed forces.[35]

The author explains the difference in production methods that are present when only sixty units are to be produced, and when an order is placed for several thousand units. The company performed much better than the customary 80 per-cent time reduction curve.

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[34] A. B. Berghell, Production Engineering In The Aircraft Industry, (New York: McGraw-Hill Book Company, 1944), Chapter 12.

[35] I. M. Laddon, "Reduction of Man-Hours In Aircraft Production," Aviation, (May, 1943), pp. 170-173.

Bureau of Labor Statistics Studies

The Productivity and Technological Development Division of The Bureau of Labor Statistics, Department of Commerce has prepared a number of studies of interest to a student of the time reduction curve. Many studies were published by this agency on the decline in man-hour requirements per unit of certain goods, unfortunately, this data is not adjusted for major changes in the product unit, therefore, it is not suitable for time reduction curve analysis, and will not be discussed here. A few other of these studies deal with time reduction curve data, and their nature will be discussed at this time.

The Liberty Vessel Study

The first time reduction curve data on ship construction was reported by Montgomery in 1943.[36] The study deals with the EC-2 Liberty ship of 10,800 dead weight tons, which was designed for mass construction. The statistical information for this study was obtained from the U. S. Maritime Commission. The man-hour requirement data represented both direct and indirect labor hours. The latter include the time of supervisory personnel, technical, clerical, office, power plant, and maintenance employees. The time of corporate officers, auditors, general managers, and general foremen is included under indirect labor. The direct man-hours had to be estimated from actual man-hours required for a group of ships, the total is then averaged for the number of units within the group.

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[36]F. J. Montgomery, "Increased Productivity in the Construction of Liberty Vessels," Monthly Labor Review, (November, 1943), pp. 861-864.

Between December 1941, when the first two ships were completed, and April 1943, when nine hundred ships were delivered, the average man-hours required per vessel decreased by more than one-half. Montgomery reports that the decline tends to be large at the beginning, and that as production continues the decline continues but at a lower rate, and states that:

> It is probable that a similar trend would be revealed by figures for a company making one automobile model or some other item of complex but standardized equipment on a large scale.[37]

Wartime Shipbuilding Study

Another important study was done at the Bureau of Labor Statistics by A. D. Searle[38] and published in 1945. The study is similar to that made by Montgomery (above) except that it covered Liberty, and Victory ships, tankers and standard cargo vessels. Searle analyzed data which was gathered by the U. S. Maritime Commission, the Navy Department, and reports of shipyards to the Bureau of Labor Statistics. The labor data used to determine labor requirements are total man-hours defined in the same way as in the Montgomery study above. The data covers the period between December 1941 and December 1944 with emphasis on the interval between April 1943 and December 1944. Searle reports that:

> Examination of the data for individual shipyards showed that every time a yard doubled its output, man-hour requirements per vessel tended to decline by a constant percentage. The percentage decreases varied

[37] Ibid, p. 861.

[38] A. D. Searle, "Productivity Changes in Selected Wartime Ship Building Programs," Monthly Labor Review, (Vol. 61, No. 6, December, 1945), pp. 1132-1147.

from yard to yard, but the average declines were almost identical for the different types of vessels considered.[39]

Searle found that the man-hour per ship data when plotted on logarithmic graph paper shows an 80 per-cent time reduction with each doubling of cumulative quantity produced. It was found that within each production program there was considerably more variation in the rate of time reduction than between programs, however, in all cases under consideration the percentage reduction in man-hours between doubled quantities produced ranged from 10 to 26 per-cent. The study concludes that differences in the types of vessel are less significant in determining the rate of man-hour requirement reduction, than the production function differences between individual yards. The above two studies seem to indicate that the time reduction curve phenomenon is present in ship construction programs.

Wartime Productivity Changes in the Airframe Industry

This is the third in a series of studies which were made by the Productivity and Technological Development Division Bureau of Labor Statistics. This study was made by Kenneth A. Middleton and was published in August of 1945, and deals primarily with productivity changes. Middleton notes that there was approximately a tripling of productivity per man-hour during the war and he attempts to explain the factors which affect productivity. Among these, he gives the greatest emphasis to increased total quantity of production and introduction of mass production methods. In anticipation of labor shortages, the industry tended to hoard labor and as time went on the

[39] Ibid, p. 1144.

companies tended to employ this labor with greater efficiency. As these productivity depressing conditions were eliminated or reduced during 1943, the increase in output was remarkable. It is pointed out that before the war there was very little specialization in the airframe industry and as a result great versatility of labor was necessary:

> These mass production techniques, so largely responsible for doubling airframe output per man-hour between early 1942 and late 1943, are characterized by specialization of labor, machines, and hand tools. The division of production into relatively simple jobs would have been necessary to allow rapid training of a great and large labor force, if for no other reason.[40]

Thus, Middleton holds that the great increase in productivity and the reduction of labor cost per unit is the result of technological changes such as standardization of models, introduction of highly specialized hand tools, and gauges. Middleton admits, that the introduction of new methods and new production techniques, that is the rate of adoption of the new methods and techniques, depend largely on the nature of existing situation and to some extent on the traditional methods of the company. It is up to the management, in other words, to change traditional methods.

In the preparation of this study Middleton examined individual plant reports and compared the levels of labor requirements for different kinds of planes. An attempt was made to construct an industry wide production index. This was accomplished by plotting on

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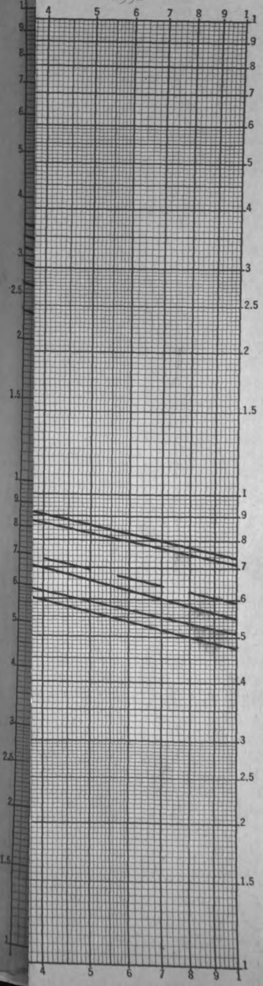
[40] K. A. Middleton, "Wartime Productivity Changes in the Airframe Industry," Monthly Labor Review, (Vol. 61, No. 2, August, 1945), p. 220.



the vertical axis the man-hours per pound of airframe and on the horizontal axis the cumulative production pounds in the particular facility. This method differs somewhat from the conventional method where the units of a particular product are plotted on the horizontal axis. Middleton finds that the decrease in man-hours required per pound is similar for all types of airplanes and therefore, this index which uses the pound quantity as a basis provides a more useful index for comparative purposes. The relative positions are very similar at all points within the range of cumulative outputs for the different plants producing various types of aircraft, although somewhat more man-hours per pound were required for a one engine fighter than for standard four engine bombers.

Middleton admits that it cannot be assumed that airframe weight is an entirely adequate tool in measuring productivity. For example, it is found that more man-hours are required to produce a hundred thousand pounds of combat planes than to produce a hundred thousand pounds of non-combat planes such as trainers. In other words, a hundred thousand pound production of a bomber should have more significance in the index than a similar increase in the production of basic trainers. Nevertheless, Middleton argues that the average direct man-hours cost per pound plotted against cumulative pounds produces a better indicator of the physical value of the work performed than the number of units.

> A general tendency for unit labor requirements to decline by constant percentage every time a plant doubles its cumulative production has often been noted. However, it appears that earlier judgments of the rapidity of this

> decline were unduly conservative. Some credence had been given a standard 20 per-cent reduction (an 80 per-cent curve) in unit labor requirements with each successive doubling of output. The present study indicates that a rate of about 30 per-cent would be a more representative average.[41]

Thus, using the above indicator of productivity, Middleton concludes that it is the 70 per-cent time reduction curve that holds for the aircraft industry during the last war instead of the normally assumed 80 per-cent curve. Middleton found that a considerable variation does exist in the slope of the curve from one plane to another. Whether this variation is of significance, Middleton does not elaborate. However, a visual examination of Middleton's chart Figure 2.4 would seem to indicate that the variation in slope is of some significance.

Daniel W. Carr

One of the writers who believes the time reduction curve should take on the "S" shape is D. W. Carr, who at the time of his writing was associated with McDonnel Aircraft Corporation. Carr does not present any empirical evidence to substantiate his "S" type curve. However, he explains the concavity in this curve as follows: First he assumes that each worker in quality production crews produces along 80 per-cent curve.[42] But since the shifts and the crews are not hired at the beginning of the program, but during the time of acceleration, there is a different slope for each crew depending upon the time that it was hired. Thus, although the curve for the individual crew may be linear function, the sum of the individual crew curves will be concave,

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[41] Ibid, p. 221

[42] G. W. Carr, "Peacetime Cost Estimating Requires New Learning Curves," Aviation, (Volume 45, April 1946), pp. 76-77.

because the new crews are producing the first unit, while the first crew may be producing their tenth unit. This condition produces the concavity in the area "B", Figure 2.5. The steep segment between "B" and "C" according to Carr, is the result of technological improvements in the production function, e.g. a greater improvement in tooling and a break down of airplane into accessible production of sub-assemblies. Quantity built is another factor which determines the steepness of the curve between "B" and "C". The flat area is reached at "D" assuming that no major changes in tooling or production techniques take place. Thus, slopes, "A" and "D" may be used for projection of costs, but ".... is incorrect for budget or actual cost finding purposes. Beyond "D" costs slowly approach optimum."[43]

> Without redesign or additional tooling, there is a definite limit below which operations cannot be performed at reduced man-hours. On fabrication, this limit is reached at any early stage, being governed by the speed of machinery and not by individual skill. In assembly accessibility may establish the minimum hours possible with all operations a flat is reached sooner or later beyond which only negligible improvements may be expected.[44]

Data on post war airframe production does not support Carr's "S" shape curve.[45]

The present study indicates that there is a high correlation of man-hour data to a straight line.

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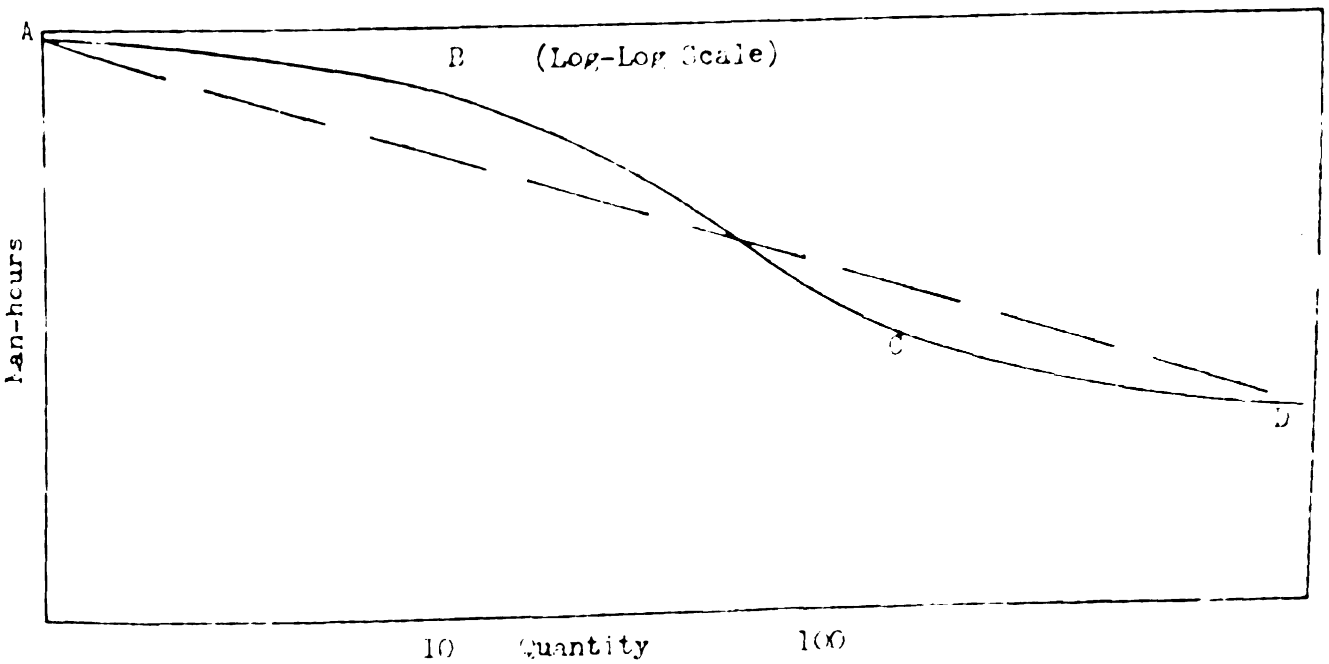
[43] Ibid, p. 76.

[44] Ibid, p. 77.

[45] Information obtained at Headquarters, Air Materiel Command, Dayton, Ohio, (1959).

FIGURE 2.5

AN "S" SHAPE TIME REDUCTION CURVE



Source: Carr, G. W., "Peacetime Cost Estimating Requires New Learning Curves" Aviation
Vol. 45, April 1946, p76

Time Reduction Curves in Great Britain

The first published evidence of time reduction curves existing in Great Britain was indicated by Eric Mensforth in an article published in the October 1947 issue of Aircraft Production.[46] Mensforth was associated with the ministry of aircraft production in the second World War, and has gathered a considerable amount of material on airframe production in Great Britain. Of special interest to us is the British experience with time reduction curves. Mensforth found that British experience was similar to that of American aircraft production. British figures show the same general trend within rough limits of 75 per-cent to 85 per-cent.

> It will be observed that when the same aircraft is made at various factories the man-hours required do fall fairly close to the curves at the same relative period of production development.[47]

Mensforth developed learning curves for various types of aircraft and found that the slope varies, but all models under consideration fall within 75 per-cent to 85 per-cent curve limits.[48] Mensforth considers the peak volume of production to be important in the reduction of man-hours. He feels that required man-hours on relatively small scale production are higher not because different methods are used, but because when the scale of production is greater it permits more specialization and more rapid achievement of full dexterity. As an example, he mentions a case of two factories in Great Britain which were producing the same

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[46] Eric Mensforth, "Airframe Production," Aircraft Production, (Volume 9, October, 1947), pp. 388-395.

[47] Ibid, p. 391.

[48] Ibid, p. 392.

aircraft with similar equipment and tooling. One factory was producing about fifteen planes per week, and the other fifty-five per week. The actual man-hours of the latter were half that of the former, and since both of the factories were on a piece work basis, and the same rate was paid, the earnings of the one producing fifty-five units per week were two hundred per-cent higher. The difference in output per man-hour of British and U. S. workers is explained in terms of different type of tooling employed in the U. S. The American plants used tooling to a much greater extent than their British counterparts.

The Hirsch Study

Werner Hirsch attempted to apply the time reduction curve to production of a large machine builder.[49] The author chose to analyze seven machines, all of which were either new products or new models. Of the nineteen time reduction curves fitted, only five had a correlation coefficient less than .85. The slope of the time reduction curve varied from 79.2 to 83.5 per-cent, depending on the type of machine that was being manufactured. The average slope for the unit curve is 81.5 per-cent. The average for the machining operations was 87 per-cent, and for assembly operations 74.4 per-cent. Hirsch concludes that there is very little relationship between direct labor requirement and scale of production in the machining and assembling of a textile machine and a semi-automatic machine tool. He explains this in part as being due to the fact that both machining and assembling in this situation require relatively fixed combinations of labor and equipment. Although in machining the setting up process is fixed regardless of the number of

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[49] W. Z. Hirsch, "Manufacturing Progress Functions," The Review of Economics and Statistics, (Volume 34, May, 1952), pp. 143-145.

units to be produced at one time, the labor savings or the decrease in labor requirements were found to be very little after twenty lots of five units each, is produced. The author describes this negative labor requirement-cumulative output relation as being due to changes in technical knowledge, which take place as cumulative output increases. The following reasons are given for this decline in labor requirements: (1) progress of direct labor, (2) progress of management, (3) progress of the material suppliers. It is stated that the learning process of the various groups in a firm is highly interrelated.

> Because of this interdependence, management, engineer, and direct labor must be in contact through joint meetings, shop visits for engineer and management, and a suggestion box. A similar effort is needed to benefit from progress outside of the firm.[50]

Hirsch also found that the height of the total direct labor reduction function reappears with little regularity. This is so because the height depends primarily on the complexity of the product. Hirsch concludes that empirical estimates of time reduction function can be used on the firm level as well as the national level for many purposes.[51] Although it is too early to draw any general conclusions with regards to the time reduction function in the machine building industry, it seems that the empirical data gathered by Hirsch is an indication that time reduction curve phenomenon exists in machine building.

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[50] Ibid, p. 147.

[51] Ibid, p. 153.

Reno Cole Survey

This survey was done by Reno Cole[52] the results of this are reproduced in Table 2.1. Because 61 per-cent of the companies surveyed reported that they do use the time reduction curve technique, it seems that this technique has found a considerable acceptance in industries other than airframe. It should be remembered, however, that this survey took place in Southern California where the aircraft industry is a dominant force and where other industries have had an opportunity to adopt this technique from the aircraft companies. The survey was restricted to non-airframe metal product manufacturing industries having three hundred or more employees. As it turned out, however, there is a large concentration of firms that supply the aircraft industry and which do not qualify as an airframe company, but which nevertheless, work closely with defense industry and are in a position where they have to work with the government and the large prime contractors. Cole states that:

> It is interesting that a high percentage of the companies surveyed who reported use of the technique considered it as a necessary part of planning. A considerable percentage of replies were qualified, however, by stating that judgment was required in the use of the technique. This is, of course, true of the application of any industrial technique, but the reply would seem to indicate the absence of a completely comfortable feeling on the part of many who use the cost quantity concept. This undoubtedly due to the limited amount of information available for industries other than airframe.[53]

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[52] Reno R. Cole, "Increasing Utilization of the Cost-Quantity Relationship in Manufacturing," The Journal of Industrial Engineering, (May-June, 1958), pp. 173-177.

[53] Ibid, p. 174.

TABLE 3.1

SURVEY RESULTS OF COST-QUANTITY RELATIONSHIP TECHNIQUE UTILIZATION BY SOUTHERN CALIFORNIA METAL PRODUCT MANUFACTURING INDUSTRIES OTHER THAN AIRFRAME

(a) Do you use the cost-quantity relationship in your manufacturing planning?

	Number	Percent
Yes	28	61
No	18	39
Total	46	100

(b) Have you developed your own data or do you use published data?

	Number	Percent
Use own data	25	82
Use 80% airframe curve	5	18
Total	30	100

(c) What is your opinion as to the usefulness of this technique?

	Number	Percent
A necessity	7	25
Very useful	11	39
Useful but must be used with judgment	10	36
Total	28	100

(d) How is the cost-quantity relation used in your operation?

	Number	Percent
Estimating	13	28
Pricing	11	24
Projecting manpower requirements	7	15
Projecting schedules	4	9
Used for standards	4	9
Facility analysis	2	4
Cost control	2	4
Budgetary control	2	4
Economic lot size	1	2
Total	46	100

Source: Cole, Reno R., "Increasing Utilization of the Cost-Quantity Relationship in Manufacturing", The Journal of Industrial Engineering, (May-June 1958), p. 174.

Stanley E. Bryan

Professor Bryan related the time reduction curve phenomenon to value concepts and collected data on its existence in a consumer goods manufacturing plant. Professor Bryan points out that there is a field of buying in which competition ceases to be the important force in determining prices. The contracting for special and non-standard equipment which is made to customer specifications is an example of this type of procurement. The pricing of this type of goods becomes largely a matter of negotiation. In negotiation, price is normally related to cost to a much greater extent than to the utility of the particular item. Under these conditions, the method of estimating and compiling cost of producing an item becomes all important not only to the buyer, but also to the seller. In the case of the seller there is a multitude of production decisions which are effected by the methods in which the costs are determined.

> In terms of direct labor the first few units of a non-standardized product are built by less efficient methods and so with correspondingly higher direct labor costs than later units. If the manufacturer does not consider the learning curve in his estimate he would quote unrealistically high cost on the labor portion of the contract. If the buyer is not aware of the learning curve phenomenon he would accept the unrealistically high labor costs quoted as being fair, when in reality they would not be fair at all. The learning curve actually helps to explain why a buyer is likely to get widely varying bids that he does on a non-standard production run. Some companies are unaware of this learning curve phenomenon.[54]

Professor Bryan presents time reduction data which was experienced by a new production group in a large company's footwear plant. This

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[54]Stanley E. Bryan, "Value and the Learning Curve," Purchasing, (September, 1954), p. 97.

particular manufacturer of footwear experienced approximately 90 percent slope time reduction curve.

World War II Acceleration of Airframe Production

An analysis of World War II production experience has been made by Crawford and Straus in 1947.[55] The study concerns itself primarily with the acceleration of airframe production, but since the time reduction curve is an integral part of any production program, time reduction curves are given a considerable amount of attention. The author states that:

> These industry and type averages will serve as a valuable aid to mobilization planners in scheduling production for a future M-day. The progress curves obtained during the present study may be used as a guide in conjunction with other planning factors to predict, for instance, the amount of production acceleration which might be reasonably expected for a given production run, and the number of direct man-hours necessary to accomplish mobilization schedules.[56]

The data for this study was derived from the Source Book of World War II Basic Data,[57] and was based on the production data of one hundred eighteen World War II models. Weighted average direct man-hours per pound at specific plane numbers were determined both for the industry as a whole and for each type of airplane. The averages were arrived at by dividing the sum of the direct unit man-hours for the total number of models available at a given cumulative plane number by the sum of the airframe unit weight of the same model. The average values thus

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[55] J. R. Crawford, and E. Straus, World War II Acceleration of Airframe Production, Hq AMC, Dayton, Ohio, 1947.

[56] Ibid, p. 59.

[57] Source Book, op. cit.

determined were then plotted on logarithmic paper and a curve was fitted to the points through the use of the least squares method. The average time reduction curve for all models was 79.7 per-cent. It was probably this study more than any other that established the 80 per-cent curve as standard in the airframe industry. The average time reduction curve slope for the major type of aircraft is reproduced in Table 2.2.

TABLE 2.2

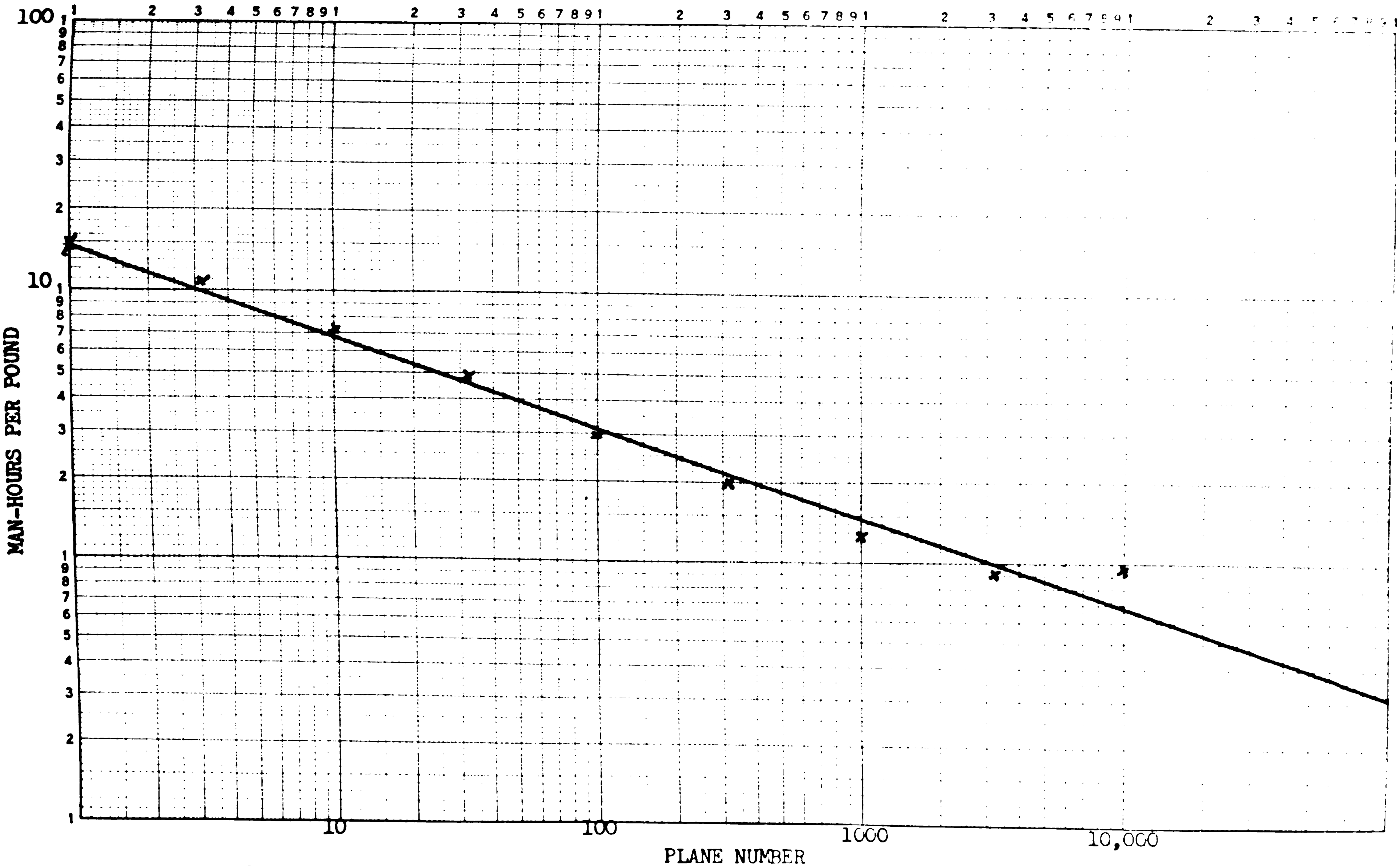
AVERAGE TIME REDUCTION SLOPE
FOR WORLD WAR II
AIRCRAFT PRODUCTION

TYPE OF AIRCRAFT	SLOPE OF TIME REDUCTION CURVE
Fighters	79
Bombers	77
Transports	77

The weighted average curve for each type of aircraft are reproduced in Figure 2.6. Fighter aircraft was the only model for which observations were available beyond 10,000 units. It should be noted that the reason for the flattening out of the average for all models beyond the approximately 3,000 unit figure is the fact that data for the other models were not available beyond this point and since the average consists of fighter aircraft data and because this type of data is consistantly above average bomber and transport curves, a plateau appears in the average curve for all types of aircraft. In the individual curve for all fighter aircraft the time reduction curve continues to decline even after ten thousand cumulative units are reached (see Figure 2.7). The analysis concludes that the type of aircraft is all important in

FIGURE 2.6

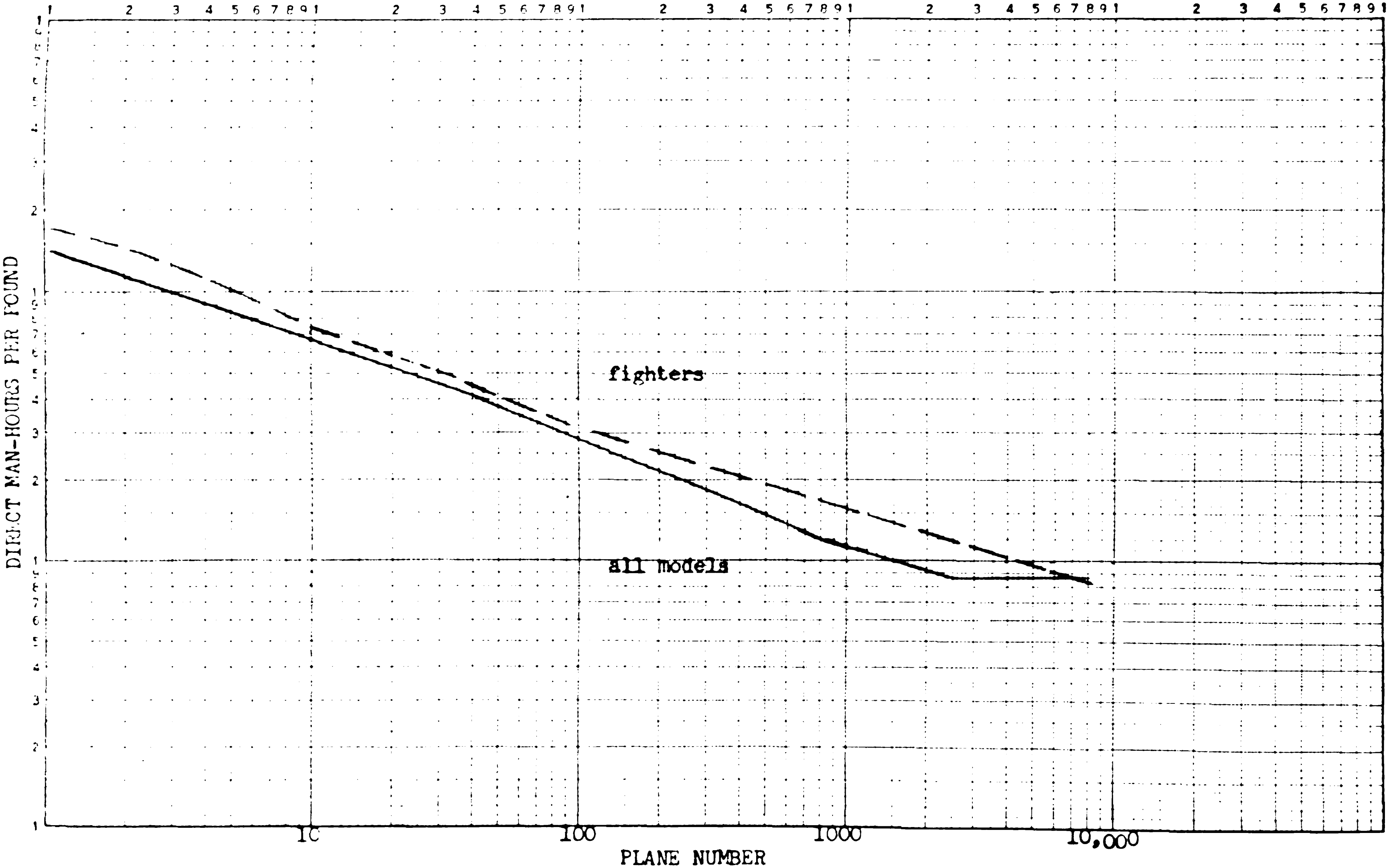
WEIGHTED AVERAGE TOTAL DIRECT MAN-HOURS PER POUND OF AIRFRAME, ALL MODELS, AT SELECTED CUMULATIVE PLANE NUMBERS



Source: Crawford, J. R., And Strauss, E., World War II Acceleration of Airframe Production, Air Materiel Command, Dayton, Ohio, 1947

FIGURE 2.7

TOTAL DIRECT MAN-HOURS PER POUND OF AIRFRAME AT SELECTED CUMULATIVE PLANE NUMBERS WEIGHTED AVERAGES, ALL MODELS AND FIGHTERS



Source: Crawford, J. R., and Strauss, E., World War II Acceleration of Airframe Production, Air Materiel Command, Dayton, Ohio, 1947 influencing efficiency because the complexity, weight or accessibility, will vary from one type of aircraft to another. Other factors such as priority status and production methods used, enter into the picture so that the type of aircraft alone does not satisfactorily explain the difference in the record man-hour efficiency between models and types. According to the authors the other two important factors are: (1) stage of development of the model, and (2) the amount of experience that a given facility has had. A new model in an inexperienced facility will normally cost more than a proven model and experienced facility.[58]

In addition to the three main factors which have been found to be responsible for deviations from the linear time reduction curve, that is type of aircraft, newness of the model, and newness of the facility, there is one other major factor which according to the authors, overshadows all others in causing variations. This fourth major factor is described as the particular circumstances and problems that surround production of each individual model. Some of the specific circumstances and problems surrounding the production of a given model are listed by the authors as: (1) the length of the production run, (2) whether or not the model has been engineered for mass production, (3) whether or not proven engineering was available when production started, (4) whether or not high production was started from low production tools, (5) introduction of design changes, (6) whether or not old tools were available when production started, (7) availability of

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[58]*Ibid*, p. 84.

materials or component parts, (8) availability of experienced man-power, (9) relative priority attached to a given model, (10) efficiency of operating controls, (11) frequency of scheduled changes and degree of pressure attached to a program, (12) economical and uneconomical use of outside production, (13) degree to which feeder plants and out-lying areas were utilized in order to tap a wider labor market, (14) whether or not the plant layout was favorable to the production of a particular model and (15) availability of specialized high production machinery. The authors state:

> Each of these factors affect direct man-hour costs. In the final analysis, foresighted management can minimize the effect of these factors, and can, in many cases, even prevent their appearance as a problem. It would be extremely difficult to attempt to measure the effect of individual circumstances or to weigh direct labor progress curves and industry average for these factors. In fact, in some cases it is not possible to isolate all of the circumstances which affect direct man-hour costs of a particular model. In spite of drawbacks, the industry average as established in this section, presents a reliable picture of the relationship of direct man-hours per pound to cumulative acceptances during World War II. They include the cumulative effect of all the individual circumstances which surrounded the production program, for each model.[59]

Company Publications

In addition to the many individual contributions to the time reduction curve technique, many of the companies using this technique have published manuals, booklets, or handbooks for the instruction of their own personnel. It should be remembered that most of these publications, as a rule, do not contain any empirical data to support statements made, but presumably, the statements are based on company

[59] *Ibid*, p. 91.

"experience." One of the earliest company publications available is the booklet published by the Boeing Aircraft Company in 1945, entitled The Experience Curve.[60] This short booklet presents a concise statement of the unit curve, the cumulative average curve and the total curve as they were used by Boeing Cost Accounting Department. The authors make what is the first allusion to the hump curve in the following paragraph:

> Experience has shown that the 80 per-cent experience curve is a pretty good average for airplane production, although specific planes or items may vary considerably from the 80 per-cent curve. In many cases more than normal preparation has been made before starting production, and this often causes what is termed a hump in the curve, the first unit starting low and the decrease to the next few being less than normal until this flatter curve meets and follows a normal curve. The method of handling a hump curve depends upon the results desired.[61]

An interesting illustration of what is a man-hour is presented in this study. The analysis of the man-hour as cumulative production increases is presented in Figure 2.8. It shows that the time devoted to production increases as cumulative production is increased. Many of the activities which infringe on production time are eliminated as the units produced are increased. In addition, this pamphlet provides an excellent mathematical presentation and development of the time reduction curve. The second publication by Boeing Aircraft Company was authored by Brown,[62] at the Boeing Training Department.

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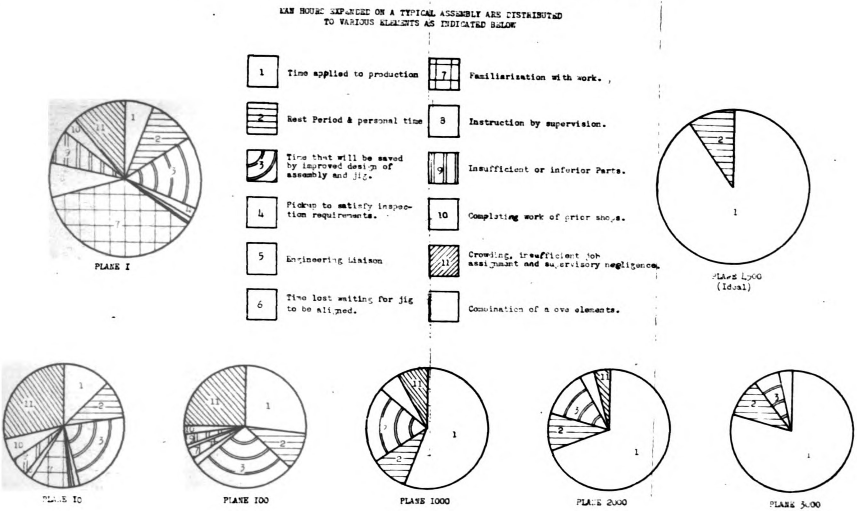
[60] Gordon W. Link and Don A. Ellis, The Experience Curve, (Wichita, Kansas: Boeing Aircraft Company, December, 1945).

[61] Ibid, p. 4.

[62] William F. Brown, The Improvement Curve, (Wichita, Kansas: Boeing Airplane Company, March, 1955).

FIG. 2.8

WHAT IS A MAN-HOUR?



Source : **LINK, G.W and ELLIS, D.A.**

THE EXPERIENCE CURVE , BOEING AIRCRAFT CO. ··· WICHITA, KANSAS

The manual presents the learning curve, as it is used by Boeing, in relatively easy to understand form. An interesting statement is made by the authors relative the rate of improvement as large cumulative quantities are produced. In speaking of manufacture of automobile bodies, the authors say:

> If a manufacturer has built three million bodies, and was building them at the rate of 500,000 a year, it would take him six years to double his cumulative total quantity of units produced. If he were operating on an 80 per-cent curve, his six millionth unit would cost him 80 per-cent of his three millionth unit, this would mean that it would take six years to gain 20 per-cent improvement an average of approximately 3 per-cent per year. Doubling production when you make 350,100 or 1,000 items is accomplished in a relatively short time; doubling production when you are producing in the millions takes years.[63]

This is clearly contrary to the opinion held by the Boeing personnel in the past, which was: after a certain number of units have been produced, the time reduction curve would reach 100 per-cent slope or in other words, a horizontal position. Boeing now holds that whereas time reduction continues to take place even after a large cumulative numbers of production have been reached, this reduction will be insignificant and may take a long time to realize. There is still another paper published by the Boeing Company on the time reduction curve.[64] This was published by the Boeing Airplane Company, Seattle, Washington Division, and consists almost entirely of the description of application of the improvement curve technique. It should be noted that all three publications by the Boeing Airplane Company

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[63] Ibid, p. 6.

[64] Roy W. Smith, William C. Lansing, and Henry G. Horton, Improvement Curve Handbook, (Seattle, Washington: Boeing Airplane Company, 1956).

follow the Boeing unit curve theory, which will be explained in greater detail in Chapter 3. An extensive development of the Wright type time reduction curve may be found in the publications of Chance Vought[65] and Northrop Aircraft.[66] Both of these works were prepared to train company personnel in the application of the linear cumulative average curve, and would be of interest to those who prefer the mathematical instead of the graphical method of derivation of the time reduction curve. Morgan is the author of the booklet published by the Glenn L. Martin Company,[67] which is also designed to instruct its personnel in the use of the cumulative average curve. It should be noted that this Martin publication is similar to that of Northrop and Chance Vought in that all three of these company publications use the Wright time reduction curve which will be discussed in greater length in Chapter 3. North American Aviation has two publications; both of them were prepared for the instruction of the purchasing personnel in the use of the learning curve in procurement of subcontracted parts. The first work is entitled Improve Your Buy,[68]

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[65] E. A. Rutan, Theory of the Learning Curves, (Dallas, Texas: Chance Vought Aircraft Company, 1948).

[66] W. A. Raborg, Jr., Mechanics of the Learning Curve, (Hawthorne, California: Northrup Aircraft Company, 1952).

[67] A. W. Morgan, "Experience Curves Applicable to the Aircraft Industry," (Baltimore, Maryland: The G. L. Martin Company, 1952).

[68] E. J. Blume, and R. E. Norris, Improve Your Buy, (North American Aviation, Inc., n.d.).

and the second one is Purchasing With the Learning Curve,[69] the latter being primarily a revision of the former. Purchasing With the Learning Curve is a concise statement of how a purchasing agent may apply the learning curve to the many procurement problems which arise in the course of his duty. The latest of company publications on the subject of the learning curve was published in 1958 by McDonnel Aircraft Corporation.[70] The distinctive features of this company manual is that McDonnel Aircraft Corporation uses a straight line for both the average and the unit curve. McDonnell Aircraft Corporation prefers to use the parallel lines because only one set of progress factors are necessary, and can be used to determine either the cumulative average or the unit average trend. The company claims that the accuracy is retained because for estimating purposes, only the mid-point is of importance.[71] Thus, McDonnell uses a straight cumulative average curve and a straight unit curve. The unit curve is displaced by the ratio of one minus the exponent of the basic curve equation. Of interest in this manual is the use to which the time reduction is being put by McDonnell Aircraft Corporation. The authors state:

> Many different types of costs pertaining to air-frame design, construction or manufacture appear to fall in a pattern that is amenable to a progress slope type of analysis. Engineering carry on, or cost after first flight, will plot to a line conforming generally to the basic equation of a progress curve. Tooling cost after peak rate tooling has been completed, including costs such as tool maintenance, facility type changes

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[69] E. J. Blume, and Donald Peitzke, Purchasing With the Learning Curve, (Columbus, Ohio: North American Aviation, 1953).

[70] A. Anzanos, R. M. Field, and R. E. Lorenz, Contract Estimating Progress Curves Factors and Application, (St. Louis: McDonnell Aircraft Corporation, 1958).

[71] Ibid, p. 4.

> etc., will also plot on this type of line. These trends will hold true until the calendar time is reached at which the project staff has been cut back to an irreducible minimum, at which time cost of engineering man-hours per airplane will become constant. Certain types of material costs will also vary with quantity based on an extremely shallow progress curve.[72]

The balance of the manual deals with the application of the progress curve techniques to the various manufacturing problems.

Most of the material in the company publications is rather repetitious and similar to Wright's formulation, and, therefore, was not discussed at very great detail.

The Rand Studies

The Rand Corporation of Santa Monica, California has prepared several studies for the Air Force which should be of interest to those interested in industrial time reduction curves. Alchian has prepared a brief statistical report on The Reliability of Progress Curves in Airframe Production.[73] In regards to the time reduction curve, Alchian poses the following question: (1) How long does this time reduction continue? (2) Can it be represented by a linear function on double log scale? All data used in this study was derived from the Source Book of World War II Basic Data: Airframe Industry, Volume I, which was prepared by Air Materiel Command at Wright Field. To the first question Alchian answers as follows:

> In every case there was no evidence of any cessation of a decline. This conclusion is based on visual examination of the graphs presented in the Source Book. No elaborate statistical analysis

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[72] Ibid, p. 4.

[73] Armen Alchian, Reliability of Progress Curves in Aircraft Production, (Santa Monica, California: The Rand Corporation, 1950).

> appears to be needed to answer this question, given the available data. Whether or not the decline would cease at substantially larger numbers could not of course be determined.[74]

In an attempt to answer the second question, namely whether the linear function is appropriate, the author finds that available observations are not sufficient to be a good test of the linear hypothesis. Since no acceptable alternative hypotheses were available to the author, he felt it would be best to postpone such tests until adequate observations were available. It should be added, that coefficients of correlation for the accumulated data exceeded .90 in sixty cases, e.g. the model facility combinations, and exceeded .80 in at least six other cases.

Another Rand report which was prepared by Hoffman[75] attempts to evaluate the modified form of the aircraft progress function, as suggested by the Stanford Research Institute. It was Hoffman's purpose to determine whether the progress curve, as suggested by Stanford's Research Institute and which includes the Beta factor, or in other words, includes an additional parameter, is superior over the original, and the more simple form of the curve in terms of the fit of the curves to the observed data. The equation $Y = ax^b$ was fitted to several series to which Stanford Research Institute had applied their formula containing the Beta factor, which reads $Y = a(x+B)^b$. The square logarithmic deviations from the several curves were obtained and compared. Hoffman concludes that:

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[74] Ibid, p. 6.

[75] F. S. Hoffman, Comments on the Modified Form of the Aircraft Progress Functions, (Santa Monica, California: The Rand Corporation, October 4, 1950), p. 6.

> There appears to be little basis for choice between the restricted form of the Stanford Research Institute curve and the original form of the curve.[76]

In several cases, the inclusion of this third parameter or the "B" factor did result in smaller sums of squared deviations, but because of the assembling problems, Hoffman feels that it is impossible to determine whether the improvement justifies the fitting of the "B" factor or even whether the Stanford curve is a true functional form in this case. An analysis of the residuals about the curve shows that these are serially correlated and follow a pattern which indicates that the Stanford curves are not sufficiently convex upward to describe the series.

One of the most recent Rand studies was prepared by Harold Asher.[77] Asher attempts to show that the time reduction curve in linear terms does not represent an accurate description of the relationship between unit man-hours and the cumulative output. To show that the time reduction curve is non-linear after a certain cumulative production number has been reached, Asher examines hourly data for a number of different departments. It is concluded that linear approximation is reasonable for all departments for an initial quantity of airframes, however, the different departments exhibit non-similar slopes for these linear segments. Asher states that:

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[76] Ibid, p. 1.

[77] Harold Asher, Cost-Quantity Relationships in the Airframe Industry, July 1, 1956, op. cit.

> This act alone is sufficient to cast doubt upon the validity of the hypothesis that the sum of the four shop group curves is linear.[78]

In addition, the author claims that data for the departments which were considered by him showed a departure from linearity in many cases even before unit 1,000 was reached. Asher then proceeded to sum the department curves. The sum unit curve shows that it begins to level off at approximately unit 125, and the author claims that if a linear extrapolation was made between units 100 to 1,000, the estimating error would be about 25 per-cent.

> It is safe to conclude, on the basis of the admittedly limited samples examined in this study, that the conventional linear progress curve is not an accurate description of the relationship between unit cost and cumulative output. Beyond certain values of cumulative output, both the labor and the production cost curves develop convexity.[79]

The above conclusion is probably premature for a number of reasons. First, Asher's analysis of the nine fighter aircraft models is too small a sample to draw any definite conclusions. Second, although mathematically it is entirely true that downward sloping linear curves which have different individual slope value will eventually cross, and, therefore, the total will level off. This overlooks the dynamic nature of a production function. In direct opposition to the conclusion made by Asher, World War II production experience even in the cases of fighter airplanes which were built in large numbers does not show a convexity at later stages. This has been

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[78] Ibid, p. 97.

[79] Ibid, p. 129.

substantiated in the Hoffman study in the above paragraphs. When static assumptions are made relative the production function, we may well expect a limit beyond which there is no improvement, and the curve becomes horizontal. In his conclusions Asher states:

> The linear curve is also useful for making extrapolations beyond unit 300, provided that the number of additional units to be produced is relatively small.[30]

He does not give any specific unit where the curve assumes convexity. In another point, Asher states that:

> It is clearly a matter of judgment whether or not in a specific instance the linear curve is appropriate.[31]

Neither the Air Force nor the airframe industry have accepted Asher's views on the linearity of the time reduction curve.

The Stanford Studies

Under contract with the United States Air Force, Air Materiel Command, the Stanford Research Institute made a study on the Relationships for Determining the Optimum Expansibility of the Elements of a Peace-Time Aircraft Procurement Program, this study was undertaken to determine the means of measuring the maximum rates in aircraft production programs. Since the maximum expansibility rates depend to a large extent on the rate of manufacturing time reduction, a decision was made to analyze the direct man-hour time reduction curve. According to the final report the project has resulted in:

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[30] Ibid, p. 129.

[31] Ibid, p. 129.

> An improved relationship involving direct man-hours, airframe unit weight and accumulative acceptances.[82]

An attempt is made to show that although the conventional formulations of the time reduction curve are represented by a straight line when plotted on logarithmic scales, a new characteristic called the "B" factor which when included in the formula, seems to describe the existing empirical production data more adequately than the straight line function for either the unit or cumulative average relationship.[83] The "B" constant, which the study suggests, is the measure of all complexities that exist in any plant relative to a given model before the model is actually produced. The thirty cases studied led to the conclusion that the data tended to deviate from a straight line when plotted on double logarithmic scales and that it tended to follow a convex shape in the upper area, particularly during the early part of the program.

There are only a few cases where time reduction curve data can be described more adequately by the introduction of the "B" constant into the conventional time reduction curve equation.[84] The time reduction curve users report that in these cases a straight line is not used, but neither is the "Stanford equation." Usually, a free

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[82] <u>Relationships for Determining the Optimum Expansibility of the Elements of a Peace-Time Aircraft Procurement Program</u>, Stanford Research Institute, Stanford, California, August, (1949), p. 4.

[83] <u>An Improved Rational and Mathematical Explanation of the Progress Curve in Airframe Production</u>, Stanford Research Institute, Stanford, California, August, (1949), p. 5.

[84] Hoffman, <u>op. cit.</u>, p. 2.

hand curve may be fitted to the data. We may only add at this point that the Stanford equation has not achieved popularity among the users or the students of the time reduction curve. Hoffman's analysis of the modified Stanford equation certainly casts doubt on the broader application of this variation.[85]

Summary

The reduction in time requirement experienced as quantities produced increase is one aspect of economic progress. Industrial psychologists have used the term learning curve to describe on the job learning of an individual worker. Many companies still use the term to denote the time reduction curve. The conventional shape of a worker's learning curve is a rapid rise at the beginning, then a slow rise until a plateau is reached. Whether there is a plateau on a long-term basis is debatable. A number of studies have shown that for the periods observed a definite leveling off in learning of an industrial task was evident.

This study shows that time reduction takes place over extended time intervals and also after large quantities of a product are manufactured. It appears that individual learning on the part of the worker is an important factor in the time reduction during the early stage of a production program. As yet the factors and their influence on time reduction have not been measured. Available information indicates that the time reduction curve cannot be attributed

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[85] Hoffman, op. cit., p. 1.

to any one factor of production. The curve summarizes progress or "learning" of the organization as a whole.

Although the manufacturing time reduction curve has been discovered in 1922, it was largely unknown until World War II. Wartime airframe and shipbuilding man-hour data was studied by a number of writers. Each study tends to substantiate significant time reduction as quantities manufactured increased.

T. P. Wright is given credit for originating the time reduction curve. His statement that cumulative average man-hours per unit decline by a constant percentage every time the quantity produced is doubled, is still the most popular formulation in existence. A number of attempts to change the concept have not been successful.

A recent regional survey reports that 61 per-cent of non-airframe metal product manufacturing companies contacted use the time reduction curve in manufacturing planning. The curve has been reported to exist in construction machinery, shoe, and other production situations.

In Chapter 3, theoretical considerations of the time reduction curve will be discussed.

CHAPTER III

THEORETICAL CONSIDERATION OF THE TIME REDUCTION CURVE

The Time Reduction Curve Theory

Analysis of World War II production experience has shown that the cumulative average hours per unit follow a predictable relationship which results in a hyperbolic function when plotted on arithmetic paper, and in a linear function when plotted on log-log graph paper.[1] The theory of the time reduction curve most frequently in use states that as the total quantity of output of a given product doubles, the total input of direct man-hours necessary for the production of the second half of the total declines by a constant and predictable percentage. Thus, if the first unit requires 1,000 hours to produce, the second unit will require 800 man-hours, the fourth 640 man-hours, and 512 man-hours for the eighth unit (assuming the existence of an 80 per-cent cumulative average time reduction curve).

TABLE 3.1

Unit No. of Product X	Required Man-hours per Unit
1	1,000
2	800
4	640
8	512
16	409.6
32	327.7
64	262.1

The cost per unit may be either the cost of individual unit, or it may be the average cost of a given number of units. The first is known as the unit average time reduction curve, and the second as the cumulative average time reduction curve.

[1] J. R. Crawford and E. Straus, op. cit., p. 56.

The fact that as a particular operation is performed repeatedly the time required to perform this operation declines has been known for a long time. The manufacturing organization beginning with the individual employee becomes more efficient each time a process or operation is repeated. There are many factors which increase the productive efficiency, and this may explain the recurring decline in direct man-hours. We shall discuss some specific factors in greater detail in Chapter 7. Among the more important causes of declining man-hours appear to be job familiarization by workman, improvement in plant organization and coordination, development of more efficient parts supply system, and development of more efficient tools and production techniques.

The time reduction curve is merely a statistical tool which is used in some firms to predict the various requirements necessary to produce a given amount of goods. The more times a given task is performed, the less time it takes, but time reduction becomes less with each successive unit.

Assumptions

Although the present writer has not been able to find any explicit assumptions in the presently available studies, a number of them are implied, and a user of the time reduction curve theory should be familiar with them. First, the above formulation of the time reduction curve theory assumes that the time reduction trend once established will continue for the quantity of production for which the man-hours are being determined. That forces responsible for the improvement tendency in the past will continue to exist in the future. The second assumption which must be made is that the unit on which factor effort is expended remains constant throughout the program. This would exclude any major changes

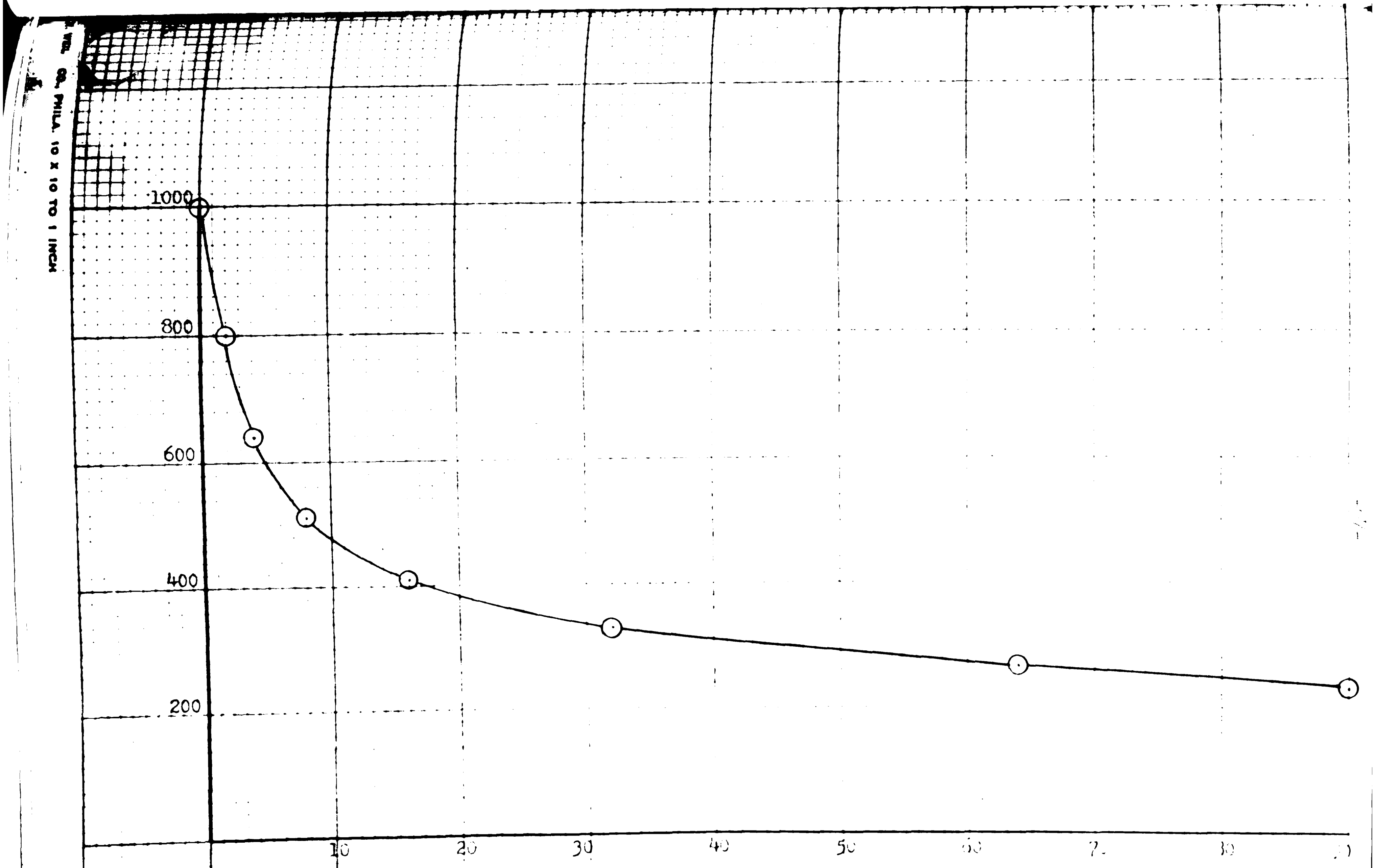

Fig. 3.1 - An 80 per cent time reduction curve on arithmetic scale
Source: Table 3.1 (Hypothetical data)

that would necessitate either an increase or decrease of man-hour requirements per unit. Third, it is assumed that there are no significant changes in labor turnover.

Fourth, it must be assumed that while production is in progress, there are no time breaks in the sequential units. This excludes the possibility of any unplanned changes in the production flow. An example of this may be a sudden termination of a defense contract or a major accident which would seriously affect the normal production activity.

How reasonable are these assumptions? A detailed discussion and empirical analysis will be taken up in Chapter 5 of this study; here we shall only make some of the more evident observations.

It is probably reasonable to expect that some of the forces which were at work in the past to continue in the future. The assumption that the unit on which effort is expended remains unchanged is made solely for convenience and is seldom true in practice. The turnover of labor is usually unchanged except in cases where a program is accelerated, and a large percentage of new inexperienced employees are hired. Major interruptions of production such as major accidents, should be considered as exceptions, which do not happen with predictable frequency, and may well be disregarded for our purposes.

The Time Reduction Curve on Arithmetic Paper

The time reduction curve may be illustrated on arithmetic graph paper. For this purpose, let us consider the 80 per-cent slope time reduction curve. Table 3.1, above, shows the man-hours required for a hypothetical product as the quantities produced are doubled.

Let us plot these man-hours expended on arithmetic paper (Figure 3.1). A connection of the plotted points results in a true curve and illustrates the reduction in man-hours as succeeding units are produced. The reader may note the sharp decline in the curve at first, and then a gentle slope downward as the percentage of improvement is distributed over a larger and larger base of production, and an increasing period of time between doubled quantities.

The horizontal axis of Figure 3.1 shows the number of items that have been produced. The numbers along the vertical axis of the graph represents the required man-hours to complete each item. From the graph in Figure 3.1 we can easily determine the number of man-hours required to produce any unit between one and sixty-four. The graph could be extended so that the curve may include any number of units desired. Even though the percentage of improvement between doubled quantities is constant in Figure 3.1 (30 per-cent), this fact is not apparent from simple observation. Another disadvantage of the curve, as portrayed in Figure 3.1 is found when we attempt to extend the curve for several thousand units, the graph paper would be overly long. Also, construction, interpretation, and projection of the curve on arithmetic paper would be most difficult. Referring to Figure 3.1 again, the sequence or unit numbers increase in geometric progression, the variable factor decreases in geometric progression. Consequently, to interpret the time reduction curve would require knowledge of analytical geometry and extensive computation. For these and other reasons the arithmetic paper is seldom used to present the time reduction curve.

The Time Reduction Curve on Log-Log Graph Paper

The major difference between arithmetic and logarithmic graph paper is that logarithmic paper (log-log) is so designed that the vertical and horizontal distances between doubled quantities are equal. That is why

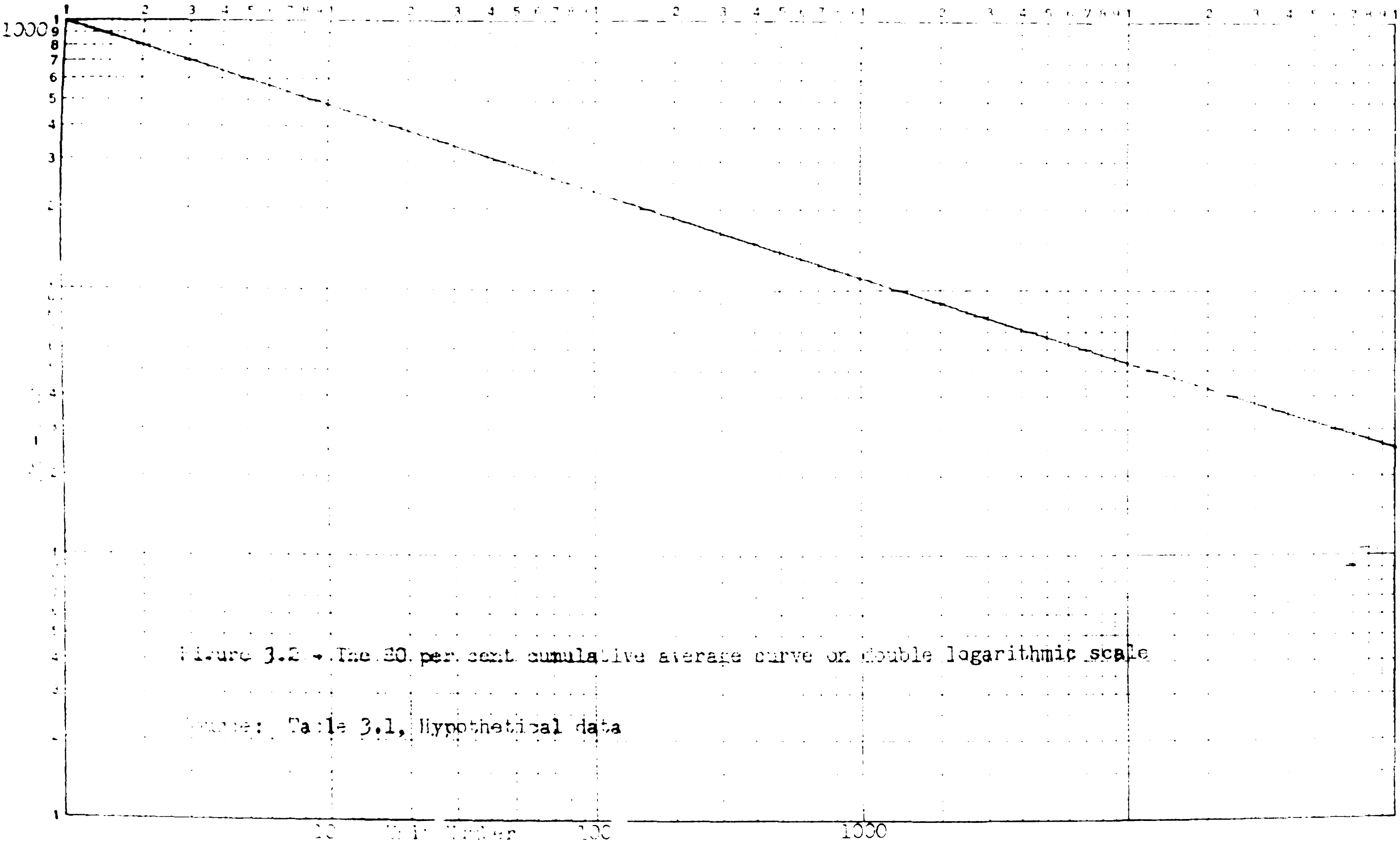

Figure 3.2 - The 80 per cent cumulative average curve on double logarithmic scale

Source: Table 3.1, Hypothetical data

when a case of constant percentage of improvement is assumed the curve becomes a straight line on log-log paper. The distance between one and two is the same as the distance between two and four, or one hundred and two hundred, or one thousand and two thousand, etc.; this is so on either axis.

Figure 3.2 shows that hypothetical data assumes a straight line when plotted on log-log paper. A line in this form is not difficult to project and interpret. The line may simply extend the approximate time required for any unit read. The curve in Figure 3.2 appears to be decreasing too rapidly. This visual illusion is actually due to the fact that on the log-log paper the scales are expanding, and the curve is declining at a decreasing rate, and therefore, for practical purpose it approaches zero at infinity. Mathematically, it is quite impossible for the time reduction curve to reach zero since this value does not exist on logarithmic paper.

The Boeing Unit Average Curve Concept

There are two basic approaches to the time reduction curve technique. The first may be called the Boeing unit average curve[2] theory, and the second the Wright cumulative average curve theory.

The unit average theory used by Boeing[3] is based on the proposition that there is an improvement of 20 per-cent between doubled

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[2] The name Boeing unit curve theory is used primarily because Boeing is the only major firm to use the concept.

[3] For a detailed discussion see Improvement Curve Handbook, Boeing Airplane Company, 1956.

quantities. According to this formulation if the first unit has cost one hundred man-hours, the second unit will cost only eighty hours, and the cumulative average man-hour cost for the two units will be ninety man-hours. Column two of Table 3.2 shows that the rate of improvement is constant between doubled quantities. The foregoing may best be illustrated through the use of a table and a graphic presentation of the values contained in Table 3.2.

The values for Table 3.2 were obtained through the use of the factor tables in the Boeing Handbook and simple calculations. The factor value may be read for the various time reduction curve slopes. The cumulative total cost is merely a summation of the individual unit cost. The cumulative average cost column, is obtained by dividing the cumulative total cost column by the cumulative number of units produced.

In the absence of readily computed factors for the different slope time reduction curves, the values in Table 3.2 may be derived by the use of the following formulae:

1. The unit curve values may be derived from

$$Y=ax^b \qquad (1)$$

where

"x" is defined as the cumulative unit number.

"a" represents the direct man-hours for unit number one.

"b" is a negative fraction which defines the slope, or the rate of improvement;

"Y" represents the direct man-hours for a given unit number.

Thus when X equals 1, then Y equals a.

2. The cumulative total equation is:

$$\text{cumulative total} = \frac{a}{b+1}\, x^{b+1}. \qquad (2)$$

This is merely the integral of the unit curve equation.

TABLE 3.2

VALUES FOR THE BOEING UNIT CURVE

UNIT NO.	UNIT HOURS	CUMULATIVE TOTAL HOURS	CUMULATIVE AVERAGE HOURS
1	100.00	100.00	100.00
2	80.00	180.00	90.00
3	70.20	250.20	83.40
4	64.00	314.20	78.55
5	59.56	373.77	74.75
6	56.17	429.94	71.66
7	53.45	483.35	69.05
8	51.20	534.59	66.82
9	49.29	583.89	64.88
10	47.65	631.54	63.15
20	38.12	1,048.50	52.42
30	33.46	1,402.00	46.73
50	28.33	2,012.17	40.20
100	22.71	3,265.08	32.65
200	18.16	5,272.00	26.36
500	13.52	9,334.73	19.73
1000	10.82	15,867.09	15.87

Source: Unit hour data obtained from the Boeing Tables of curve slope values, published by the Boeing Aircraft Company, Wichita, Kansas, (n.d.), columns three and four were computed.

3. The cumulative average values may be obtained by dividing the cumulative total equation by the number or units or

$$C.A. = \frac{a}{b+1} x^{b}$$

In practice, analysis is confined to the graphic method. This consists of constructing a curve for the applicable slope and then reading off the values at various cumulative quantitites of output. This method does not yield exact accuracy. It is believed that only three point accuracy can be obtained from reading logarithmic graph paper. In many estimating situations the graphical method will provide sufficient accuracy and, because of its simplicity, is the preferred method.

When the Table 3.2 data is plotted in Figure 3.3, it is obvious that the unit curve and the cumulative average curve take different paths. The cumulative average curve is always above the unit curve since the preceeding values always tend to raise the cumulative average curve. We should note that even though the cumulative average line is plotted on log-log paper, it does not begin to approach a straight line until about twenty units have been produced. At the beginning the cumulative average line in the Boeing system is actually a curve, and therefore is more difficult to plot and interpret than the unit curve. The projection of the Boeing cumulative average curve can be easily distorted in the initial stage of the curve, and its use is undesirable when projecting up to twenty units. Mathematically, the cumulative average will never exactly parallel the unit curve, although it will approach it closely after twenty units have been produced so that for practical purposes they may be considered parallel. The important point to keep in mind is that the unit curve is a straight line

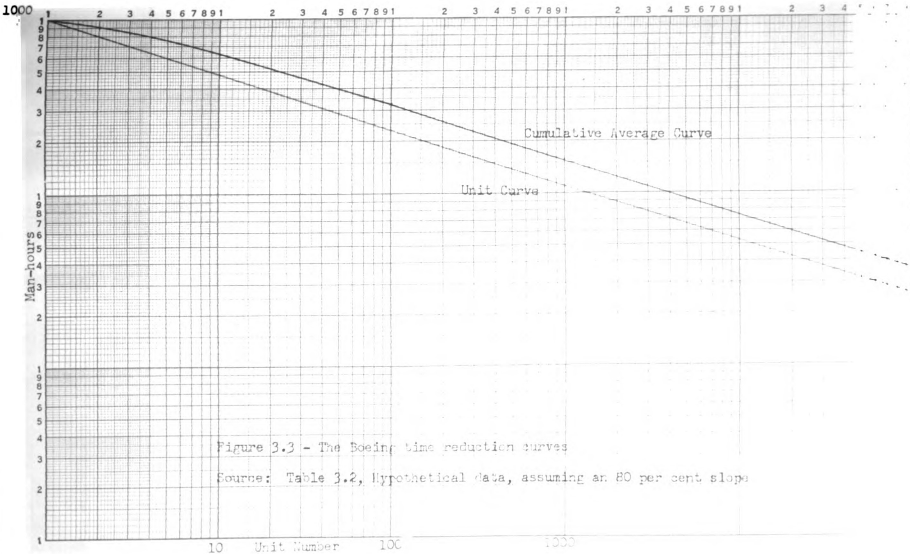

Figure 3.3 - The Boeing time reduction curves

Source: Table 3.2, Hypothetical data, assuming an 80 per cent slope when plotted on log-log paper and the cumulative average line is developed.

The Wright Cumulative Average Curve Concept

The Wright cumulative average curve is based on the hypothesis that as the number of units produced doubles, the cumulative average man-hours required to manufacture the units will decline by some constant percentage.[4] Table 3.3 below illustrates the values for the Wright time reduction curve theory. Assuming an 80 per-cent slope of time reduction, if the first unit cost one hundred man-hours, the second unit curve will cost only sixty man-hours; the average cost for the two units is eighty hours.

When the unit cost and the cumulative average cost columns of Table 3.3 are plotted on log-log paper in Figure 3.4, it is the cumulative average curve that is represented by a straight line from unit number one. The unit line is now curved for about the first ten units of output. After that the unit line approaches a parallel position, without actually ever reaching it. Thus, using this concept of the time reduction curve, the cumulative average curve is now the preferred method of projecting the man-hours for the first twenty units. For those preferring the mathematical method, the following equations for the curves based on the Wright concept may be used:

1. The unit curve values may be derived from: $Y=(b+1)\ ax^b$ with all the symbols still representing the same variables.

2. The cumulative average values may be derived from: $Y = ax^b$. It will be recalled that this formula is identical to the one used to derive values for the Boeing unit curve, and this is possible because the

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[4] The reason for this designation is that this concept was originally purposed by Wright, and is still in use by most firms.

TABLE 3.3

VALUES FOR THE WRIGHT 80 PER-CENT CUMULATIVE AVERAGE CURVE

UNIT NO.	UNIT HOURS	CUMULATIVE TOTAL HOURS	CUMULATIVE AVERAGE HOURS
1	100.00	100.00	100.00
2	60.00	160.00	80.00
3	50.63	210.63	70.20
4	45.37	256.00	64.00
5	41.82	297.82	59.56
6	39.19	337.01	56.17
7	37.13	374.14	53.45
8	35.46	409.60	51.20
9	34.05	443.65	49.29
10	32.86	476.51	47.65
20	26.06	762.42	38.12
30	23.02		33.46
50	19.31	1,419.14	28.38
100	15.42	2,270.62	22.71
200	12.33	3,632.99	18.16
500	9.17	6,762.32	13.52
1,000	7.34	10,819.71	10.82

Source: Cumulative average hours obtained from the Boeing Tables of curve slope values, published by the Boeing Aircraft Company, Wichita, Kansas, (n.d.), columns two and three were computed.

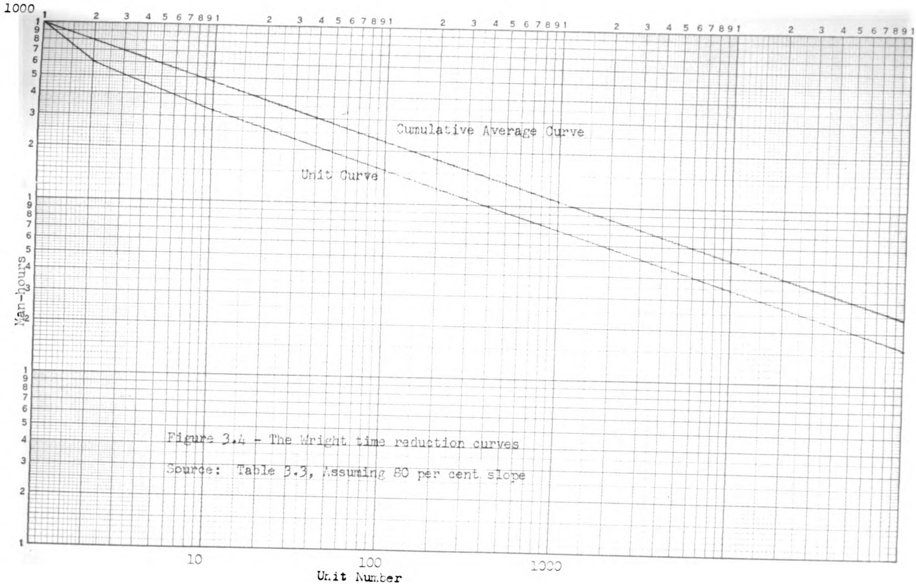


Figure 3.4 - The Wright time reduction curves

Source: Table 3.3, Assuming 80 per cent slope cumulative average curve in this formulation is a straight line on logarithmic paper.

3. The cumulative total equation is still: $c.t. = \frac{a}{b+1} x^{b+1}$.
The graphic method of computation suggested in connection with the Boeing curve, holds true in the case of the Wright curve as well.

<u>The Alternative Time Reduction Curve Theories</u>

Examination of Table 3.2 and 3.3 will reveal that the straight line values in the two theories are identical. Plotting the values contained in Column two of Table 3.2 and Column four of Table 3.3, will result in a single straight line for both formulations. This result may be observed in Figure 3.5. It will be recalled that although the value at specific quantities and the position of the straight line is identical, the Boeing theory claims that these values are for the unit line, whereas the Wright theory assumes that the straight line represents the cumulative average values. It is evident that there will be a different result in the cumulative average and cumulative total values when an 80 per-cent slope is assumed and when both methods are applied to identical unit number one value. The cumulative total and the cumulative average values at 1000 units are about 50 per-cent higher in the case of the Boeing method. In other words, given an identical unit number one value the Wright method will show about 50 per-cent greater improvement than that found in the Boeing method.

The large difference in cumulative results is primarily due to the fact that in the above example both the unit and the cumulative average curves are treated as linear functions. This is illogical

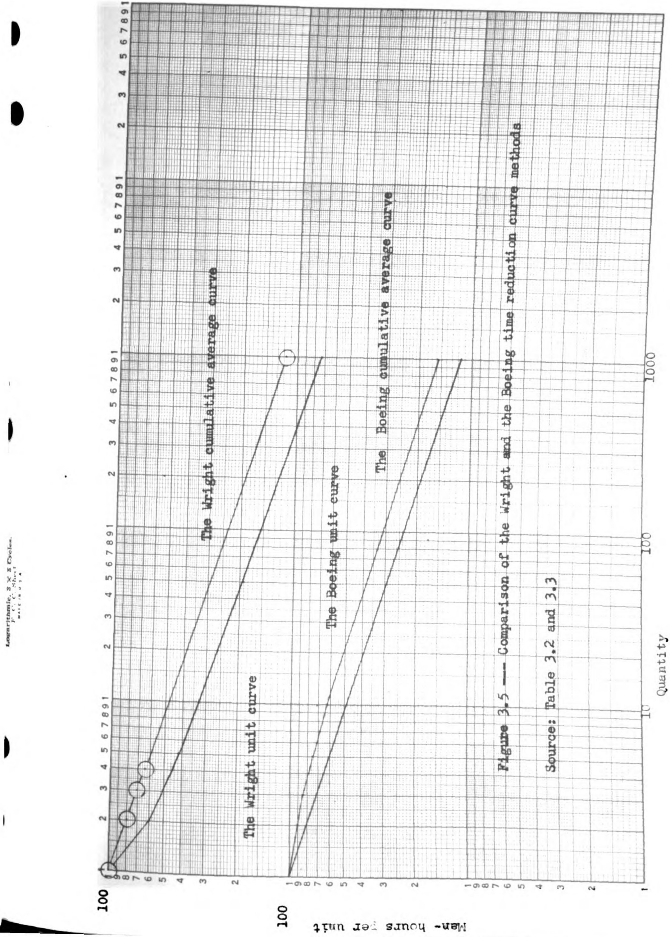


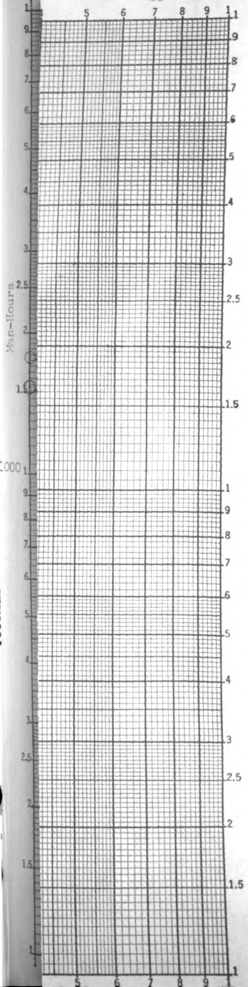
Figure 3.5 — Comparison of the Wright and the Boeing time reduction curve methods

Source: Table 3.2 and 3.3

from the mathematical point of view. Without referring to either method, it may be stated that the straight line may be fitted to the unit or cumulative average data. When this is done the two straight lines will not start at the same point on the vertical axis. This result may be observed in Figure 3.7, where the least squares method was used to obtain the unit and the cumulative average line of best fit. It should be noted that the unit and the average lines are approximately parallel so that if these lines were used for estimating purposes, similar results should be obtained. (For proof that similar results will be obtained see paragraph on estimating with the alternative methods).

On the other hand, when an assumption is made that the unit and the average curve is linear and starting at the same point on the vertical axis different estimating results will be obtained. It cannot be otherwise because the same equation and slope percentage is being applied to the unit line in the Boeing and cumulative average line in the Wright method. At unit number two the Boeing method shows eighty man-hours for unit number two, and ninety man-hours as being the average for units one and two. Using the Wright method we get sixty man-hours for unit number two. The average for the first two units is eighty hours.

An observation of Figure 3.5 indicates that the unit line in the Wright theory and the cumulative average line in the Boeing theory are curved for about the first ten units and tend to parallel the straight line in each case after that initial quantity. The exact quantity of units at which the two curves in either theory become


Man-Hours
1000

parallel may be determined by simply dividing the unit (or average) value at a given quantity by the unit (or average) value at half that quantity.

For example: To find at what point the unit curve in the Wright formulation is approximately parallel to the cumulative average curve the slope at various double quantity points may be obtained. Computing the slope for values contained in Column two of Table 3.3, using the above method, we get a 60 per-cent slope between units one and two, 75.6 per-cent slope between units two and four, 78.2 per-cent slope between units four and eight, 79.1 per-cent slope between unit eight and sixteen and 80 per-cent slope between units sixteen and thirty-two. It is evident that the two curves tend to be parallel after a number of units have been produced.

As a matter of practice, despite the differences in the initial stages, most firms treat the two curves as parallel. The reason for this practice seems to be that when differential calculus is used to determine the unit line when the cumulative average line is known, the unit line obtained will also be a straight line and parallel to the cumulative average line. The exact position of the unit curve in this method may be determined by multiplying the man-hours at given quantity by a factor. The factor is obtained by subtracting the slope exponent from unity (or 1-b).[5]

The above analysis may be summarized as follows:

1. There is a significant difference in results obtained when the Boeing and the Wright methods are applied to an identical unit number

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[5] For more detailed description see Relationship of Wright Cumulative Average and Unit Curves, below.

one value.

2. The difference is in that the same equation is applied to the unit curve in the Boeing method and the cumulative average curve in the Wright method. This, in effect, assumes that both lines are parallel. Actually, one or the other must be developed; both cannot be straight lines. When actual data is used to project with either of the linear formulations, they start at different points on the vertical axis, and the estimated results should be similar.

3. The unit line in the Wright method and the cumulative curve in the Boeing method are curved for quantities of about thirty units, and therefore, at this stage they are not parallel or of the same slope characteristic as the straight line.

4. After thirty units are produced the curved lines will evidence the same slope as the straight line (within less than 1 per-cent) and may be considered parallel to the straight line.

Comparison of Curve Characteristics

A question may be raised what difference in results, if any, will be obtained when the Boeing and the Wright method is applied to the same data. Eleven curves were fitted to a straight line through the use of the least squares method. The line of regression was computed using the Wright and the Boeing method. The relationship of actual data values to the straight line characteristics will be found in Table 3.4. A comparison of the curve characteristics indicates that significant differences exist. Both the Wright and the Boeing theories assume that a linear function will result on logarithmetic scales. Which of the two methods will result in a better fit of a straight line? In nine of the eleven cases, the Wright method, which assumes

TABLE 3.4

TIME REDUCTION CURVE CHARACTERISTICS FOR

ACTUAL DATA, USING WRIGHT CUMULATIVE

AVERAGE AND BOEING UNIT CURVE METHODS

Product	Index of Correlation		Slope Per-Cent		Per-Cent Standard Error of Estimate	
	Wright Method	Boeing Method	Wright Method	Boeing Method	Wright Method	Boeing Method
Magnetic Tape Handler (Table 4.6)	.97	.85	87.0	80.5	2.1	16.3
Data Storage Unit (Table 4.20)	.95	.81	90.3	82.1	4.3	24.7
Computer Component 1B (Table 4.25)	.99	.86	84.9	7[illegible].9	2.2	23.1
Computer Component 5B (Table 4.18)	.99	.97	85.1	80.5	3.0	8.9
Binding Machine #1 (Table 4.27)	.99	.97	84.[illegible]	81.4	1.2	4.4
Binding Machine #8 (Table 4.33)	.97	.83	96.2	95.3	0.8	4.0
Binding Machine #9 (Table 4.34)	.97	.80	91.0	92.7	1.3	6.3
Printing Press #2 (Table 4.43)	.999	.996	98.5	97.5	0.7	1.[illegible]
Printing Press #7 (Table 4.48)	.999	.97	91.2	90.3	0.5	4.3
Printing Press #8 (Table 4.49)	.994	.992	95.4	93.4	3.1	4.6
Printing Press #9 (Table 4.50)	.986	.96	92.0	90.8	2.1	5.0

the cumulative average line to be linear, produces a significantly higher index of correlation. In two cases the difference is less than .01 and is considered as insignificant. Which of the two methods will produce a more reliable linear function? In each of the eleven cases use of the Boeing method results in a standard error of estimate significantly larger than that obtained when the Wright method is used. It should be noted that the difference in curve characteristics is much greater in those cases where data was available for only about fifty units.

It is logical to expect a greater correspondence to a linear function when the Wright method is used because the averaging tends to smooth some of the assignable deviations which will be more evident in the case of Boeing method. Assignable deviations may be defined as major fluctuations in man-hour requirements which are caused by changes in the product or errors in recording data. It is inherent in the Wright method that deviations from the straight line are minimized. One "bad" lot or unit value will have less effect on the cumulative average than on the unit curve.

Estimating Results Comparison

It was stated in the preceding paragraphs that theoretical analysis shows significant differences in results obtained when the Wright and the Boeing methods are applied to a hypothetical unit number one value. In practice when the straight line is fitted to cumulative average values and unit values the theoretical unit number one value is not the same. This is due to the fact that the least squares line is a product of all the points plotted and not just the first unit value.

The backing up of this line of best fit to unit number one will produce a different unit number one value depending on whether the Wright or the Boeing method is used.

Table 3.4 indicates that in terms of reliability, as measured by the computed index of correlation and the standard error of estimate, the Wright method is more desirable. Another question relative to the two methods is: how close can actual total man-hours be predicted through the normal application of the Wright and the Boeing method? Accordingly, total man-hours consumed at specific quantities were estimated. The Wright and the Boeing method was used to project man-hour data. The estimates were compared with actual man-hours and the actual percentage error computed. The results may be observed in Table 3.5.

The estimates were computed using the Wright and the Boeing method. The linear function was used in both cases, and of course, least squares method was applied to comulative average and unit data. The forecast was made on the assumption that the applicable slope was known. This assumption may or may not hold in a specific situation.

In general, it may be stated that the Wright method produces more accurate results than the Boeing method. However, in most cases both methods produce comparable results. In eight out of eleven cases the difference in cumulative total man-hour estimating error is about 2 per-cent. Greater accuracy may be expected from the application of the Wright method. It should be noted that the error is smallest in cases where changes in the product during production were of minor influence on man-hour consumption.

COMPARISON OF ACTUAL TO ESTIMATED MAN-HOURS

Case No.	Quantity	Wright Method Cumulative Total Man-Hours	Actual Cumulative Total Man-Hours	Boeing Method Cumulative Total Man-Hours	Error in Estimate Wright Method	Error in Estimate Boeing Method
4.6	1	625	621	603	0.7	2.1
	10	3,900	3,950	3,841	1.3	2.8
	20	6,700	7,120	6,377	6.3	11.2
4.20	10	2,377	2,395	2,708	0.8	13.2
	50	9,375	9,605	9,049	2.5	6.1
	100	16,960	16,135	15,017	5.1	7.4
4.18	10	1,575	1,530	1,642	2.9	7.3
	50	5,390	5,380	5,358	0.2	0.4
	70	6,965	6,740	6,819	3.3	1.1
4.25	10	1,062	1,165	1,206	9.7	3.5
	50	3,750	3,725	3,843	0.7	3.2
	80	5,440	5,125	6,236	6.1	21.7
4.27	10	10,073	9,900	10,319	1.1	4.2
	30	23,370	23,710	23,274	1.5	1.9
	56	37,800	36,902	41,088	2.4	11.1
4.33	9	2,900	2,601	2,631	11.5	1.2
	30	8,190	8,352	8,111	2.0	2.97
	66	17,160	17,091	16,890	0.4	1.2
4.34	16	3,440	3,456	3,340	0.5	3.5
	40	7,600	7,572	7,653	0.4	1.1
	57	10,374	10,523	10,531	1.4	0.1
4.43	50	44,450	44,540	45,342	0.2	1.8
	90	72,000	71,640	73,638	0.5	2.8
	110	84,700	84,740	86,856	0.1	2.5
4.40	55	37,290	37,650	36,934	1.0	1.9
	111	63,487	63,224	67,305	0.4	1.4

COMPARISON OF ACTUAL TO ESTIMATED MAN-HOURS

Case No.	Quantity	Wright Method Cumulative Total Man-Hours	Actual Cumulative Total Man-Hours	Boeing Method Cumulative Total Man-Hours	Error in Estimate Wright Method	Error in Estimate Boeing Method
4.48 (Cont'd)	403	210,769	211,453	201,712	0.3	4.8
	523	262,456	261,073	251,720	0.5	3.7
	671	320,733	320,091	311,059	0.1	3.2
4.49	66	38,742	40,222	38,160	3.3	5.4
	136	67,723	67,992	65,341	0.4	4.1
	286	119,548	116,992	113,175	2.2	2.5
4.50	70	43,650	51,110	47,657	5.1	7.2
	205	125,665	126,440	121,136	0.6	4.4
	339	193,230	191,500	187,283	0.9	2.3

SOURCE: Firm A, B, and C data, case number equivalent to Table No. in Chapter 4.

Despite the large difference in results obtained when the Wright and the Boeing method is applied to an identical unit number one value, this condition should not become a reality in practice. It was pointed out above that the difference in projection results from the fact that both the unit and the cumulative average lines were assumed to be straight lines and starting out at the same point on the vertical axis. This procedure is incorrect. When both lines are used for estimating purposes, one of them must be integrated and this will result in that the two lines will start at different points on the vertical axis.

The foregoing may be proven in another manner. When a least squares line is fitted for an actual set of data, the unit and the cumulative average line will start out at different points on the vertical axis. This result may be readily observed in Figure 3.7.

Another indication that the two methods will yield similar results may be observed in Table 3.5, where a comparison of the error in estimate suggests that the similarity in total man-hours estimated is close.

It is evident that neither of the two methods of estimating man-hours can be termed as being wrong. It may be stated that in cases where data is available in lot form, it is more convenient to use the Wright method. Under these conditions the unit data can only be estimated.

A Method of Unit Curve Derivation

For some applications it is necessary to have an estimate of hours expended on a specific unit. There are several methods which may be used to obtain the unit curve when the cumulative average curve is known. It will be recalled that the Wright theory is based on the hypothesis that the cumulative average man-hours per unit decline at a constant percentage as the quantity manufactured is doubled. If the cumulative average line is straight the unit line will be curved for the first ten units, after that it will tend to approximate a linear function on log-log paper.

Figure 3.5 presents graphical view of the relationship between the Wright cumulative average and the unit curve. The hypothetical values for the cumulative average curve were obtained from Table 3.3. The value for the Wright unit curve may be easily obtained when the cumulative average man-hour values at given quantities are known. For example, assuming an 80 per-cent slope cumulative average curve and one hundred man-hours for unit number one the cumulative average value for unit number two will be eighty man-hours. To obtain the unit value for unit number two we need only subtract the cumulative total for the previous unit from the cumulative total applicable to the specific unit number for which unit value is being determined. To continue our example: cumulative total at unit number two is one hundred and sixty man-hours at unit one it is one hundred hours, the difference between the two must equal the unit value (sixty hours in this case).

The above method was used to develop the unit curve in Figure 3.5. It is apparent that the Wright unit curve is curved until about ten units are produced. Thereafter, the unit curve tends to parallel the cumulative average line. Strictly speaking, the two curves are not exactly parallel, even past the ten units, but the variation in distance between the curves is small and difficult to observe. For practical purposes the curves may be considered parallel when the unit curve exhibits a slope which is similar to the cumulative average curve. It was stated above that in the case of data contained in Column two, Table 3.3, the unit curve exhibits an 80 per-cent slope characteristic when we move from 16 to 32 units.[6]

As a matter of practice most of the airframe firms, whose publications were reviewed in Chapter 2, state that they consider the two curves parallel after the initial quantity where the unit line is curved. To determine the position of the unit curve at any point in production, a factor for each slope is multiplied by the cumulative average cost. The factor shows relative values of unit-man-hour cost to cumulative average man-hours. A factor may be obtained by subtracting the slope exponent from one (1-b). Since the slope exponent for any 80 per-cent curve equals to .322, the factor will be: 1.-.322 = .678.

Applying the factor to Figure 3.5, the unit line will equal to 67.8 per-cent of the cumulative average line value at any point on the curve. But most users of the curve realize that at the beginning the unit line is curved and plot the first several units and thereafter use the unit curve as though it were a straight line.

The above method is based on the following mathematical computations:

let y be the cumulative average man-hours per unit

a is the man-hours required to produce unit number one

x is the given unit number

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[6] The 80 per-cent is obtained by dividing unit value at unit 32 by unit value at unit 16, or 32.77:40.96=80.004 per-cent.

TABLE 3.6

FACTORS SHOWING THE RELATIONSHIP BETWEEN THE

CUMULATIVE AVERAGE AND THE UNIT CURVE

Percentage of Time Reduction Curve	Factor Showing Relative Value of Unit Man-Hours to Cumulative Average Man-Hours
60	.263
61	.287
62	.310
63	.333
64	.356
65	.379
66	.401
67	.422
68	.444
69	.465
70	.485
71	.506
72	.526
73	.546
74	.566
75	.585
76	.604
77	.623
78	.642
79	.660
80	.678
81	.696
82	.714
83	.731
84	.748
85	.766
86	.782
87	.799
88	.816
89	.832
90	.848
91	.864
92	.880
93	.895
94	.911
95	.926

b is the exponent which defines the slope then,

cumulative average man-hour per unit = $y=ax^b$

total man-hour expended = $\frac{ax}{b+1}^{b+1} = ax^{b+1}$

According to the theory of integral calculus, if a formula for a unit curve was available, and if that formula were integrated for a given number of units, the total number of man-hours expended could be found. The formula for cumulative total man-hours is known. Since differential calculus is integral calculus in reverse, it is possible to differentiate the above formula to obtain a formula for the man-hours per unit line, or the unit man-hour time reduction curve in terms of the cumulative average time reduction curve.

$$\frac{d(T)}{dx} = \frac{d(ax^{b+1})}{dx}$$

Unit man-hours per unit = $(b+1)\ (ax^b)$

Since $(ax^b) = y$, we have unit man-hours per unit = $(b+1)\ (y)$

Thus the factor b+1 multiplied by the cumulative average man-hours for any unit will give the unit man-hours. In this manner a value on one time reduction curve can be converted into a value on the other curve by the use of the conversion factor b+1.

Table 3.6 provides a series of factors for various slope percentages, which may be used to convert the cumulative average values to unit values.

Summary and Conclusions

In Chapter 3 theoretical considerations pertaining to the time reduction curve were discussed. The time reduction curve theory as originally proposed by T. P. Wright is based on the hypothesis that the cumulative average direct man-hours per unit decline by a constant percentage as the quantity produced is doubled. Another formulation known as the Boeing unit average curve theory is based on the hypothesis that the unit average man-hours per unit decline by a constant percentage as the quantity produced is doubled.

The time reduction curve theory assumes that the established trend of the rate of time reduction will continue, that the product is unchanged, that the labor accession or separation rate remain the same, and that there are no major interruptions in the production cycle. When any of the above factors are present, serious irregularities in the time reduction curve may be expected to appear.

Because of the difficulties in making projections of this phenomenon on arithmetic scales, it is seldom used for this purpose. The man-hour data plotted on double logarithmic scale has a tendency to correspond to a linear function. The relationship may be presented through the use of a formulae or graphically, depending on the required accuracy.

Application of the alternative Wright and Boeing theories to actual data indicates that similar estimating results may be expected. The minor differences are primarily due to differences in construction. As may be expected, the Wright cumulative average line is more stable than the Boeing unit line. This is primarily due to the greater influence that individual unit values have on the unit line. However, man-hour estimates obtained through the use of the two methods do not indicate clear cut superiority of one method over the other.

In cases where data is available in lot form, it is desirable to use the Wright method.

The Wright cumulative average curve method is used throughout this study. Method of determining the unit line when the cumulative average curve is known is also presented.

In Chapter 4 the method of obtaining data, reliability of data, and the data itself is presented.

CHAPTER IV

TIME REDUCTION CURVE DATA

Introduction

The time reduction curve is an accepted tool of forecasting direct man-hour requirements in the airframe industry. It will be recalled that most of the presently available studies on the time reduction curve, which were reviewed in Chapter 2, were based on data collected by the Air Force through periodic reports from the airframe manufacturers.

It should not be assumed that the application of the time reduction curve to the planning of operations will be neutral on the observed data. The time reduction curve is used as a basis for setting prices, cost targets, man-hour requirements, leadtime, and delivery schedules. As in the case of other techniques of planning, once commitments have been made, management will do its best to live up to these. If operations turn out to be as the time reduction curve based plan intended, there is no compulsion to take remedial action. On the other hand, when experience begins to deviate from the time reduction curve, management goes all out to find and eliminate the causes of deviation.

In order that a number of important questions relative the usefulness of the time reduction curve may be answered, it appeared desirable to analyze man-hour data experienced in production situations which have not used a time reduction curve.

The three firms which consented to release man-hour data, did so only after being assured that the company's name and product's trade name will not be revealed. The information was obtained through personal examination of the firms' records and interviews with management personnel.

Method of Obtaining Data

Twelve manufacturing concerns were approached to obtain man-hour data on specific products as the cumulative quantity manufactured increased. Seven of the firms approached refused to release actual data, stating that the data is of highly confidential nature. Two of the firms denying use of data, agreed to let the writer examine the man-hour figures on the firms' premises in the presence of a management representative. It may be added that a definite reduction in man-hours, as cumulative quantity produced increases, was observed. No statements can be made relative other characteristics of the time reduction curve, since there was no opportunity to compute these. As an example, one production executive who agreed to consider the request for data, wrote the following:

> I am afraid I am not in position to give you the kind of information you would really like, namely actual man-hour production cost changing at a constant rate as experience is gained. The reason I cannot give you the information is the fact that it must be considered confidential both relative to my current and past connections. I know it does not help to say this learning curve is factual (for thesis purposes) without substantiating data, but I am not in a position to disclose operating data.

Two firms were willing to make man-hour data available, but upon extensive reviews it became obvious that it would be economically impossible to get accurate data. This was due to the fact that the firms' accounting procedures did not report man-hours in either unit or lot form. An attempt to refer to individual operator time sheets did not produce satisfactory results. Non-availability of time records was one of the difficulties encountered.

Nature of Man-Hour Data

The selection of a firm for study purposes is a serious problem in itself. This is because of the fact that many operating procedures used by a number of firms are not conducive to the time reduction phenomena nor to the collection of time reduction data. To begin with, firms which operate under an incentive piece rate for wage payments or control purposes are likely to create an environment which is conducive to restriction of output and inaccuracy of time recording. Thus, some of the firms which were initially contacted could not be used in this study because operating standards are set, and the worker is paid on the basis of the percentage of standard reached in performing a given task. During the investigation it also came to the attention of the writer that once the standard is reached, the workers tend to do other activities than those which are normally associated with production. In one instance the standard would be reached Friday morning, the rest of the day workers would engage in non-productive activities. Further inquiry into the behavior of production workers who work on tasks where standards were established, indicates that restriction of output is not an uncommon case. Another frequent occurrence is the inaccuracy of time recording where either standards or piece work wage payment plan is in effect. Again the time that the units were produced is not necessarily the time that it is to the advantage of the worker to report on the time sheet.

The other major difficulty was a result of the type of accounting system used. The type of system in use not only affects the availability of data in the form desired for the purposes of time reduction curve research, but also the data is often found in aggregate form which defies ex post analysis. It is probably true that most of these difficulties can be overcome with a great deal of time and effort. In one case it was estimated that it would take a year to come up with the cost applicable to a certain product. It is with these possible difficulties in mind that the writer approached the problem of obtaining empirical data on production time reduction.

In all cases we have accepted the firms' accounting definition of direct man-hours, and have used the data in the form it was found in company files. There was little opportunity to adjust the data for changes introduced when the units were in production. This would certainly be most desirable. Unfortunately, none of the firms in question keep a cost history which would enable us to know the magnitude of change in terms of requirements of man-hours or the date and the unit number the change was incorporated.

<u>Data Reliability</u>

At this point it may be well to consider some of the differences in the three firms methods of accumulating the man-hour data. This is not intended to be an exhaustive or complete examination of the firm's accounting system; our purpose is to indicate what are considered to be important peculiarities in the system that have a bearing on the accuracy of the data.

Company A is a leading manufacturer of business machines. The net sales for 1958, amount to over half a billion dollars. The company's electronic work started in 1953, when it received a contract for small computers and related items. This work came to an end when the customer placed the business with a competitor. Placing the data processing system into production was the most extensive product development project ever undertaken by the company. Company A employs a standard cost system throughout its production facilities engaged in manufacturing a standard line of products. The electronics assembly department is a notable exception. Here the job order costing system has been used ever since the inception of this program. The reason for going to the job order cost system was that this work was new to the company, and it was decided that this would be the best way to keep track of the cost. Also, in pricing the units the company wanted to be certain it would cover the actual cost connected with production. Also, company officials are anxious to determine any decreases in cost as cumulative production continues. The company had little information on what the electronic system program would involve as far as costs were concerned.

The job order cost system used by Company A is similar to job order cost systems found in other situations. Briefly, when an order is placed on a computer unit, a ledger is set up for the particular order. The particular computer will have a unit number assigned to it and the various operations on the unit are assigned job numbers.

The worker's time tickets are then posted to the particular job number and then to the ledger. The procedure was reviewed step by step and it doesn't seem that there is a built-in prejudice against accuracy in the system itself. One of the interesting variations from the usual procedure may be found in that the company charges the time of the inspection force to direct labor. And whereas it was found that there is very little opportunity or incentive for direct labor to charge time improperly, in the case of inspection labor there is some reason to believe that it may be more convenient for an inspector to charge all of his time to one particular unit whereas, he may have worked on three different units. This would then cause a considerable fluctuation from one unit to the next. It should be stressed that this is only a suspected possibility. Interviews with the department head and the foreman did not indicate that this condition actually exists. It should be also mentioned at this time that the practice of including inspection labor in direct labor would seem to introduce a conservative bias to the time requirements for the unit. There is no pressure on the inspection labor either to complete the unit at the specified time or to become more efficient in its work.

It should also be stressed that the direct labor data obtained was that for assembly operation only. Since the parts machining labor is compiled on the basis of standard cost and not on a per unit basis, it is impossible to trace the man-hours to the point where they would become useful in time reduction analysis. Furthermore, the parts which are produced by the company are produced in a department where an incentive piece rate wage plan is used. Close to 70 per-cent of the parts are procured from outside vendors, and these are charged to material cost. Data was obtained for two different programs. The first program covered the period from 1953 through 1957, and the data covers five computer components, one converter unit and one control unit. The computer components were produced simultaneously as were the control unit and the converter unit. Although these parts would at a later date be assembled by the buyer into a unified data processing system, each one of the computer components was especially designed and different from the other units. The company made these to order for one of the larger electronics manufacturers. The production of the company's line of unified data processing system equipment began in May of 1958. The first shipments were made during the first quarter of 1959.

Company B is a newcomer to the electronics manufacturing field, having started operations only fourteen years ago. It has steadily grown until present with sales running approximately ten million dollars annually. Small electronic motors is the specialty of the company. All of the production items are made to order.

Firm B has a modified job order cost system of accumulating time data for fixed interval units in the total quantity produced. Thus, the first two lots consist of five units each. Thereafter time data is accumulated for lots of ten, and occasionally for a lot of twenty. Only assembly time data was obtained from firm B, because close to 80 per-cent of the parts going into the assembly are procured from outside vendors, and man-hour data for parts produced by the company would be misleading. This is due to the fact that company B has a policy of manufacturing certain parts in lot sizes greater than assembly lots. The parts in excess of assembly needs are stored for future assembly needs or issued as spare parts orders are received. Only the time of direct hourly workers is charged to the assembly hour account. The firm's output for which data was obtained consists entirely of specialized components used in data processing systems and automated control systems. The manufacture of these computer components and data storage units started in 1949 and ended in 1951.

Company C is one of the oldest printing press and bindery machine manufacturers. It is considered a leader in its field. Sales for the fiscal year ending June 30, 1959, were over twenty-five million dollars. Unlike in the case of firms A and B, where it was possible to obtain data only on part of the products produced, at firm C man-hour data was obtained on all products manufactured, beginning in 1950 until the present.

The cost system used by firm C, may best be described as a job lot system. The company initiates the production process only after orders are received. Normally, action on the first few purchase orders is delayed until enough additional orders are received to make up what is considered a sufficient number of units for the lot. Only in the case of one model was the company known to deviate and produce a few units at a time. It should be noted that the data obtained from this manufacturer represents both assembly and machining time. In this case, it appears to be significant because over 95 per-cent of the parts used in assembly are manufactured by the company. (It may be added that a large percentage of the parts are bought in the form of unfinished castings and then machined to specification in the plant. Foundry work was formerly done in the plant but it was discovered that castings could be bought for less than it cost the company to make the same.)

The company redesigned its line of printing and binding equipment in the early part of 1950. It seemed logical to start with this date in obtaining time data. If the time reduction phenomenom was in existence it would be most apparent after a significant change in the product. New products added since 1950 were picked up at the time that man-hour data became available, and, of course, dropped when the product was discontinued. Only one printing press, the production of which began in 1950, is still being produced and continuous data was obtained.

Whenever possible, the data used in this study has been checked for accuracy and completeness. In a number of instances, the departmental data, as recorded when the operation is completed, was compared with payroll data for the same period and showed no discrepancies. Furthermore, it is judged that, since the workers or the timekeepers do not have an incentive to be biased in either direction or toward specific units, any unintentional errors will offset one another. All observations are reported in spite of the fact that greater consistency would be obtained, had a selection been made.

Data obtained from firm A may be found in Tables 4.1 through 4.14. It will be noted that this data consists of two programs. Tables 4.1 through 4.6 cover man-hours expended in the manufacture of an electronic data processing system, and was available on a per unit basis. To obtain a common basis of analysis cumulative average man-hours per unit were computed and used. Man-hour data contained in Tables 4.7 through 4.14, represents small computer components and one control unit. The data was obtained in totals for quantities produced. Data in Tables 4.15 through 4.26 was obtained from firm B and was in lot average form. Cumulative average man-hours per unit were computed and may be found in the last column of each Table. Tables 4.27 through 4.54 represent firm C man-hour data experienced in the manufacture of bindery and printing equipment.

TABLE 4.1
DIRECT MANHOURS PER UNIT
CONTROL UNIT NO. 2

UNIT NO.	MANHOURS PER UNIT	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1,137.8	1,137.8	1,137.8
2	578.7	1,716.5	858.3
3	517.6	2,234.1	744.7
4	493.1	2,727.2	681.8
5	425.2	3,152.4	630.5

TABLE 4.2
DIRECT MANHOURS PER UNIT
HIGH SPEED PRINTER NO. 1

1	3,089.8	3,089.8	3,089.8
2	2,022.6	5,112.4	2,566.2
3	1,962.9	7,075.3	2,358.3
4	1,857.9	8,933.2	2,233.3
5	1,274.5	10,207.7	2,041.5
6	1,195.2	11,402.9	1,900.4
7	1,134.5	12,537.4	1,791.0
8	1,134.8	13,672.2	1,709.0
9	1,066.0	14,738.2	1,637.5
10	1,004.7	15,742.9	1,574.3
11	988.7	16,731.6	1,521.0

TABLE 4.3
DIRECT MANHOURS PER UNIT
HIGH SPEED PRINTER NO. 2

1	1,580.4	1,580.4	1,580.4
2	1,506.1	3,086.5	1,543.2
3	1,341.6	4,428.1	1,476.0
4	1,314.9	5,743.0	1,435.7
5	1,211.0	6,954.0	1,390.8
6	1,166.0	8,120.0	1,353.3
7	1,222.9	9,342.9	1,334.7
8	1,185.8	10,528.7	1,316.0
9	1,278.4	11,807.1	1,311.9
10	1,201.8	13,008.9	1,300.9

TABLE 4.4
DIRECT MANHOURS PER UNIT
CARD READER UNIT NO. 1

1	1,470.4	1,470.4	1,470.4
2	974.1	2,444.5	1,222.3
3	926.7	3,371.2	1,123.7
4	595.8	3,967.0	991.8

TABLE 4.5
DIRECT MANHOURS PER UNIT
TAPE PERFORATION UNIT NO. 1

UNIT NO.	MANHOURS PER UNIT	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	630.8	630.8	630.8
2	560.4	1,191.2	595.5
3	642.4	1,833.6	611.2
4	548.4	2,382.0	595.5
5	472.5	2,854.5	570.9
6	511.9	3,366.4	561.1

TABLE 4.6
DIRECT MANHOURS PER UNIT
MAGNETIC TAPE UNIT NO. 1

1	620.7	620.7	620.7
2	493.5	1,114.2	557.1
3	338.4	1,452.6	484.2
4	479.4	1,932.0	433.0
5	292.4	2,224.4	444.6
6	369.1	2,593.5	432.3
7	274.4	2,867.9	409.7
8	310.8	3,178.7	397.3
9	412.0	3,590.7	399.0
10	359.0	3,949.7	394.9
11	330.3	4,280.0	389.1
12	239.8	4,519.8	376.7
13	253.4	4,773.2	367.2
14	358.9	5,132.1	366.6
15	339.5	5,471.6	364.8
16	292.9	5,764.5	360.3
17	264.6	6,029.1	354.7
18	218.4	6,247.5	347.1
19	248.6	6,496.1	341.9
20	181.9	6,678.0	333.9
21	225.3	6,903.3	328.7
22	217.1	7,120.4	323.7

TABLE 4.7
DIRECT MANHOURS DATA
CONTROL UNIT NO. 1A

LOT NO.	UNITS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	659	137
2	6-10	1,091	109
3	11-20	1,731	87
4	21-30	2,289	76
5	31-37	2,601	70

TABLE 4.8
DIRECT MANHOUR DATA
COMPUTER NO. 1A

1	1-5	749	152
2	6-10	1,430	143
3	11-2	2,918	146
4	21-30	4,350	145
5	31-39	5,558	142

TABLE 4.9
DIRECT MANHOUR DATA
COMPUTER NO. 2A

1	0-5	1,210	242
2	6-10	2,328	233
3	11-20	4,355	218
4	21-30	6,200	207
5	31-40	7,947	199

TABLE 4.10
DIRECT MANHOURS DATA
COMPUTER NO. 3A

1	1-5	3,085	617
2	6-10	4,971	497
3	11-20	7,218	361
4	21-30	8,980	299

TABLE 4.11
DIRECT MANHOUR DATA
COMPUTER NO. 4A

LOT NO.	UNITS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	3,233	647
2	6-10	5,681	568
3	11-20	9,640	544
4	21-30	12,316	410

TABLE 4.12
DIRECT MANHOUR DATA
COMPUTER NO. 5A

1	1-5	6,243	1,249
2	6-10	9,917	992
3	11-15	12,578	839
4	16-23	15,384	668

TABLE 4.13
DIRECT MANHOUR DATA
COMPUTER NO. 6A

1	1-5	8,234	1,647
2	6-10	13,338	1,334
3	11-20	19,167	958
4	21-30	24,054	802

TABLE 4.14
DIRECT MANHOUR DATA
COMPUTER NO. 7A

1	1-5	4,744	949
2	6-10	8,992	899
3	11-15	13,416	894
4	16-20	17,626	881
5	21-30	25,937	864
6	31-38	32,119	845

NOTE: Data contained in Table 4.1 through 4.14 obtained from Company A.

TABLE 4.15
DIRECT MANHOUR DATA
COMPUTER NO. 2B*

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	604	3,020	604
2	6-10	670	6,370	637
3	11-20	157	7,940	397
4	21-30	169	9,630	321
5	31-40	164	11,270	282
6	41-60	165	16,140	269
7	61-70	157	17,710	253
8	71-80	153	19,240	241
9	81-90	139	20,630	229

TABLE 4.16
DIRECT MANHOUR DATA
COMPUTER NO. 3B

1	1-5	232	1,160	232
2	6-10	212	2,220	222
3	11-20	197	4,190	210
4	21-30	153	5,720	191
5	31-40	150	7,220	181
6	41-60	123	9,680	161

TABLE 4.17
DIRECT MANHOUR DATA
COMPUTER NO. 4B

1	1-5	381	1,905	381
2	6-10	300	3,405	341
3	11-20	322	6,625	331
4	21-30	257	9,195	307
5	31-40	210	4,295	282
6	41-50	192	13,215	264
7	51-60	176	14,975	250
8	61-70	147	16,445	234

*NOTE: Data contained in Table 4.15 through 4.26 obtained from Company B.

TABLE 4.18
DIRECT MANHOUR DATA
COMPUTER NO. 5B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	183	915	183
2	6-10	123	1,530	153
3	11-20	123	2,760	138
4	21-30	109	3,850	128
6	31-40	79	4,640	116
7	41-50	74	5,380	108
8	51-60	69	6,070	101
9	61-70	67	6,740	96
10	61-70			

TABLE 4.19
DIRECT MANHOUR DATA
COMPUTER NO. 6B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	208	1,040	208
2	6-10	102	1,850	185
3	11-20	148	3,330	167
4	21-30	172	5,050	168
5	31-40	116	6,210	155
6	41-50	98	7,190	144
7	51-60	86	8,050	134
8	61-70	72	8,770	125

TABLE 4.20
DIRECT MANHOUR DATA
DATA STORAGE UNIT NO. 1B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	247	1,235	247
2	6-10	232	2,395	240
3	11-20	198	4,375	219
4	21-30	194	6,315	211
5	31-40	170	8,015	200
6	41-50	159	9,605	192
7	51-60	174	11,345	189
8	61-70	165	12,995	185
9	71-80	139	14,385	180
10	81-90	89	15,275	170
11	91-100	86	16,135	161
12	101-110	74	15,875	153

TABLE 4.21
DIRECT MANHOUR DATA
DATA STORAGE UNIT NO. 2B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	206	1,030	206
2	6-10	99	1,525	153
3	11-20	98	2,505	125
4	21-30	121	3,715	124
5	31-40	77	4,485	112
6	41-50	70	5,185	104

TABLE 4.22
DIRECT MANHOUR DATA
DATA STORAGE UNIT NO. 3B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	128	640	128
2	6-10	124	1,260	126
3	11-20	70	1,960	98
4	21-30	82	2,780	93
5	31-40	62	3,400	85
6	41-50	63	4,030	81

TABLE 4.23
DIRECT MANHOUR DATA
COMPUTER NO. 7B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	550	2,500	550
2	6-10	374	4,370	437
3	11-20	304	7,410	371
4	21-30	180	9,210	307
5	31-40	164	10,850	271
6	41-50	149	12,340	247
7	51-60	113	13,470	225
8	61-70	107	14,540	208

TABLE 4.24
DIRECT MANHOUR DATA
COMPUTER NO. 8B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	176	880	176
2	6-10	161	1,685	169
3	11-20	108	2,765	138
4	21-30	130	4,065	136
5	31-40	98	5,045	126
6	41-50	99	6,035	121
7	51-60	79	6,825	114

TABLE 4.25
DIRECT MANHOUR DATA
CONTROL UNIT NO. 1B

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-5	110	550	110
2	6-10	123	1,165	117
3	11-20	73	1,895	95
4	21-30	78	2,675	89
5	31-40	51	3,185	80
6	41-50	54	3,725	75
7	51-60	63	4,355	73
8	61-70	48	4,835	69
9	71-80	29	5,125	64

TABLE 4.26
DIRECT MANHOUR DATA
COMPUTER NO. 1B

1	1-5	482	2,410	482
2	6-10	338	4,100	410
3	11-20	251	6,610	331
4	21-30	305	9,660	322
5	31-40	234	12,000	300
6	41-60	203	16,060	268
7	61-70	162	17,680	253

TABLE 4.27
DIRECT MANHOUR DATA
BINDING MACHINE NO. 1

1	0-10	990	9,900	990
2	11-13	810	12,330	948
3	14-19	697	16,512	869
4	19-23	662	19,160	833
5	24-30	650	23,710	790
6	31-36	537	26,932	748
7	37-51	502	34,462	676
8	52-56	488	36,902	659

TABLE 4.28
DIRECT MANHOURS DATA
BINDING MACHINE NO. 2

1	0-1	509	509	509
2	2-4	518	2,063	516
3	5-12	448	5,647	471
4	13-17	395	7,622	448
5	18-25	357	10,478	419

TABLE 4.29
DIRECT MANHOURS DATA
BINDING MACHINE NO. 3

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	0-7	605	4,235	605
2	8-11	612	6,683	608
3	12-16	507	9,218	576
4	17-23	468	12,494	543
5	24-27	421	14,178	525

TABLE 4.30
DIRECT MANHOURS DATA
BINDING MACHINE NO. 4

1	0-2	800	1,600	800
2	3-3	702	2,302	767
3	4-4	668	2,970	743
4	5-5	545	3,515	703
5	6-8	472	4,931	616

TABLE 4.31
DIRECT MANHOUR DATA
BINDING MACHINE NO. 6

1	0-6	262	1,572	262
2	7-10	205	2,392	239
3	11-18	198	3,976	221
4	19-28	182	5,796	207
5	29-37	171	7,335	198

TABLE 4.32
DIRECT MANHOUR DATA
BINDING MACHINE NO. 7

1	0-6	335	2,010	335
2	16	276	4,770	298
3	24	245	6,730	280
4	32	251	8,738	273
5	41	236	10,862	265

TABLE 4.33
DIRECT MANHOUR DATA
BINDING MACHINE NO. 8

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-9	289	2,601	289
2	10-17	270	4,761	280
3	18-22	275	6,136	279
4	23-30	277	8,352	278
5	31-39	238	10,494	269
6	40-48	243	12,681	264
7	49-57	242	14,859	261
8	58-66	248	17,091	259

TABLE 4.34
DIRECT MANHOUR DATA
BINDING MACHINE NO. 9

1	0-16	216	3,456	216
2	17-29	177	5,757	199
3	30-40	165	7,572	189
4	41-48	163	8,876	185
5	49-57	183	10,523	184

TABLE 4.35
DIRECT MANHOUR DATA
BINDING MACHINE NO. 10

1	0-12	223	2,676	223
2	18-18	183	3,774	210
3	19-25	172	4,978	199
4	26-39	169	7,344	188
5	40-50	182	9,346	187

TABLE 4.36
DIRECT MANHOUR DATA
BINDING MACHINE NO. 11

1	0-2	302	604	302
2	3-13	257	3,413	263
3	14-25	235	6,251	250
4	26-33	227	8,067	244
5	34-43	215	10,217	238

TABLE 4.37
DIRECT MANHOUR DATA
BINDING MACHINE NO. 12

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	0-3	253	759	253
2	4-4	202	961	240
3	5-8	194	1,737	217
4	9-15	176	2,969	198
5	16-22	164	4,117	187

TABLE 4.38
DIRECT MANHOUR DATA
BINDING MACHINE NO. 13C

1	0-12	592	7,104	592
2	13-42	306	16,284	388
3	43-72	305	25,434	353
4	73-102	295	34,284	336

TABLE 4.39
DIRECT MANHOUR DATA
BINDING MACHINE NO. 14C

1	0-10	547	5,470	547
2	11-25	456	12,310	492
3	26-40	365	17,785	445
4	41-55	334	22,795	414
5	56-70	330	27,745	396
6	71-85	320	32,545	383

TABLE 4.40
DIRECT MANHOUR DATA
BINDING MACHINE NO. 15

1	0-20	467.0	9,340	467
2	21-40	356.0	16,460	412
3	41-70	282	24,920	356

TABLE 4.41
DIRECT MANHOUR DATA
BINDING MACHINE NO. 16

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	0-20	385	7,700	385
2	21-40	310	13,900	348
3	41-60	244	18,780	313
4	61-80	213	23,040	288
5	81-100	175	26,540	265
6	101-120	169	29,920	249

TABLE 4.42
DIRECT MANHOUR DATA
PRINTING PRESS NO. 1

1	0-5	2,550	12,750	2,550
2	6-15	1,730	30,050	2,000
4	16-30	1,385	50,825	1,694
5	31-45	1,175	68,450	1,521
6	46-60	1,099	84,935	1,416

TABLE 4.43
DIRECT MANHOUR DATA
PRINTING PRESS NO. 2

1	0-10	1,170	11,700	1,170
2	11-30	890	29,500	983
3	31-50	752	44,540	891
4	51-70	685	58,240	832
5	71-90	670	71,640	796
6	91-110	655	84,740	770

TABLE 4.44
DIRECT MANHOUR DATA
PRINTING PRESS NO. 3

1	0-10	1,275	12,750	1,275
2	11-20	1,065	23,400	1,170
3	21-35	850	36,150	1,033
4	36-50	770	47,700	954
5	51-65	755	59,025	908
6	66-80	735	70,050	876

TABLE 4.45
DIRECT MANHOUR DATA
PRINTING PRESS NO. 4

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	0-10	1,295	12,950	1,295
2	11-35	902	35,500	1,014
3	36-60	716	53,400	890
4	61-85	625	69,025	812
5	86-110	510	81,775	743
6	111-135	514	94,625	701

TABLE 4.46
DIRECT MANHOUR DATA
PRINTING PRESS NO. 5

1	0-4	965	3,860	965
2	5-14	893	12,790	913
3	15-34	674	26,270	773
4	35-54	619	38,650	716
5	55-74	647	51,590	697
6	75-94	589	63,370	674

TABLE 4.47
DIRECT MANHOUR DATA
PRINTING PRESS NO. 6

1	0-5	2,625	13,125	2,625
2	6-15	1,878	31,905	2,127
3	16-30	1,580	55,605	1,854
4	31-50	1,414	83,885	1,678
5	51-70	1,232	108,525	1,550
6	71-90	1,152	131,565	1,461

TABLE 4.48
DIRECT MANHOUR DATA
PRINTING PRESS NO. 7

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	1-10	832	8,320	832
2	11-30	694	22,200	740
3	31-55	618	37,650	684
4	56-85	565	54,600	642
5	86-111	524	68,224	615
6	112-140	498	82,666	590
7	141-167	491	95,923	574
8	168-195	503	110,007	564
9	196-225	503	125,097	556
10	226-253	502	139,153	550
11	254-283	515	154,603	546
12	284-313	496	169,483	541
13	314-343	462	183,343	535
14	344-373	474	197,563	530
15	374-403	463	211,453	525
16	404-433	415	223,903	517
17	434-463	410	236,203	510
18	464-493	412	248,563	504
19	494-523	417	261,073	499
20	524-553	411	273,403	494
21	554-581	406	284,771	490
22	582-611	400	296,771	486
23	612-641	395	308,621	481
24	642-671	410	320,921	478

TABLE 4.49
DIRECT MANHOUR DATA
PRINTING PRESS NO. 8

1	0-6	962	5,772	962
2	7-16	734	13,112	820
3	17-36	601	25,132	698
4	37-66	503	40,222	609
5	67-96	435	53,272	555
6	97-136	368	67,992	500
7	137-186	328	84,392	454
8	187-236	322	100,492	425
9	237-286	330	116,992	409

TABLE 4.50
DIRECT MANHOUR DATA
PRINTING PRESS NO. 9

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	0-10	845	8,450	845
2	11-20	782	16,270	814
3	21-40	638	29,030	726
4	41-70	552	51,110	730
5	71-90	580	62,710	697
6	91-115	556	76,610	666
7	116-145	562	93,470	645
8	146-175	565	110,420	631
9	176-205	534	126,440	617
10	206-235	529	142,310	606
11	236-255	494	152,190	597
12	256-270	462	159,120	589
13	271-285	443	165,840	582
14	286-295	475	170,590	578
15	296-305	480	175,390	575
16	306-315	459	179,980	571
17	316-327	464	185,548	567
18	328-339	496	191,500	565

TABLE 4.51
DIRECT MANHOUR DATA
PRINTING PRESS NO. 10

1	0-10	611	6,110	611
2	11-20	546	11,570	579
3	21-35	516	19,310	552
4	36-50	486	26,600	632
5	51-60	520	31,800	530
6	61-80	506	41,920	524
7	81-100	499	51,900	519
8	101-120	492	61,740	515
9	121-150	468	75,780	505
10	151-168	469	84,222	501

TABLE 4.52
DIRECT MANHOUR DATA
PRINTING PRESS NO. 11

LOT NO.	UNITS	LOT AVERAGE MANHOURS	CUMULATIVE TOTAL MANHOURS	CUMULATIVE AVERAGE MANHOURS PER UNIT
1	0-8	1,275	10,200	1,275
2	9-12	1,124	14,696	1,225
3	13-30	966	32,084	1,069
4	31-43	826	42,822	996
5	44-57	791	53,896	946
6	58-72	768	65,416	909
7	73-86	833	77,078	896
8	87-103	764	90,066	874
9	104-122	898	107,128	878
10	123-140	958	124,372	888
11	141-156	817	137,444	881
12	157-171	884	150,704	881

TABLE 4.53
DIRECT MANHOUR DATA
PRINTING PRESS NO. 12

1	0-5	1,927	9,635	1,927
2	6-7	1,484	12,603	1,800
3	8-18	1,269	25,562	1,476
4	19-20	1,111	28,784	1,439
5	21-27	1,017	35,903	1,330
6	28-33	982	41,795	1,267
7	34-38	953	46,560	1,225
8	39-39	971	47,531	1,219
9	40-42	887	50-192	1,195
10	43-43	931	51,123	1,189
11	44-45	974	53,071	1,179
12	46-49	855	56,491	1,153

TABLE 4.54
DIRECT MANHOURS DATA
BINDING MACHINE NO. 5

1	0-5	679	3,395	679
2	6-8	581	5,138	642
3	9-10	564	6,266	627
4	11-13	554	7,928	610
5	14-16	468	9,332	583
6	17-18	432	10,196	566
7	19-21	433	11,494	547

NOTE: Data contained in Tables 4.27 through 4.54 was obtained from Company C.

Summary

One of the serious difficulties encountered, during the process of gathering empirical man-hour data, was the reluctance of firms to release such data. Even after consent to release data was obtained it was found that in some cases the firm's accounting system did not report data in the desirable form.

Historical direct man-hour data consumed at various cumulative quantities of output was obtained from three manufacturers. The data represents five production programs of a total of fifty-four products. These fifty-four products were produced in various quantities, ranging from seven to about one thousand units. There was also a considerable difference in the total production time for the products.

The period covered by the five programs varies as to the date and also the duration, ranging from 1949 until July of 1959. The program duration ranges between two years for computer components, to about ten years for a printing press. Three programs represent production of various data processing system components. The other two are bindery equipment and printing presses.

The firms' methods of man-hour recording were reviewed in detail and departures from standard practice were noted. All three firms use a variation of the job cost system. The review did not indicate the presence of incentives to biased recording of time. Whenever possible, the data used in this study were checked for accuracy. No discrepancies were discovered.

Analysis of data contained in Tables 4.1 through 4.54 will be found in Chapters 5 and 6.

CHAPTER V

RELIABILITY OF THE TIME REDUCTION CURVE

Introduction

It will be recalled that in Chapter 1 it was stated that the objective of this study is to determine whether or not the time reduction function, as proposed by Wright, is a reliable tool of forecasting direct man-hour requirements. The following specific questions were posed:

1. Does the time reduction curve phenomenon exist in manufacturing situations other than those where production activities are based on a planned time reduction function? No assumptions were made relative to the effect that such use of a preconceived time reduction model will have on observed man-hour data. On the other hand, it should not be assumed that the use of a time reduction model for the purpose of budgeting and controlling man-hours will be neutral on manufacturing time requirements. Therefore, it appeared desirable to analyze empirical data observed in situations where the time reduction curve is not used for purposes of budgeting and controlling of man-hour requirements.
2. The second question, which will be considered in this chapter, concerns the reliability of the linear function of the time reduction curve on log-log scales. An attempt will also be

made to determine the reasons for deviations from the straight line on double logarithmic scale.

The above order of analysis will be used for the balance of this chapter.

Pattern of Time Reduction

A time reduction curve was computed for each of the fifty-four products. There can be little argument as to whether the slope is positive or negative. In each of the fifty-four cases for which data were analyzed the time reduction curve had a significantly negative slope. The question whether the time reduction curve phenomenon exists in manufacturing situations where a curve is not used for planning purposes may be answered in the affirmative. It has been suggested that the belief and the use of the curve in planning is responsible for the existence of this phenomenon.

The Linearity of the Curve

It is the purpose of this section to evaluate the reliability of the time reduction curve in its linear form. An index of correlation for the fifty-four products was computed. The index of correlation is identical to ordinary correlation coefficient except that the former term is applicable to curvilinear correlation. The index of correlation for each product will be found in Column three of Tables 5.1 through 5.5. An average was also computed for each program and is shown at the bottom of each Table. In support of the linearity proposition, it may be stated that all but one of the fifty-four empirical time reduction functions computed resulted in a close

TABLE [illegible]

SUMMARY OF [illegible] CHARACTERISTICS
ELECTRONIC DATA PROCESSING SYSTEM COMPONENTS
PROGRAM NO. 1, [illegible]

PRODUCT	PER CENT SLOPE	INDEX OF CORRELATION	STANDARD ERROR OF ESTIMATE (per cent)
Control Unit No. 2	77.7	.9[illegible]	[illegible].25
High Speed Printer No. 1	81.4	.992	2.[illegible]2
High Speed Printer No. 2	99.7	.9[illegible]4	2.64
Card Reader No. 1	84.8	.965	2.13
Tape Perforator	97.8	.9[illegible]	1.84
Magnetic Tape Handler	[illegible].7	.9[illegible]	1.[illegible]
Average	[illegible]7.[illegible]	.979	2.[illegible]

TABLE 5.2

SUMMARY OF P. R. C. CHARACTERISTICS
ELECTRONIC COMPUTERS
PROGRAM NO. 2 FIRM A

PRODUCT		PER CENT SLOPE	INDEX OF CORRELATION	STANDARD ERROR OF ESTIMATE (per cent)
Control Unit	1A	79.4	.992	3.09
Computer	1A	96.0	.738	1.62
Computer	2A	93.7	.986	1.15
Computer	3A	75.4	.995	2.69
Computer	4A	85.[illegible]	.9[illegible]	7.20
Computer	5A	85.0	.971	5.30
Computer	6A	75.4	.995	2.[illegible]
Computer	7A	96.5	.984	.[illegible]
Average		85.9	.946	3.06

TABLE 5.3

SUMMARY OF T. A. C. CHARACTERISTICS
ELECTRONIC DATA PROCESSING SYSTEM COMPONENTS
PROGRAM NO. 3, FIRM B

PRODUCT	PER CENT SLOPE	INDEX OF CORRELATION	STANDARD ERROR OF ESTIMATE (per cent)
Computer 1 B	84.9	.995	2.22
Computer 2 B	77.8	.972	9.01
Computer 3 B	[illegible]	.955	3.74
Computer 4 B	80.8	.980	4.52
Computer 5 B	85.1	.990	2.95
Computer 6 B	88.8	.962	4.46
Computer 7 B	77.7	.993	3.62
Computer 8 B	91.4	.911	2.22
Average	85.1	[illegible]	4.20
Data Storage Unit 1 B	90.3	.995	4.92
Data Storage Unit 2 B	82.5	.981	4.43
Data Storage Unit 3 B	78.8	.925	[illegible]
Average	83.8	.934	6.93
Control Unit 1 B	86.3	.934	6.01

TABLE 5.4

SUMMARY OF T. R. C. CHARACTERISTICS
BINDERY EQUIPMENT
PROGRAM NO. 4, FIRM C

BINDING MACHINE NUMBER	PER CENT SLOPE	INDEX OF CORRELATION	STANDARD ERROR OF ESTIMATE (per cent)
1	84.8	.996	1.18
2	96.0	.865	3.93
3	92.6	.935	2.09
4	87.0	.987	2.36
5	96.9	.984	1.17
6	90.1	.999	1.64
7	91.8	.998	.38
8	96.2	.989	.84
9	91.0	.975	1.30
10	91.5	.988	1.05
11	94.8	.999	.40
12	90.6	.999	.37
13	82.9	.980	1.70
14	88.8	.997	1.34
15	86.1	.994	2.78
16	84.4	.962	3.80
Average	89.98	.977	1.65

TABLE 5.5

SUMMARY OF T. R. C. CHARACTERISTICS
PRINTING PRESSES
PROGRAM NO. 5, FILM C

PRINTING PRESS NO.	PER CENT SHORT	INDEX OF CORRELATION	STANDARD ERROR OF ESTIMATE (per cent)
1	84.9	.999	.85
2	[illegible].5	.99[illegible]	.7[illegible]
3	86.3	.977	3.39
4	85.[illegible]	.994	2.13
5	91.9	.987	3.[illegible]9
6	87.[illegible]	.999	.7[illegible]
7	91.2	.999	.5[illegible]
8	85.4	.994	3.11
9	92.[illegible]	.9[illegible]	2.10
10	95.4	.9[illegible]	[illegible]
11	91.2	.9[illegible]	2.[illegible]
12	[illegible]3.4	.9[illegible]	.[illegible]
Average	88.7	.9[illegible]	2.1[illegible]

approximation of linearity. The straight line was computed through the use of the usual least squares method. In fifty-one out of fifty-four cases the index of correlation was greater than .90. In one instance the correlation index was .738. The average index for all products is .95. The average index for the various electronic data processing system components is .972, the range for (program No. 1) the six components being between .890 and .998. Program No. 2 experienced the lowest correlation, the average being .946, and a range between .738 and .996. Program No. 3, Firm B, consisted of eight computer components, three data storage units, and one control unit. The correlation average for computer components is .967, with a range of .911 and .995 the average index for data storage units is .954. The average index for the sixteen bindery units is .977, with a range of .868 and .999 at extremes. The twelve printing press models exhibit an average index of .990, and a range of .967 and .999.

Evidently, the index of correlation is higher than one would conclude merely from observation of the actual time reduction curves (Figures 4.1 through 4.23). On the basis of above analysis, we may conclude that actual time reduction curve data when plotted on double logarithmic scale tends to exhibit essentially a linear function.

Despite the high index of correlation to a straight line that is exhibited by data, a visual examination of the various time reduction curves found in Figures 4.1 through 4.23 indicates that there are numerous deviations from a straight line, which would, at those specific points, introduce serious error to our estimate. (Figures 4.1 through 4.23 may be found in the Appendix).

Departures from linearity

It is possible to have a relatively high index of correlation and yet find individual values to deviate widely from the straight line. Simple visual observation of time reduction curve derived from the plotting of actual data does not enable us to make any precise statements relative the reliability of the function. The important question that may be asked here is: with what degree of confidence may estimates be based on the linear form of the time reduction curve? In cases where the relationship between two variables is perfect, all of the plotted values for individual product units would fall on the line of regression. If such were the case, the regression line equation could be used as an exact tool for predicting the value of one variable from a given value of the other.

In most real life situations the values for the individual units do not fall on the straight line, and the relationship is not perfect. This latter case is certainly true of data for all products analyzed in this study. Under these circumstances, when the linear equation is used to estimate the man-hours per unit at a given cumulative quantity, the man-hour figure becomes only an estimate which is indicative of the average relationship between the two variables. Before this average relationship may be used in prediction with confidence, a value measuring the reliability of the average relationship and the concentration of the values about the least squares line must be computed.

The standard error of estimate is a statistical tool which provides a measure of reliability and concentration of values about the regression line. The standard error of estimate is similar to standard deviation except that the former deals specifically with curvlinear relationship, and values are developed through the use of logarithms. Hereafter, the standard error of estimate will be expressed as "S". Given an approximately normal distribution of points about the line of regression, the following statements may be made: (1) About sixty-eight cases out of one hundred will fall about the line within plus or minus 1S. (2) Ninety-five cases out of one hundred will fall within plus or minus 2S. (3) And 99.7 cases out of one hundred, will fall about the line within plus or minus 3S. If an estimate of an aggregate value of man-hours is desired for a given quantity of production, the estimated line of regression may be used with confidence. The actual value may not be on the regression line but in 99.7 out of one hundred cases, it will be within the limits of 3S. It is evident that the standard error of estimate (S) affords a measure of reliability of basing estimates on a line of regression.[1]

Because the time reduction curves were computed by means of logarithms, the S is also expressed in terms of logarithms. Since the standard error is difficult to interpret in this form, we have computed actual percentage values. The S for each of the fifty-four products will be found in Tables 5.1 through 5.5, column 4. It should be stated that the percentage error values are for 1S only. To obtain percentage values for 2S and 3S we need only to multiply

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[1]A detailed description of the statistical methods used in this study may be found in F. E. Croxton and D. J. Cowden, Applied General Statistics, (New York: Prentice-Hall, Inc., 1940), Chapter 23.

the value given by the number of S desired. The standard error of estimate percentage value is identical at any cumulative quantity, and is directly related to the least squares line fitted to actual data. It represents a constant ratio, in percentage terms, of the top line to the average line, and the average line to the lower line (-1S).

Obviously, a fitted average line with a small standard error of estimate is more reliable than one with a large S. The average S for programs one and two, experienced by firm A, are 2 and 3 per-cent respectively. These deviations are considered small and the line is reliable for estimating purposes. Firm B time reduction curves exhibit a larger S. In only three cases in ten, is the S larger than five per-cent. However, the data storage units have a high percentage S, the average being about seven per-cent, which is due largely to a twelve per-cent error in unit 3B data. The average S for program No. 3, computer component data is 4.20 per-cent, the highest being for unit 2B which amounts to nine per-cent.

The lowest S percentage was experienced by firm C, for bindery equipment and printing presses. For the twenty-eight products on which data was obtained from firm C, in ten cases the S from the least squares line is less than one per-cent. The S average for binding machine is 1.65 per-cent, while for printing presses it amounts to 1.73 per-cent (Table 5.4 and 5.5).

Before any conclusions relative the reliability of the time reduction curve in prediction can be made, we must first make a decision as to what percentage of S will be considered as reliable.

The accuracy necessary in a specific case depends on the use to which the estimate will be put. For the purpose of this investigation, an arbitrary limit of S of 4 per-cent magnitude was chosen. It is believed that S of less than 4 per-cent will provide sufficient accuracy for many purposes. Of the fifty-four lines of regression computed in only nine cases does the S percentage exceed this arbitary test of reliability. It should be noted that in six out of nine cases the reliability is of some usefulness because the S is less than 5 per-cent.

It is concluded that within certain confidence limits (4 per-cent) actual data tend to correspond to a linear function on log-log scale. Test of reliability of the linear function, as measured by the index of correlation and the standard error of estimate, indicates that the relationship is reliable.

Some Reasons for Departures from Linearity

While the industry average data may be useful for comparative purposes, in order to use the time reduction curve in specific situations, it becomes necessary to analyze the time reduction curve for individual models within individual production facilities. In Chapter 3, it is stated that the relationship between cumulative average man-hours required per unit and cumulative unit number will tend to exhibit a straight line on logarithmic paper. Unfortunately, the real situation is quite different from theory. It would be an unusual case if actual production was predicted with a great deal of accuracy. If this were the case, it would mean that the time reduction curve has anticipated all the possible factors that might arise to interfere with the expected course of events.

Usually, as a production program is put into effect and as actual direct man-hour data becomes available, deviations from the initial estimate of the time reduction curve are likely to appear. This should be expected since individual time reduction curves will usually reflect the individual factors that influence a specific production program. A visual examination of Figures 4.1 through 4.23 indicates that in a number of instances the deviations from the line are considerable. In many of the cases under consideration, the data approximates the linear function remarkably well.

It seems appropriate that an analysis be made of the possible causative factors responsible for the deviations. A conference was held with the department head concerned, cost analyst, and a foreman in order that the deviations be discussed. There was a general agreement that one of the most important factors responsible for deviations from linearity was the numerous engineering changes introduced while the units were in production. (The problem of engineering changes will be discussed in detail in Chapter 8). A large number of engineering changes of varying magnitude have been incorporated into the various units produced by firms A and B. Unfortunately, neither the additional man-hours required nor the time of incorporation can now be reconstructed, since many of the changes are effected without a change in blueprints, and in some cases, it takes a year to bring the latter up to date.

The second important deviation causing factor seems to be due to qualitative failures of parts and assemblies. It should be noted that this situation arises as a result of lack of proven design of the components and assemblies. A great amount of pressure was applied by top management of the company to be the first one on the market with a data processing system. As one company official put it:

"We had to give our sales force something to talk about."

Thus, as soon as the product left the research department, it went to design engineering where it was designed with top priority. Another rather unique situation existing in Company A, that may well add to the problem, lies in that the company has no production engineering department. Therefore, when assembly problems arise, as they are likely to on a new unit, they have to be solved by the assembly technicians. It is reasonable to expect that production or process engineering would foresee, and solve some of the problems arising in assembly.

A close examination of the qualitative failures reveals the following conditions to exist in firms A and B: (1) Over 70 per-cent of the parts going into the assembly are furnished by vendors over which the firms have no direct quality control. (2) Some of the parts received from vendors do not fit, and additional machining operations are performed. This time is charged as direct assembly labor, whereas, actually, it belongs to machining labor. In cases where a significant amount of this type of labor is expended, it should introduce a conservative bias into the time reduction curve for that unit. (3) Certain parts do not function when received in the assembly department. Unfortunately, because of the newness of the sub-assembly, it takes an excessive amount of time to determine whether or not it functions properly. The optical instrument going into one of the assemblies is a case in point. It took about two days to discover that the instrument was not operating properly. A few more weeks were required to return the instrument to vendor for repair and rework. (4) Often the assembly upon reaching one of the several inspection points will not function properly, and even after the problem is discovered it takes time to make the necessary adjustments.

Any of the above factors, when present interfere with the normal progress of time reduction. Even though the workers are kept busy at other tasks, the management feels that these interruptions cause the workers to be engaged inefficiently. Finally, it should be remembered that errors in time recording, in spite of the absence of a biased direction, will cause considerable dispersion below and above the time reduction curve.

A question may well be raised at this time whether the absence of factors disturbing normal progress would eliminate the serious deviations from linearity? The present data do not warrant any definite conclusions on this point. However, the time reduction curves on units which had a minimum of the disruptive factors to contend with show a remarkably linear pattern (see Figures 4.1, 4.12, 4.14, 4.17). It would, therefore, appear that a significantly better fit would be obtained if the technology were at a level which would permit interruption free assembly. Had this been a product where the state of the art were such that most of the construction problems had been overcome, it would be reasonable to expect a much closer approximation of a straight line. The data for firm C tends to support this indication. The manufacture of printing presses and binding machinery may be considered relatively standard. At least there have been no revolutionary changes for decades. Some engineering changes are incorporated while the unit is in production, but these are infrequent and most often do not affect man-hour requirements significantly.

It would appear on the basis of this analysis, that even though in specific instances deviations are significant, these are mainly a result of voluntary action on the part of management. In general, the time reduction may be closely approximated by a negatively accelerated linear function. The deviations will be greatest in those cases where technology has not reached a state of know-how necessary for uninterrupted production.

It would be desirable in the analysis of linearity of the time reduction curve to ascertain which of the major deviations from linearity are assignable to a change which was subject to managerial control. It would then be necessary to establish the amount of work added or deleted as a result of this change. The data should then be adjusted for the change, and any additional deviations might be termed unassignable, and therefore, most difficult to predict. It would not necessarily mean that the unassignable fluctuation is also unpredictable. It would probably mean that our knowledge of the fluctuation was such that we had no reason to expect the factor which has caused the deviation to be present. At any rate, it is impossible to make the assignable fluctuations adjustments in the present data for a number of reasons already stated above. Since there were a number of significant assignable changes in the products studied, it appears that failure to adjust the data would introduce a negative bias to the index of correlation and the standard error of estimate.

Summary and Conclusions

In this chapter empirical data was analyzed to obtain some evidence to several questions relative the time reduction curve phenomenon.

Empirical data was obtained from three midwest manufacturers. The data represents the direct man-hours consumed in the manufacture of fifty-four products and five distinct production programs.

Certain data generated by the airframe industry is also used to ascertain consistency of the relationships.

Despite the many difficulties and unsolved problems, it appears that some positive conclusions can be drawn.

First, empirical evidence strongly indicates that the existence of time reduction curve phenomenon is not predicated on the use of a planned time reduction function. The firms, from whom data were obtained, did not employ the time reduction curve for the purposes of planning operations. A time reduction curve was computed for each of the fifty-four products. In each case the regression line had a significantly negative slope.

Second, empirical man-hour data when plotted on double logarithmic scales tends to evidence an essentially linear function. In addition, it was determined that the linear function is reliable, within stated confidence limits, for the purpose of estimating man-hours. In all but three cases the data plotted on double logarithmic scales resulted in a close approximation of a straight line. The average index of curvilinear correlation for all fifty-four cases is greater than .95. The standard error of estimate was used as a measure of reliability. It was found that in 84 per-cent of the cases, estimates based on the linear form of the time reduction are highly reliable (less than 4 per-cent standard error of estimate). The small standard error of estimate indicates that there is a high degree of concentration of values about the computed line.

In a number of cases significant deviations from the straight line were observed. Analysis of these deviations indicates that most of them are assignable to changes in the product and in some cases to low level of technical knowledge. It was found that in situations where product changes and component failure was relatively absent, deviations from the straight line are minor.

The next chapter is devoted to an analysis of slope uniformity of the empirical time reduction curve, as well as to problems of forecasting slope for the purpose of projecting man-hours to be consumed in production.

CHAPTER VI

ESTIMATING THE RATE OF TIME REDUCTION

Introduction

The slope characteristic of the time reduction curve is of prime importance to the users of this tool. Slope, as defined in the time reduction curve usage, determines the rate of time reduction as additional units of a product are manufactured. Thus, the steeper the slope of the time reduction curve, the greater will be the time reduction between doubled quantities. Even more important is the question whether or not there is sufficient uniformity in the rate of time reduction experienced by a firm so that this typical rate may be used in forecasting man-hour requirements of future production.

The purpose of this chapter is to determine the magnitude of variation in the rate of time reduction for the following situations: Several firms manufacturing similar products, non-similar products manufactured by one firm, and also various models of a basic product type manufactured by one firm. For the purpose of this analysis similar products are defined as those products whose function and construction are basically the same, even though they may be produced by different firms. For example, all models of B-24 bomber aircraft are considered similar to each other. A printing press is considered as a basic product type although there may be a number of models of this type product.

Another task of this chapter is to explore the possibility of estimating the rate of time reduction on the basis of man-hour data obtained after an initial quantity of units have been produced. Man-hour estimates based on the forecasted rate of time reduction will be made, and the resulting error will be indicated.

It must be recognized that failure to predict the rate of time reduction places a serious limitation on the usefulness of the time reduction curve for the purposes of forecasting direct man-hours required in a production program. However, the potential gains from projections after a limited quantity has been produced should not be overlooked.

Uniformity in Slope

The percentage slope of the time reduction curves for fifty-four products was computed. In each case the least squares method of fitting the straight line was used. This method is more laborious but is considered more accurate than the simple observation method frequently used in practical applications.

The computed slope characteristics for each of the fifty-four products are given in Tables 5.1 through 5.5 of Chapter 5. The slope for each of the five production programs will be considered separately. There is no reason to expect uniformity in slope for the data processing equipment because the design and the function of the various units may be considered to be different.

The percentage slope for program one ranges from 77.7 to 97.6. In program two (firm A), which consists of various computer components, the production process is similar in that all direct work may be classified as being concerned with electronic precision work. The eight computer components are different to the extent that each unit is designed to perform a function in an automated system. The variation in the percentage slope of program two units ranges from 75.4 to 96.5 per-cent.

A somewhat greater regularity of slope was experienced by firm B. The dispersion from the average of 85.1 per-cent is not as large, the range being between 84.9 and 90.6 per-cent, resulting in a slope variation of about 6 per-cent.

The time reduction curve slope experienced by firm C, on programs four and five shows a surprising amount of irregularity. The slope range for bindery equipment (Table 5.4) is from 82.9 to 96.2 per-cent, or a variation of 13.3 per-cent at extreme points. The range for printing machines is a little smaller, being between 84.9 and 95.4 per-cent, with about a 10 per-cent interval. It appears that for most situations the error in the man-hour forecast, which would result from a 5 per-cent error in choosing the proper slope, would be of such magnitude as to make the man-hour prediction highly unreliable. The wide ranges in the slope of similar products indicates that the possibility of an error greater than 5 per-cent is large.

A Boeing study of World War II airframe production man-hours indicates that significant variation in the slope of the time reduction curve may be expected.[1]

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[1] Boeing Document No. 12331, (Wichita, Kansas: The Boeing Airplane Company, n.d.).

Analysis of World War II production experience of a number of firms shows that the average slope of time reduction for all firms and models was 79.8 per-cent. However, the time reduction curve slopes for individual airframes of the same period varied from 65 to 93 per-cent. The individual time reduction curves for the various models and facilities are shown in Table 5.6.

TABLE 5.6*

PERCENTAGE SLOPE OF TYPICAL WORLD WAR II TIME REDUCTION CURVES

Boeing-Wichita (first 900 B-29's)	71.8%
Boeing-Wichita (last 800 B-29's)	69.5
Boeing-Renton (first 400 B-29's)	80.5
Boeing-Renton (last 700 B-29's)	79.0
Lockheed-Burbank (B-17)	65.3
Douglas-Long Beach (first 1000 B-17's)	77.4
Convair-Forth Worth (first 1000 B-24D's)	76.4
Douglas-Tulsa (B24E)	75.0
Ford-Willow Run (B-24)	70.8
North American-Dallas (B-24)	75.0
Beech-Wichita (AT-10)	76.7
North American-Dallas (AT-6)	93.0
Republic-Farmingdale (P-47N)	89.0

*SOURCE: Boeing Document No. 12381, The Boeing Airplane Company, Wichita, (n.d.).

Table 5.6 shows that a different slope was experienced in the following cases: (1) For airframe types that were different. (2) For different models of the same types of airframe. (3) For the same model airframe produced by the same company at different plants (B-29's produced by Boeing). (4) The same model airframe produced in the same plant (B-29's at Boeing) at various cumulative quantities.

This study and the above study of World War II production by Boeing indicate that considerable variation in the percentage slope may be expected in several categories.

First, there is a wide range of variation in the percentage slope among firms manufacturing either similar or identical products. Comparison of electronic data computer components manufactured by firms A and B shows that slope varies from 77.7 to 97.6 per-cent. A question relative the extent of similarity may be raised in the case of products manufactured by firms A and B. On the other hand, even when the product is identical a considerable variation in slope was experienced. Table 5.6 shows that the four firms producing the B-24 bombers experienced a time reduction curve slope range of 70 to 76 per-cent. In the production of B-17 bombers Douglas experienced a curve slope of 77.4 per-cent as compared to 65.3 per-cent experienced by Lockheed.

Second, analysis of data obtained from firms A and C indicates that the variations in the percentage slope for programs within a firm are extensive. In each case the range in variation is over 10 per-cent.

Third, there appears to be significant variation in the percentage slope experienced by a firm manufacturing several models of a product type. The difference in slope for the sixteen models of bindery machines manufactured by firm C is 13 per-cent between the lowest and the highest experienced time reduction curve. The range in curve slope characteristics for the twelve printing press units is from 84.9 to 95.4 per-cent. In view of the size of the variation in the slope of time reduction curve for various models of a product type, it is concluded that there are serious limitations in applying the slope experienced in the manufacture of a given product to the forecasting of man-hours of future models of the same product.

In general, it may be stated that the time reduction curve slope tends to vary among firms manufacturing similar products, among products manufactured by a firm, and also various models of a basic type of product manufactured by a firm. The variation in slope of historical time reduction curves is so large as to preclude the use of experienced slope in forecasting of man-hour requirements of subsequent models of a product. It must not be assumed that slope which was experienced in the past is of no value. Where the accuracy needed is less than 5 per-cent, and where extensive knowledge of slope determinants exists, a firm may find it useful to make projections along experienced slope despite the dangers of error. Under these circumstances the question may well be not how accurate does the time reduction curve predict, but how well does it predict as compared to an alternative method.

Next, a method of forecasting the time reduction curve slope will be discussed.

A Method of Slope Prediction

The time reduction curve slope is highly irregular and therefore unpredictable in the required accuracy range.

It may be possible to obtain an indication of slope early after production data on a certain number of units has become available. In practice the slope for following units to be produced is often projected on the basis of several units produced.

When a firm wishes to forecast the slope of the time reduction curve to be used in projection of man-hours required in production it is necessary to determine how many units of a product must be produced before the percentage slope of specified accuracy may be predicted.

It is logical that the number of units which must be plotted before a prediction of slope can be made, is a function of: (1) The index of correlation of data to the line of regression. (2) The required accuracy in the percentage slope. (3) The actual error which will be tolerated in any given situation. Given the preceding, an equation may be used to obtain the number of units which must be plotted before slope can be predicted.

Let N be the number of observations we need. Let r be the value of the index of correlation coefficient. Let t_{N-2} be the t value corresponding to n=N-2 for a given alpha (say alpha = .05 for example). Let e be the per-cent slope error which is acceptable. Then the solution for N may be obtained in the following equation:[2]

$$N = \frac{t_{N-2}}{\sqrt{N-2}} = \frac{(e)\quad(r)}{\sqrt{1-(r)^2}}$$

As an example, this method is applied to a case where six units were plotted and an index of correlation (r) is .98. Assume that it is required that alpha (confidence limit) equal .05, i.e. 95 per-cent confidence of results is required. Assume that the actual error in slope which will be tolerated is equal to .10.

$$\text{Then,}\quad \frac{t_{N-2}\ (.05)}{\sqrt{N-2}} = \frac{(.10)\quad(.98)}{\sqrt{1-(.98)^2}} = .492$$

Referring to the t-table (may be found in most statistics texts) for 5 per-cent confidence the n which approximates .492 may be obtained as follows:

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[2] For proof that the equation is correct the reader is referred to J. F. Kenny and E. S. Keeping, Mathematics of Statistics, (2d ed. rev.; New York: Van Nostrand, 1951), p. 210.

Try n = N-2 = 18 in t-table, then

$$\frac{t_{18}(.05)}{\sqrt{18}} = \frac{2.101}{\sqrt{4.243}} = .495$$ which is approximately

.492. Hence, N = 18 + 2 = 20. Thus, 20 is the required number of observations that are needed before curve slope, of above confidence limits, can be estimated.

It is evident from the preceding example that the greater the required accuracy the larger number of units (N) will have to be plotted before slope can be predicted. When using this method it is advisable to report man-hour data on a per unit or small lot basis, because in cases where the man-hour data is reported and plotted on a lot basis, the quantity produced may be so large as to negate any benefit derived from the use of the curve. The usefulness of the above method is questionable when the number of units to be manufactured is small, and when the index of correlation is lower than .95.

There are two assumptions which must be made before the validity of the above method can be accepted. We must assume that the items for which slope prediction is being made are essentially the same as those on the basis of which the slope is being predicted, and also that the basic circumstances of manufacturing are unchanged.

It appears that the reliability of the time reduction curve for forecasting purposes depends on how many points are needed before slope can be predicted. If fifty per-cent of the total to be produced is necessary, the benefits derived from the use of the curve are doubtful at least. On the other hand, our data indicates that the slope trend is established and may be observed relatively early. Whether or not it is worthwhile to use the curve in a given case, must be answered in the context of a specific situation.

The isolation and analysis of factors which affect the slope is beyond the scope of this study. For a discussion of some general factors, which are judged to have an important influence on the time reduction curve, the reader is referred to Chapter 7. Slope is probably a result of the unique production function which may differ among firms of a given industry, as well as for various products manufactured by a single firm.

Estimating from Initial Quantity

The foregoing analysis indicates that at present it is not possible to estimate the rate of time reduction applicable to future manufacturing on the basis of past experience. There is another alternative available to a firm faced with the problem of forecasting direct man-hour requirements. It may be possible to estimate the slope of the time reduction curve on the basis of data which becomes available after an initial quantity of a product is manufactured.

Following is a brief description of the method used to estimate the slope. Cumulative average man-hours per unit were plotted on double logarithmic scales. It appeared logical that a greater number of man-hour values will have to be plotted in those cases where the deviations from the straight line are pronounced. Accordingly, at first only three values were plotted. If the three values approximated a straight line, these values were used to estimate the slope to be used for projecting man-hour requirements of follow-on production.

If it became apparent, through observation, that one of the three plotted values showed a pronounced deviation from the straight line another two points were added and a total of five values were used in estimating slope. Of the twenty-eight cases for which computations were made, three values were used in twenty-two cases, four values were used in three cases, and five values were used in three cases.

The results of the analysis may be observed in Table 6.1. Column one shows the case number, which in turn corresponds to the Table number in Chapter 4, where the original data may be found. Column two shows the percentage slope which was estimated on the basis of the number of man-hour values given in column three. Because most of the data were available on a lot basis, column four gives the number of units that are included in the number of lots shown in column three. It will be noted that in the first three cases (Table 6.1) the data was available on a unit basis and the unit values were used directly.

In each case the estimated slope characteristic pertains to the line of best fit computed on the basis of the values reported in column three and four. The straight line of best fit was computed through the use of the least squares method. The actual slope for the production run is shown in column five. The error in slope estimate is given in column six. There is a tendency to underestimate the steepness of the line when the latter is being estimated on the basis of a limited quantity of units. In twenty-one of the twenty-eight cases the slope was underestimated, in six cases the slope was overestimated, and in one case the estimated and the actual were identical. The largest difference between the actual and the estimated amounts to 4.3 per-cent.

TABLE [illegible].1

COMPARISON OF ACTUAL VS. ESTIMATED, MAN-HOURS AND RATE OF TIME REDUCTION

Case No.	Estimated Slope Per-Cent	No. of Lots Used to Estimate Slope	No. of Units in Lots	Actual Slope for Production Run Per-Cent	Error in Slope Estimate Per-Cent	Quantity	Estimated Cumulative Average Man-Hours Per-Unit	Actual Cumulative Average Man-Hours Per-Unit	Error in Estimate Per-Cent
4.1	76.4	-	3	77.7	-1.7	5	618	631	-2.1
4.3	96.0	-	3	93.7	+2.5	7	1,415	1,335	+5.9
						10	1,336	1,301	+6.5
4.6	86.7	-	5	86.7	0.0	20	343	334	+2.7
4.15	78.2	4	30	77.0	+1.6	70	274	253	+3.3
						90	239	241	-0.8
4.17	92.6	4	30	88.6	+4.5	50	299	264	+13.3
						70	269	234	+24.0
4.18	82.4	3	20	85.1	+3.3	50	83	108	-23.0
						70	80	96	-20.0
4.19	89.6	3	20	88.6	+1.1	50	148	144	+2.3
						70	140	125	+12.0
4.20	94.2	3	20	90.3	+4.3	70	196	185	+5.9
						90	192	170	+12.9
						110	188	153	+22.9
4.23	74.7	3	20	77.7	-4.0	50	232	247	-6.5
						70	202	208	-2.9
4.24	88.5	3	20	88.4	+0.1	40	122	126	-3.3
						60	113	114	-0.9

TABLE 6.1 - Continued

Case No.	Estimated Slope Per-Cent	No. of Lots Used to Estimate Slope	No. of Units in Lots	Actual Slope for Production Run Per-Cent	Error in Slope Estimate Per-Cent	Quantity	Estimated Cumulative Average Man-Hours Per-Unit	Actual Cumulative Average Man-Hours Per-Unit	Error in Estimate Per-Cent
4.25	89.2	5	40	86.4	+3.2	50 80	78 72	75 64	+4.3 +12.1
4.26	84.8	4	30	84.9	-0.1	40 70	297 260	300 253	-1.0 +2.7
4.27	86.8	3	19	84.8	+2.4	36 56	775 709	748 659	+3.6 +7.6
4.33	97.1	3	22	96.2	+0.9	48 66	267 263	264 259	+1.1 +1.5
4.38	81.4	3	72	82.9	-1.8	102	300	336	-12.0
4.39	90.5	3	40	88.8	+1.9	70 85	402 391	396 383	+1.5 +2.1
4.41	88.0	3	60	84.4	+4.3	80 120	300 278	288 249	+4.2 +11.6
4.43	89.0	3	50	88.5	+0.6	90 110	809 783	796 770	+1.6 +1.7
4.44	89.0	3	35	86.3	+3.1	65 80	935 903	908 876	+3.0 +3.1
4.45	86.7	3	60	85.0	+2.0	110 135	814 781	743 701	+9.6 +11.4
4.46	93.3	3	34	91.9	+1.5	74 94	721 703	697 674	+3.4 +4.3

TABLE 6.1 - Continued

Case No.	Estimated Slope Per-Cent	No. of Lots Used to Estimate Slope	No. of Units in Lots	Actual Slope for Production Run Per-Cent	Error in Slope Estimate Per-Cent	Quantity	Estimated Cumulative Average Man-Hours Per-Unit	Actual Cumulative Average Man-Hours Per-Unit	Error in Estimate Per-Cent
4.47	87.4	3	30	87.0	+0.5	70 90	1,529 1,453	1,550 1,461	-1.4 -0.5
4.48	91.7	5	111	91.2	+0.5	403 671	543 511	525 473	+3.5 +6.8
4.49	85.0	3	36	85.4	+0.5	136 236	480 404	500 409	-4.1 -1.4
4.50	92.7	3	40	92.1	+0.6	205 339	631 598	617 565	+2.2 +5.9
4.51	94.7	3	35	95.4	-0.7	120 168	517 504	515 501	+0.4 +0.6
4.52	91.0	3	30	91.3	-0.3	122 171	849 811	879 881	-3.4 -8.6
4.53	85.7	3	13	85.4	+0.2	38 49	1,119 1,124	1,225 1,153	-0.6 -0.2

The average error for all twenty-eight cases is 1.8 per-cent. Evidently, relatively accurate slope estimates may be obtained on the basis of a limited quantity of a product.

Another indication of the accuracy in estimates may be obtained from using the estimated slope to project man-hour values for greater quantities. The estimated cumulative average man-hours per unit are shown in column eight of Table 6.1. These values were obtained through the extension of the line computed for the limited quantity of units. The size of the actual error is given in column ten of Table 6.1

TABLE 6.2

FREQUENCY DISTRIBUTION OF ERROR IN ESTIMATE

Size of Error in Per-Cent	No. of Cases	Per-Cent of Cases
0 to 2.99	24	40.8
3 to 4.99	11	20.4
5 to 6.99	6	11.1
7 to 9.99	4	7.4
10 to 12.99	6	11.1
13 to 16.99	1	1.8
17 to 20.99	1	1.8
21 to 24.99	3	5.6
	54	100.0

Table 6.1 indicates that the size and the direction of error may vary at different quantities. An error in estimate was computed at fifty-four points of the twenty-eight cases. In other words in many of the cases the error was computed at two quantities. Table 6.2 presents the distribution of errors. It is found that in 72.3 per-cent of cases the error is less than 7 per-cent, in 90.8 of cases the error is less than 13 per-cent. However, in 7.4 per-cent of cases the error (in 4 cases) range is from 20 to 25 per-cent. In six cases the cumulative average value was converted into unit data and compared to actual unit hours. The error in estimate of the unit values is only slightly

greater. The increase in error was well within 2 per-cent of the error in cumulative average hour estimates.

Summary and Conclusions

Chapter 6 was devoted to the analysis and discussion of the magnitude of variation in the rate of time reduction of the fifty-four empirical time reduction functions. Problems of forecasting the applicable rate of time reduction were considered and the possibility of estimating slope on the basis of an initial quantity of units of a product was explored in detail. Using the estimated slope of the time reduction curve, man-hour projections for various quantities were made, and the resulting error indicated.

First, the computed time reduction curve slope tends to vary among firms manufacturing similar products, non-similar products manufactured by one firm, and also models of a basic product type manufactured by one firm. In every category the variation in slope is in excess of 6 per-cent. This amount is judged to be excessive for forecasting man-hour requirements.

It should not be concluded from the preceding that past experience is of no value in estimating. Past experience is most valuable providing it is recorded and analyzed in sufficient detail to establish relationships. It appears that the high variation in slope which was found in present data is at least partly due to the fact that we have assumed that know how and learning were comparable for all products and models when the production program was started. To the extent that previous learning of various degrees was present at the time production started, we may expect the slope of individual models to vary. If proper adjustments in the data are made, a greater uniformity of slope should be obtained.

Second, a method of estimating slope percentage after a certain number of units have been manufactured is proposed and should yield satisfactory results in most cases. This mathematical method of estimating slope is of doubtful value in cases where the number of units to be produced is small or where the index of correlation for the early units is low. Under these circumstances it would be difficult to predict the slope characteristic sufficiently early to be of value in forecasting.

Third, estimating the rate of time reduction on the basis of three to five initial man-hour values (plot points) at various quantities produces a relatively close approximation of the actually experienced rate. The average error in slope estimate for all cases is 1.8 per-cent. The largest error was 4.5 per-cent.

Fourth, the rate of time reduction estimated in this manner was used in forecasting man-hour requirements of follow-on product quantities. Comparison of estimated and actual direct man-hours for twenty-eight products indicates that the error in estimate, at various quantities of production, is less than 7 per-cent in 72.3 per-cent of cases. In 90.8 of the cases the error is less than 13 per-cent. However, in 7.4 per-cent of the cases the error ranges between 20 and 24 per-cent.

The conclusions of this Chapter and Chapter 5 are limited by the fact that data were obtained from three manufacturers only. However, man-hour requirements of five production programs and fifty-four products were studied.

In Chapter 7, factors which are judged to have an important influence on time reduction curve characteristics will be discussed briefly.

CHAPTER VII

SOME FACTORS AFFECTING SLOPE

Introduction

There is a large number of factors that affect the time reduction curve characteristics. An intensive analysis of the nature of these factors would be desirable, but is beyond the scope of this investigation. No attempt will be made to determine the relative importance of the various factors or their effect on time reduction. It appears pertinent to discuss a number of variables which are judged to be important in their influence on man-hour requirements.

The following discussion is based on information which was obtained from interviews held with personnel of the three firms, and some published material available.

Manual Dexterity and Group Skills

The importance of workers as a group and as individuals should not be overlooked in any manufacturing time reduction scheme. The data obtained from firm C, shows that the decrease in man-hours for one of the models continues to take place after nine years of production (see Figure 4.17, printing press No. 7), and after cumulative output has reached close to one thousand units. In Chapter 2 it was stated that most of the experiments on the acquisition of skills tend to support the proposition that a plateau is reached in learning an industrial task. It should be added that these controlled experiments were of relatively short duration (less than six months). There is no general agreement on the shape of an individual learner's curve over longer periods of time. At this time it is impossible to state how much of the time reduction contained in the time reduction curve should be credited to worker's learning. It may well be that the high percentage of time reduction per unit experienced at the initial stages of a production program is due to workers' learning.

In connection with learning on the part of production employees, some troublesome questions are raised when an attempt is made to determine what influence, if any, learning has on future manufacturing time reduction. It is reasonable to assume that in manufacturing there are always some operations which are similar or identical to those performed in the past. It may be expected that in those cases where similarity or change is accurately estimated and incorporated in the adjusted time reduction curve, this problem will be minor.

On the other hand, there are certainly some operations, riveting for example, where it is not at all reasonable to assume that as far as improvement is concerned, the organization is on the 5th or 50th unit, where in fact, the operation has not changed in the last 5,000 units. In other words, although a plant's production program of a particular item may be in its early stages on the time reduction curve, many of the parts and perhaps even subassemblies used in production may be at an advanced stage which on the man-hour per unit basis will aproximate a constant level. Because of accumulated learning, it should be emphasized that the time reduction curve technique cannot be applied without regard to previous manufacture of similar products. Obviously, learning on the part of the workers carries over from one product to the next. How can this be explained in view of the empirical data on the shape of

the time reduction curve? It seems that the foregoing substantiates the view that in an experienced facility the improvement rate is primarily a result of management and methods improvement. Also, although it may be useful to know the exact amount of previous learning, this is not essential for working purposes, nor has a usable method been developed to measure such.

Some Long Range Factors

There are a number of factors which may be found existing in a firm, and which are probably responsible for some of the variation in slope. For example, firms A and B have manufactured small electronic components, which are somewhat similar yet the variation in slope is considerable. Some qualitative factors which in the past have been reported to have an influence on man-hour consumption will be discussed. These are termed long-range because it is assumed that it takes an extended period of time to develop these manpower attributes.

A number of studies have shown that morale and motivation on one hand, and workers' productivity on the other, are positively related. The Hawthorne works study at Western Electric, performed by Roethlisberger and others seems to indicate that morale and attitude are important to productivity.[1] Since this pioneering effort, others have come up with similar results.[2]

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[1] F. J. Roethlisberger and W. J. Dickson, Management and the Worker, (Cambridge: Harvard University Press, 1950).

[2] Arthur H. Brayfield and Walter H. Crocket, "Employee Attitudes and Employee Performance," Psychological Bulletin, (September, 1955), pp. 396-424.

When an organization has a sound suggestion system, all employees may participate in the improvement effort, and this should result in greater production efficiency. Studies have shown that employees can make suggestions that improve machines, develop new devices, procedures, and techniques that result in more efficient production.[3] The number of shifts that a firm operates will also affect the time reduction curve. It was found that the slope of the time reduction curve for second and third shift operations is not as steep as for the first shift because the latter shifts are less efficient. As a rule of thumb, a number of airframe manufacturers use ten, eight and six as indices of efficiency for first, second and third shifts.[4] Therefore, we may expect the time reduction curve to be flatter on a multishift plant as compared to a single shift operation, though the item produced and all other things are assumed to be equal.

Turnover of production personnel is very expensive in terms of production lost and low initial output of a new employee. While some turnover is not avoidable, excessive turnover rates in a specific plant may cause the slope of the time reduction curve to be flatter than in cases of low turnover percentage.

The above discussion deals with only a few of the more obvious manpower management factors that affect the production efficiency and therefore both the slope and the position of the time reduction curve.

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[3] J. L. Himes, "Suggestion Schemes--A Summary of the Literature," Industrial Psychology and Personnel Practice, Vol. 8, No. 1, (March, 1952), pp. 27-35.

[4] Information obtained from several airframe companies.

This discussion is brief because the material is covered in greater detail in sources indicated.

The engineering departments may influence the rate of improvement in several ways, both before actual production gets under way and during production. This includes clarification of drawings, clarification of engineering errors, simplification in designs, and normal development of new techniques. Often in the case of various high priority programs, production commences long before the model is engineered for mass production. Thus, production exceeds engineering provisions and thereby results in relatively flat time reduction curve slope. The quality of engineering liaison with the production organization will also affect the rate of improvement.

In addition to design engineering, the activities of the industrial engineering department play an important role. Time and motion study may be expected to have a direct influence on the number of man-hours required. Methods analysis, systems and procedures improvements, and development of manufacturing aids will bear on time reduction.

The production control functions are all important to a smooth operation of all production phases. Dispatch, planning, routing, shoploading, and the general efficiency of operating controls is required. Tooling is another factor that is often mentioned in connection with the rate of improvement. Occasionally production starts with temporary or low production tools. It may be expected that these tools will require extensive maintenance attention and production delays. Again, because of great demand for some items it may be necessary to start production before all tools are available.

Modernization and automation will have drastic effects on the rate of improvement. Recently, for example, The Boeing Airplane Company plant in Wichita, Kansas, installed four punched tape controlled machines that are building relatively complex wing panels for the B-52G stratofortress. Only two men are required to run the new machines replacing forty-eight former riveters.[5] This type of change that is taking place in many industries cannot help but reduce the man-hour requirement.

Procurement of effective material sizes that minimize cutting, handling, and scrap all enhance production efficiency. Making certain that materials and component parts are on hand, development of efficient sources of production, and economic use of outside production can make a great contribution to the reduction in man-hour requirements.

The Effect of Scale of Production

Scale of production is seldom mentioned in connection with the time reduction curve, and is believed to have little effect. It cannot, however, be assumed that the rate of production has no effect on man-hour requirements per unit. A visual examination of time reduction curves of different facilities manufacturing like models at varying rates, does not indicate correlation of rate of production and slope or position of the time reduction curve.[6] It seems that in airframe production there are certain essential requirements in machinery and

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[5] Newsweek, February 23, 1959, p. 80.

[6] Source Book, op. cit., Vol. II.

and equipment which do not vary in kind as rates of production are increased. The only thing that is necessary for higher rate of production are additional sets of equipment and machinery and, of course, larger floor space. Mr. Hirsch comes to the same conclusion in his study of a machine tool manufacturer. Hirsch explains this phenomenon as being at least partly due to the fact that relatively fixed quantities of machining and assembling require relatively fixed combinations of equipment.[7] Mr. Asher, in a study of costs, says that there are two costs that rate of production will affect: set up costs and the number of subassemblies that will be used.[8]

It seems that the volume of production is of minor importance and is overshadowed by the importance of cumulative production. These two are of course related, in that the rate will determine the flow time of a particular model. Our knowledge of time reduction curve at extremely low rates is too meager to warrant any conclusions. An examination of data obtained from firm C, to see if there is a relationship between volume of output and the slope of the curve did not result in any evidence to the affirmative.

Man-hours Required and Type of Product

One of the inquiries into causes of variation in the slope of the time reduction curve is The Acceleration of Airframe Production,[9] report prepared at Headquarters, Air Materiel Command in 1947. During

[7] W. Z. Hirsch, "Manufacturing Progress Functions," The Review of Economics and Statistics, Vol. 34 (May, 1952), pp. 143-145.

[8] H. Asher, op. cit., p. 87.

[9] J. R. Crawford and E. Strauss, The Acceleration of Airframe Production, Air Materiel Command, Dayton, Ohio, 1947.

World War II, the aircraft industry became what may be termed as mass production enterprise. This production experience furnished an attractive opportunity for study and analysis of factors which influence the rate of improvement in man-hours. The above report was primarily interested in discovery of planning factors, which might be useful as a guide in present and future production planning and analysis. Since variations in the slope of the time reduction curve have a direct influence on lead time, a number of potential causes were analyzed to see if there was a relationship between slope and product characteristics. To determine the influence of airframe unit weight, the data were analyzed to see if unit weight had an influence on direct man-hours. Plotting of direct man-hours per pound on the vertical axis and the airframe unit weight on horizontal axis did not indicate any relationship.[10] It seemed reasonable to expect that airframe type would influence the direct man-hours required. Samples were taken for various types of airframes and at various unit numbers. Deviations from the average direct man-hours per pound for each type of plane were large. A further analysis of averages and deviations shows significant variances within the particular type of plane. For example, the study of direct man-hours for fighter aircraft reveals that although the average was relatively high, some fighter data consistently showed lower man-hour ranges. In each case of these low man-hour cases, the fighters were manufactured by what was considered large, experienced, and well organized companies.

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[10] Ibid, p. 83.

The series for bombers, fighters, transports, and trainers were plotted at selected cumulative plane numbers to compare with the average for the industry as a whole. The bomber curve is slightly below the industry average curve, and this may be ascribed to the fact that in general, bomber aircraft permit greater accessibility and the fact that this program was given top priority. The position of the fighter curve is consistently above the industry average and this is probably due to the fact that fighter aircraft are usually thought of as being more complex than other types of aircraft. Also, this production never reached the stability enjoyed by the bomber program. The cumulative average curve for trainers starts out above the average for all aircraft and then drops below average, and finally, rises above it at the conclusion of the war. In part, this behavior may be explained in that no mass production assembly line methods were employed at first. The urgency of early pilot training and introduction of mass production methods accounts for the rapid improvement. As the demand for trainers was satisfied and the rate of production declined sharply, the improvement was less than average for all other programs.

Although the above brief analysis leaves some questions unanswered, it indicates what may reasonably be expected, e.g. the characteristic of an individual product will influence its own rate of improvement to be unlike that of other units. Thus, characteristics of complexity, accessibility, priority status, and production methods all enter into the picture to present a partial explanation of man-hour deviations in terms of type product.

Another attempt to explain variation from the industry average man-hours is an analysis of the influence of comparative newness of a particular model or facility. Each model was classified as to whether it was new or proven, and as to whether it was produced in a new or experienced facility. The classes which were developed are listed below:[11]

Class	No. of Models in Class
(1) Proven models, experienced facility	43
(2) Proven models, new facilities	22
(3) New models, new or experienced facilities	53

Next, weighted averages of direct man-hours per pound at selected cumulative intervals were calculated for each of the above classes. The data indicates that the early units of proven models produced at experienced facilities cost less in terms of direct man-hour input than does the average for all models. As more units were produced, this advantage was not maintained.

The new facilities consisted primarily of secondary and tertiary producers. The new facilities curve follows industry average curve very closely until it reaches about the middle portion of the progress curve. Then, the savings that secondary sources realize, as a result of the introduction of engineering changes already proven by the primary source, become apparent. The production of a new model, whether the facility is experienced or not, requires consistently above average man-hours per unit. Production problems which arise when engineering changes are introduced are worked out by the facility which developed the original model. Therefore, secondary sources

[11] Ibid, p. 84.

benefit from receiving changes in already known form. The indication is strong that the relative newness of a model and facility did have an effect on the rate of improvement.

The above tends to support findings reported in Chapter 5. There are many assignable reasons for the significant variation in slope, and therefore, the industry average slope for a particular product type is of little use for predictive purposes.

Management Learning

As management becomes increasingly aware of the special problems involved in the manufacture of a new or modified product, the performance of the basic managerial functions may become more efficient. Management may be expected to anticipate production problems to a greater extent, and be prepared to deal with them in an expeditious manner. The quality of management may be an important variable. Especially in the introduction of new models, procedures, techniques and general organization of work, management must take the lead.

Summary and Conclusions

Although empirical analysis of the reasons for decline in man-hours is not the purpose of this study, nevertheless, it seemed appropriate to discuss some of the forces which are judged to be important in determining time reduction curve slope and the decrease in man-hour requirements.

It would be all but impossible to assign a quantitative weight to the almost endless number of possible factors that may influence the time reduction curve. It is hoped that a study of the major factors will be made in the future. At present the best approach seems to be to consider each individual case separately and take into account the expected influences. Here the historical shape of an individual firm's improvement curve may be helpful. But at the same time we must realize that history does not always repeat itself, nor are conditions of a production situation always duplicated.

However, past time reduction curve of an individual firm may be expected to continue. In other words, although we cannot make an objective determination of the various factors that affect the slope of time reduction or the position of the curve on the vertical axis, an adjusted historical curve may have most of these factors already incorporated. In the final analysis management can to a large extent control the negative influence of the many factors that affect the rate of time reduction once the factors that are expected to cause production inefficiencies become known.

As yet, empirical evidence does not indicate that all the factors that affect the slope of improvement or position of the time reduction curve are known or have been discovered.

In Chapter 8, the problems of time reduction curve analysis, after a product change is introduced, will be discussed.

CHAPTER VIII

THE PROBLEM OF DESIGN CHANGE

Introduction

It will be recalled that until now we have assumed that the model is unchanged during any particular period of production and, therefore, no allowances for change were necessary. This simplifying assumption was necessary in order for the time reduction curve to hold true in any given situation. The fact that absence of model changes is seldom found needs no elaboration. Continuous change of product design is one of the most important characteristics of our economy. An example of this may be the consumers goods market where the annual model change is an accepted practice, and where change in design is expected and demanded. In some cases even in the absence of physical change, the manufacturers claim that the product is new, presumably in the hope that this will increase the salesability of the product.

A great deal of variability as to the amount and frequency of changes that are introduced during a particular fiscal year or within a production program may be expected. Certain industrial products undergo major change on what amounts to a continuous basis. Here the pace of technological development is probably the most important single factor in determining, or rather initiating, the change in design. The extreme example of the rapidity of design change is undoubtedly today's defense industry. In order to keep ahead of adversaries, the weapon system design change has to be carried on a continuous basis if it is going to be up to date in any sense of the word. In some cases, major production programs never get beyond the experimental stage and have to be phased out before the production stage is reached. In an attempt to accelerate some of the major weapon system programs, production has started long before the weapon has been engineered and designed for production. These factors make major design changes mandatory.

While the design change may make a product more saleable, or a weapon system more efficient in terms of operational objectives, it creates serious problems for production management attempting to forecast, plan, and control operations. Frequent design changes complicate the problem of production planning. Professor Moore in his book states: "The problem of design change is a deterrent to broader adaptation of the time reduction curve technique."[1]

Admittedly, a number of techniques are used to adjust for a product change in order that time reduction curve analysis may be continued. However, it seems that present methods and techniques are inadequate for a number of reasons. First, the present methods fail to predict the time reduction after a product change is incorporated. There is no way to determine the equivalent point on the time reduction curve after the change. Second, there is no way that we may determine the amount of deviation, nor for that matter, to say whether or not a deviation at all exists in a particular program after a change has been introduced. The changed and the unchanged parts of a product will

[1] Franklin G. Moore, Production Control (New York: McGraw-Hill, 1958), Chapter 9.

exhibit different time reduction velocities, with the result that future time reduction will not be at the rate which was experienced before the design change had been introduced. Third, unless forecasting and comparative analysis can be continued even after a product change is introduced, the time reduction curve would loose most of its value in many cases where product changes are necessary.

In the following paragraphs we shall review the various views in regard to transfer of skills from one task to another, review the present methods of dealing with design changes, and finally, suggest a new and improved method of dealing with design changes when the time reduction curve technique is used.

Some Theoretical Aspects of Transfer

To a large extent, the problems of change that are set off by a change in product design, are also problems of determining transfer of skills, individual or organizational, from the old work situation to the new one.

Thorndike is generally considered the father of contemporary theories of transfer.[2] His experimental research at the beginning of the twentieth century resulted in the conclusion that transfer takes place according to the existence of "identical elements" in the two situations. The identical elements theory of transfer proposes that the possibility of transfer depends on the presence of identical factors in an original situation and a new situation.[3] This identity

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[2]Ernest R. Hilgard, Theories of Learning, (New York: Appleton-Century-Crafts, 1948), p. 68.

[3]Ibid., p. 70.

of elements may be found in the content, procedure, or ideal. Thorndike states:

> . . . a change in one function alters any other only in so far as the two functions have as factors identical elements. The change in the second function is in amount that due to the change in the elements common to it and the first.[4]

In contrast to Thorndike, who maintains that there must be a specific identic bond between situations, Judd proposed his theory of generalization in which he emphasizes the importance of transfer of general abilities.[5] One must only accept a particular mode of behavior as part of his "general principles," and it will recur even when the situation is a new one.

Whether one chooses to support the identical elements or the generalization theory, the concern is about the relation between two groups of activities. As one authority points out:

> It may be questioned, moreover, whether these theories may be considered different statements ...... The elements called identical are general to the degree that they extend beyond the situation in which they were originally earned; they are identical only in the sense that they belong to the same class of events. Generalizations are also common to both training and test situations and are, then, as identical as the features subsumed under a theory of identical elements.[6]

Thus, the two theories are not mutually exclusive, since both interpret that transfer is a function of the relations between the old and the new activity.

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[4]Edward L. Thorndike, The Phychology of Learning, (New York: Columbia University, 1914), p. 353.

[5]Hilgard, op. cit., p. 76.

[6]John A. McGeoch, The Psychology of Human Learning, (New York: Longmans, Green, and Co., 1947), p. 330.

The current gestaltist claim that a solution once arrived at may be used in new situations. "Insight is often accompanied by a verbal formula which permits the principle to be applied readily to new problems."[7]

There is no doubt that positive and negative transfer occurs. Transfer effects may be defined as positive when training or experience in one activity facilitates the acquisition of skills necessary in another activity. Transfer may be defined as negative when the training in one activity inhibits training in another. Transfer is zero or indeterminate when training in one has no observed effect on the acquisition of skills required in a new situation. The vast number of experiments have produced both negative and positive transfer, the latter being more numerous. A few have yielded zero transfer.[8] Since the results of these experiments are already well covered elsewhere, they will not be discussed here.[9]

Theories of transfer are concerned with what is retained from the training or experience and used to facilitate learning in a new situation. While there is a considerable amount of knowledge in existence, which describes the basic conditions of transfer, a scientific theory which will permit satisfactory quantitative prediction is not now available. We shall next review the various methods that are now used by those firms where the time reduction curve has been used for a number of years.

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[7] Hilgard, op. cit., p. 194.

[8] McGeoch, op. cit., p. 394.

[9] Ibid., pp. 380-420.

Present Industrial Methods for Estimating the Effect of Changes on the Time Reduction Curve

Changes in a product will affect the number of hours required to produce that product and therefore the slope and also the position of the time reduction curve. The time reduction curve will have to be so constructed as to reflect these changes. But even more important is the fact that it must be so constructed as to enable analysis and prediction of the path that the time reduction curve will take.

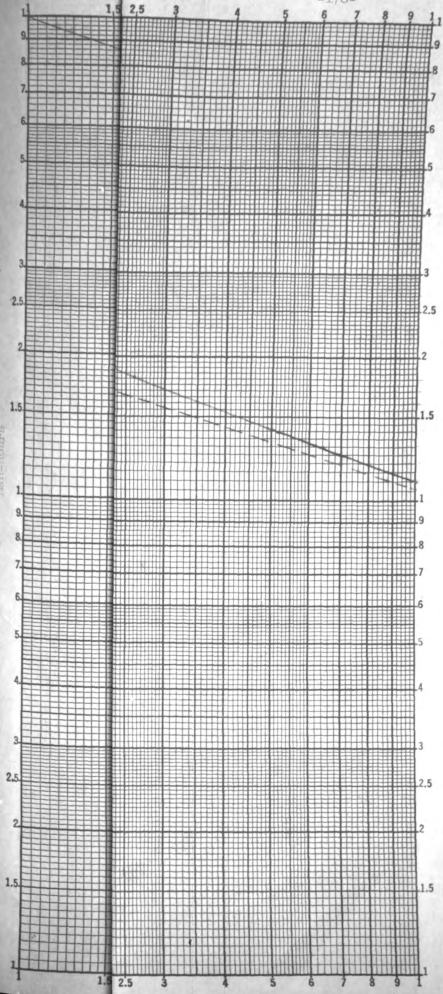
Figure 5.1 illustrates the cumulative average time reduction curve derived from data in production of product X. The hypothetical data is contained in Table 8.1. When changes in design are made at customers' request, the effect of these changes on costs, as well as many other aspects of production, have to be forecasted. As far as the cost in man-hours is concerned, there are two elements that have to be dealt with. The first is the cost of the design change which includes the cost of the additional work that has to be performed as a result of this change, less the cost of the work that has been deleted. One of the alternatives available to us is, of course, to plot the actual data as it accrues and disregard the design change all together. Figure 5.1 indicates the shape of the time reduction curve without any adjustment for the design change. It shows a sharp rise in the shape of scallops at unit one hundred and one where the change was introduced. At unit one hundred and one, the projection along the original curve to forecast the next unit would be quite meaningless. Also, any projection of the data of the additional units would fail to indicate when actual production would again reflect the

TABLE 8.1

MAN-HOUR DATA ADJUSTED FOR PRODUCT CHANGE*

Unit No.	Man-Hours Per Unit Original Estimate	Man-Hours Per Unit Part A (Unchanged)	Man-Hours Per Unit Part B (Changed)	Total Man-Hours Per Unit After Change	Composite Unit No.
1	1000.0				
64	262.1				
100	227.1				
101	226.3	113.2	500.0	613.2	4.7
102	225.6	112.8	400.0	512.8	8.2
103	224.9	112.5	351.0	463.5	11.5
104	224.2	112.1	320.0	432.1	14.0
105	223.5	111.8	298.0	409.8	16.5
110	220.2	110.1	238.3	348.4	27.8
125	211.3	105.7	177.4	283.1	53.5
175	189.6	94.8	124.6	219.4	115.0
230	173.7	86.8	104.3	191.2	185.0
350	151.7	75.8	84.5	160.3	320.0
400	145.3	72.5	79.5	152.0	390.0
600	127.5	63.7	67.5	131.2	600.0
1000	108.5	54.5	55.9	110.4	1000.0

* SOURCE: Hypothetical data


Man-Hours

original rate of time reduction experienced for the units before the change was introduced. It may be expected that sooner or later the curve will fare into the original slope, but as to when this will occur it is impossible to state.

Because there are a number of major design changes that are introduced, great difficulties are encountered in constructing useful time reduction curves. A number of techniques have been developed to overcome these difficulties. These will be presently considered.

Because the time reduction curve had been developed in the airframe industry, it appeared desirable to contact a number of the leaders in this industry to determine the method being followed in solving problems of forecasting the effect of changes on the curve.

Individual Company Practice

Following, is a summary of individual company practices in the method of estimating the effect of changes. Because certain phases of this information are considered by those companies, which have graciously furnished information, to be of proprietary interest to a particular company, the names are disguised through the use of a symbol.

Company D in estimating a major change to an aircraft, uses an engineering estimate of the hours which are involved. The changed work is then plotted on the time reduction curve which is separate from the rest of the airframe. The percentage slope of the time reduction curve, that is, the new curve which is being estimated for the changed part, is estimated by evaluating factors of design materials, method of machining, production techniques, complexity, etc. The new work is then compared to past work performed in the plant. Unlike some of the other companies, this manufacturer does not use the weight comparison factor except in some unusual circumstances, but even if a weight comparison factor is used it is still adjusted for a complexity factor. Needless to say, judgments relative to the size of the complexity factors have to be quite subjective.

Company E uses a method that is pretty much the same as the basic method, which will be discussed below. Manufacturer F estimates major design changes to an aircraft by subjectively evaluating all the factors involved in a particular change situation. Weight is only one of the factors which are considered. The company reports that in incorporating a change, special problems often arise in meeting specifications. These would not be reflected if man-hours were estimated on a weight comparison basis. It is also stated that many changes require little or no structural modification, and these usually will show very little weight change. Once the design change man-hours have been derived, a separate time reduction curve is projected for the changed part.

Company G estimates the cost of a major change by developing a detailed bill of materials for the added and deleted work. Man-hours are estimated for all of the operations at the one thousandth unit. This basic labor hour estimate is then adjusted to include special factors such as complexity. After the individual curve is constructed for the change at unit one thousand, the work is estimated to start at a subjectively determined unit which is usually not unit number one. The management of company G feels that there is a carry over of learning between the unchanged work and the changed work so that there is no need for going back to unit number one. It should be recalled that this is a departure from the practices of some of the other manufacturers under discussion here.

Company H method of estimating a major engineering change is similar to the methods followed by other airplane manufacturers. The company uses the weight comparison method. The unchanged weight of an airframe is projected from the unit number at which change is put into effect. In other words, if the effective point of a design change is unit one hundred and one, then the company would normally project the unchanged work also as unit number one hundred and one. On the other hand, the changed portion of work is projected as unit number one. This method makes the separation of the various components for accumulation of time data mandatory. Projection for the changed and unchanged portion of work is at the same slope time reduction curve which was experienced before the change was introduced.

A somewhat unusual procedure which is being followed by this manufacturer H may be found in that this manufacturer adds a disruption factor to the unchanged work. The management of this company feels that when a change is introduced the whole production process is disrupted from its normal efficiency. The mere fact that the changed work starts at unit number one does not adequately compensate for this disruption. It should be remembered that the disruption factor is to a large extent a subjective evaluation of the effect that the change will have on the remaining unchanged work. To obtain the unit time the company adds unchanged and changed work.

Firms J, K, L, and M, use a method which is very similar to the basic method to be discussed below and, therefore, will not be repeated here.

The various methods employed in estimating the effect of a major engineering change have been briefly discussed. (The term major is in itself not well defined, Company J, for instance, defines a change as major if its cost is one hundred hours or more.) There is one common denominator in use by the manufacturers which were surveyed. This is found in the fact that aside from the minor variation, all companies project the changed portion of the work separately, and then add the changed portion at specific unit number to unchanged portion of the work to get the total unit time. There is a considerable variation in the choice of the slope that is being made for the changed portion of the work. Also, the majority of the firms project the changed man-hours at unit number one. The practice is not universal. At least one manufacturer feels that there is enough transfer of learning from the old to the new, to justify consideration of the changed portion as being other than unit number one in the sequence.

Another point of departure in practice is the method employed by some companies of adding a contingency factor which is over and above the estimated change hours at unit number one. There is no agreement at this point among the several users, but it appears that the estimates for the disruption, or complexity factors, do contain a large amount of subjectivity.

The major difference in estimating the effect of major changes is found in the method of estimating the change hours. The firms surveyed are split about even, with about half using the weight comparison factor method, while the rest use what may be called industrial engineering estimate of man-hours. In the case of the former, the weight of the changed portion of the work is estimated, then past experienced time at specific unit numbers is applied to the estimated weight. The latter method does not consider weight of the changed work, but rather concentrates on the operations involved. While no definite conclusions can be made as to the desirability or accuracy of either method, it appears that the time estimate for each new operation is the more desirable method for a number of reasons.

First, in a situation where technology and complexity are advancing rapidly the weight change is not an accurate indicator of the work which has to be performed. Second, certain changes require very little or no change in weight (for example specification changes), yet increase the amount of work that has to be performed. This is also true in a case of equipment changes. Another variation of these methods that was discussed is that used by Company F, which considers all the factors bearing on a particular change. Further inquiry as to how the various factors are weighed did not result in illuminating answers.

One of the surprising aspects of this survey was the amount of latitude and variation found in the practice of the firms under consideration. This suggests that possibly there is more than one way to arrive at the solution to the problem of estimating the effect of the major engineering change. It also suggests that there is no exact scientific method that can be readily applied to this problem and that at best the present methods need a considerable amount of judgment and knowledge of a specific situation before they can be used with a great deal of confidence. Next, a method for estimating the effect of design changes which seems correct from the logical as well as useful from the practical standpoint in dealing with change

TABLE 8.2

SUMMARY OF METHODS OF ESTIMATING THE EFFECTS OF CHANGE

COMPANY	CONTINGENCY FACTOR	BASIS FOR ESTIMATING THE CHANGE PERCENTAGE	UNIT NUMBER AT WHICH THE CHANGED WORK IS PROJECTED
D	Yes	Estimate of time required for added work	No. 1
E	Yes	Uses both methods depending on the situation	Usually No. 1 with occasional variation
F	No	Evaluated all factors affecting change	No. 1
G	Yes	Estimate of time required for added work	Variable
H	Yes	Weight Comparison	No. 1
I	Yes	Weight Comparison	No. 1
J	No	Weight Comparison	No. 1
K	Yes	Estimate of time required for added work	No. 1
L	No	Weight Comparison	No. 1
M	No	Estimate of time required for added work	Variable

problems of the time reduction curve will be presented.

A Method for Estimating the Effects of a Major Product Change

When a major change in the product is made a number of problems in forecasting man-hours will arise. Depending upon the extent of the change, the time reduction curve will assume a non-linear shape. Figure 5.1 shows the shape of the curve when a 50 per-cent change is introduced at unit number one hundred and one. The broken line in Figure 5.1 indicates the line of the curve if there was no change. Forecasting along this previously established trend would be hazardous and inaccurate. Because of the change in the work pattern the previous rate of time reduction should not be expected to continue.

In deciding whether a product change merits the analyst's attention the significance of the change, in terms of the effect on man-hour requirements, must first be determined. As yet there is no completely satisfactory standard which would make a distinction as to whether a product change should be termed major or minor. For the purpose of this study a major change is defined as one which causes a 5 per-cent change in total man-hour consumption.

Once a decision is made as to whether a change is major or minor, the treatment of the change will differ. Minor changes are usually ignored. The justification for this treatment of the minor changes is that a change of this type will not have an important effect on the expected trend of the time reduction curve. This was found to be true in connection with firm C data discussed in Chapter 4 of this study. The incorporation of numerous, but minor, changes over a period of several years did not result in undue instability in the linear trend.

Clearly, if the time reduction curve is to have value it must be useable in the following tasks: (1) Forecasting in the usual manner and with a single curve for a product as a whole. (2) Indicate the immediate effect of the change on the previously forecasted man-hours, and, (3) indicate at what quantity the effects of the change will be overcome and the linear form of the time reduction curve may again be used for estimating purposes.

It should be stated that the present methods may be used to forecast man-hours after a change in product is incorporated. The shortcomings are in that in using the reviewed method it is mandatory that there be separate reporting of man-hours required by the changed and the unchanged parts of a product. Furthermore, if the changes are numerous and major, the task of separate reporting and forecasting of man-hours becomes difficult and perhaps unmanageable. This elaborate procedure is unnecessary when the composite curve is used. In the following paragraphs this simplified method is presented.

For the purpose of illustrating a method of dealing with major product changes a hypothetical case of the Z firm will be considered. The Z firm is engaged in the manufacture of electronic equipment. Although the firm has a history in electronic work, the order for one thousand units of product X is considered new work for this firm. One thousand man-hours were required to produce the first production unit of X, and it was established that the time reduction curve was applicable to the proposed production.

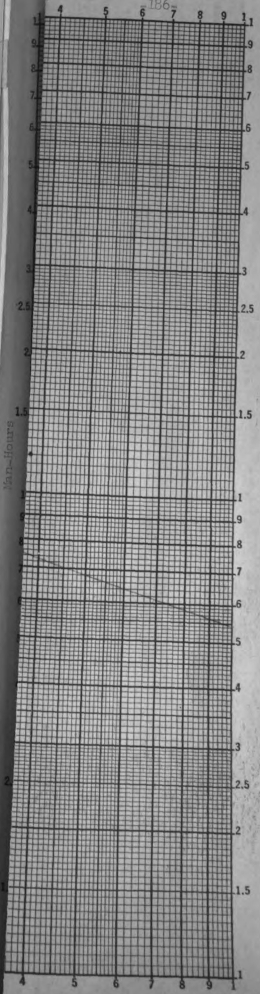
Column 2 of Table 8.1 gives the forecasted man-hours required to produce the quantity of units on order. It was decided that an 80 per-cent time reduction curve slope will be used.

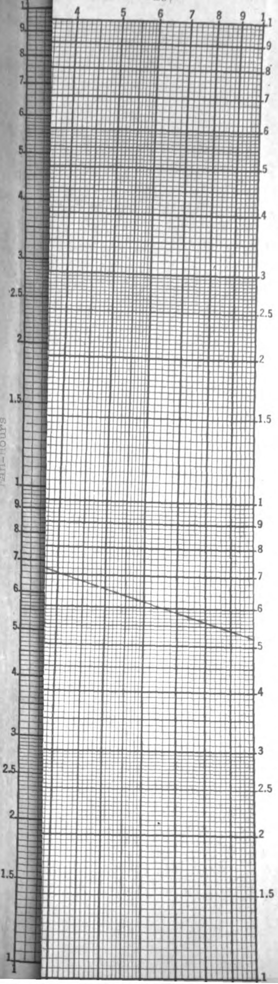
Shortly after production of product X started the customer informed firm Z that a major change was mandatory and effective at unit one hundred and one.

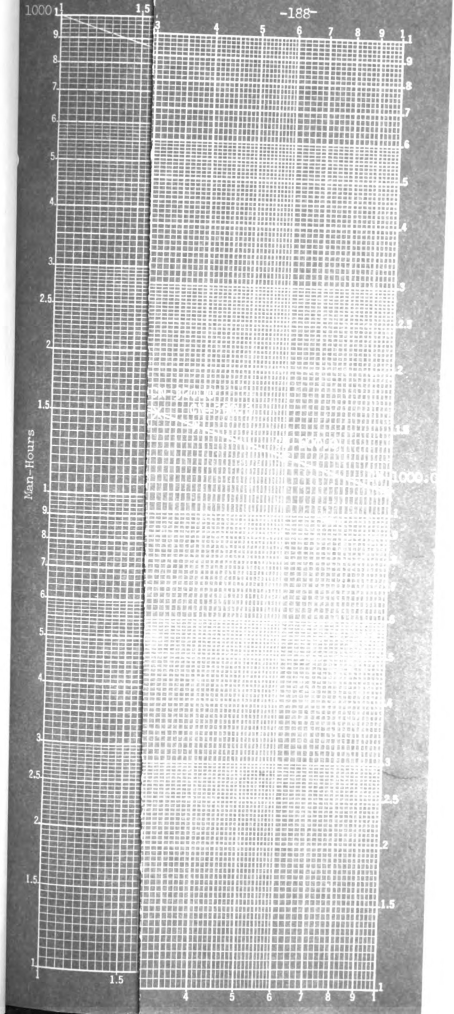
After a thorough study of the new design, the company's industrial engineering department decided that the incorporation of this change would result in the revision of approximately 50 per-cent of the man-hours necessary to produce the assembly. Column 3 Table 8.1 shows the unit man-hours for the unchanged portion of the product. Since the change amounted to 50 per-cent beginning with unit one hundred and one, the unchanged work would require only 50 per-cent of the time that it would normally require for a 100 per-cent completion of the product at that point. The unchanged portion of product X will be referred to as part A.

The man-hours per unit on the changed portion of the work are shown in column 4. Since there was a 50 per-cent change, the one hundred and first unit was estimated to cost half of the original first unit which amounts to five hundred man-hours. In other words, the changed portion of the work would have to go back to unit number one and be projected from there. The changed portion of product X will be referred to as part B.

To obtain the total man-hours per unit to produce product X after the change has been made, columns three and four should be


Man-Hours


Man-Hours


Man-Hours

added. The total man-hours per unit are given in column five.

The above may be presented in graphical form. Figure 5.2 shows the time reduction curve for part B of product X. The first unit of the changed part B will require five hundred man-hours and is projected as unit number one. Figure 5.3 gives the man-hours required to produce part A of product X, and is projected from unit one hundred and one.

What is the equivalent unit number of experience that firm Z will have when unit (changed) one hundred and one is produced? In other words, at what point of the original man-hour estimate will unit one hundred and one fall? The answer to these questions may be found in Figure 5.4, (page 188).

Table 8.1, column five shows that unit one hundred and one will require six hundred and thirteen hours. This amount is equivalent to about 4.7 units on the composite curve (Figure 5.4). The composite curve is identical to the curve originally estimated for product X.

It will be noted that unit one hundred and two does not equal 5.7, the next consecutive number, it equals to about 8 units on the composite curve. The reason for this is that the amount of time reduction is different for part A from that for part B. Part B (new work) improves more than part A. Therefore the unit at which the change becomes effective cannot be considered as unit number one or unit one hundred and one. Actually it is somewhere between those two numbers. The composite number indicates the approximate location on the original curve in terms of man-hours required. This means that until the effects of the change have been overcome, part A and B of product X must be projected separately. However, extended use of this approach is impractical for several reasons stated above.

How many units must be produced before the effects of a change in product have been overcome? When can the composite curve be used to forecast man-hours in the usual consecutive manner, without resorting to adjustments? The composite curve may be used for forecasting at that quantity of production where the man-hours required to produce the changed product X approximate the original man-hours forecasted for that quantity of units. The two values need not be perfectly equal. The estimates developed with the time reduction curve are not so exact as to warrant the demand that the original and the changed estimates be equal. It is assumed that when the man-hours required to build the changed unit equal the estimate without change, the curve may be used for forecasting without additional adjustments.

For example: 145 hours are required to build 400th unit without change. 72.5 hours are required to produce 400 units of part A (Figure 5.3), and 79.5 hours are required to produce 300 units of part B (Figure 5.2). Thus, it will require 152 hours to build unit 400 of the changed product X. This is within 4.1 per-cent of the original estimate, and therefore, at this quantity the curve may be used to forecast man-hours without further adjustments.

Summary and Conclusions

In Chapter 8, problems created by product changes are discussed. These problems appear to be serious, and in some cases may be a deterrent to broader adaptation of the time reduction curve.

Theories of individual skill transfer are concerned with what is retained from experience and used to facilitate learning in a new situation. A satisfactory method of quantitative prediction of transfer of knowledge of an organization is not available.

Present methods of estimating the effect of design changes, as used by a number of major airframe firms, were reviewed. Considerable variation in practice was found.

Major changes will cause the time reduction curve to deviate from its expected trend and assume various non-linear shapes. In this form the curve is most difficult to interpret and too uncertain to be of value in estimating. This result is evident unless corrective adjustments are made.

A method of adjusting for major product changes is presented. In using this method it is necessary that the direct man-hours for the changed and the unchanged part of the product be projected separately. The required man-hours at specific quantities may be determined by adding the man-hours of the changed and unchanged parts. The composite unit number may be determined by locating the point at which the total average man-hours per unit computed will equal to those found on the composite time reduction curve.

The proposed method enables forecasting after a change in product with a single curve. It indicates the immediate effect of the change on the original (before change) forecast of man-hours required. Finally, the composite curve method indicates at what quantity of production the effects of the change will be overcome, and the linear form of the time reduction curve may again be used for forecasting.

The next chapter contains a summary and conclusions of the thesis.

CHAPTER IX

SUMMARY AND CONCLUSIONS

In a number of the large manufacturing concerns the time reduction curves is used as an important tool in the forecasting of direct man-hours required in production. The time reduction curve is designed to express the relationship between direct man-hours used in the manufacture of a given unit of product and the cumulative total quantity that has been produced.

The conventional formulation of the time reduction curve theory is based on the hypothesis that the cumulative average direct man-hours per unit decline at a constant percentage every time the quantity of units manufactured is doubled.

This relationship results in a hyperbolic function when plotted on arithmetic scale. In this form the curve is difficult to interpret. The same data when plotted on logarithmic scale results in a linear function.

An indication of importance of the time reduction curve may be inferred from the following situations to which the curve is being applied:

1. Most airframe manufacturers use the curve to predict man-hour requirements of various production programs.
2. The U.S.A.F. Air Materiel Command uses the time reduction curve to establish the expansion and mobilization potential of productive facilities.

3. The Air Materiel Command uses the curve to appraise contractor's performance efficiency, progress, and production dependability.

4. The Air Force and contractors use the curve in planning, predicting and testing the feasibility of schedules.

5. Airframe manufacturers use the curve to determine floor space and assembly tool requirements.

6. Determination of working capital requirements, cost control, profit planning, and sub-contract pricing are some other areas where the curve has reportedly been applied successfully.

7. A recent regional survey of metal manufacturers, other than airframe, reports that 60 per-cent of the firms use the time reduction curve relationship in forecasting.

The purpose of this investigation is to study the reliability of the linear form of the time reduction function, proposed by Wright, as a tool for forecasting direct man-hours required in production.

Historical direct man-hour data, consumed at various cumulative quantities of output, were obtained from three manufacturers. The data represents fifty-four models, and five production programs. Twenty-six of the products may be classified as major components of electronic data processing systems. Sixteen units were bindery machines, and twelve were printing presses. Because necessary information relative to changes in the product was not available, the data were not adjusted for design changes.

Data obtained were fitted to a straight line on logarithmic scales through the use of the least squares method.

For purposes of forecasting man-hour requirements, it is necessary that the time reduction curve contain reliability in its linear form as well as uniformity in slope. An index of correlation was computed for each of the fifty-four curves. It may be stated that the resulting empirical time reduction functions exhibit remarkable linearity on logarithmic scales. The correlation to the least squares computed line of regression is high. In fifty of the fifty-four cases the index is greater than .90. The twelve printing press cases produced an index of correlation range of .97 and .99. However, it is possible to have a high index of correlation and also high departure from linearity. Standard error of estimate is a tool which provides a measure of reliability of basing estimates of man-hours on the linear form of the time reduction curve. Over 84 per-cent of the time reduction curves computed were found to be reliable, e.g. did not exceed an arbitrarily set standard of reliability of 4 per-cent standard error of estimate.

A number of factors appear to be responsible for deviations from linearity. Analysis indicates that engineering changes, low level of knowledge of component performance characteristics, and placing into production items of unproven design were some of the major causes of deviations from the line. It would be desirable to adjust the present data for fluctuations in man-hour consumption which were initiated by management and which are assignable to these actions.

The percentage slope characteristic of each of the fifty-four time reduction curves was computed. An analysis of slope characteristics of various models of a certain product type shows that the variation in slope is extensive. In every category of production the variation in slope among models or product runs exceeded 6 per-cent. The required accuracy will vary depending on the use to which the results will be put. However, the variations in curve slope characteristics are of such magnitude as to limit seriously the usefulness of slope experienced on past models when determining what slope should be used in forecasting man-hours of future models of a product type.

The possibilities of estimating the time reduction curve slope on the basis of a limited initial quantity of production were explored.

A mathematical formula which gives the exact number of observations required before slope characteristic of certain confidence may be determined has been proposed. When this approach to the estimating of time reduction curve slope is used, it is recommended that for the quantity required in slope estimating, man-hour data be reported on a per unit basis or in small lots.

This appears desirable because in cases where the data is reported on a lot basis the quantity produced may have to be so large as to negate most of the usefulness of the time reduction curve.

An attempt was made to estimate the slope on the basis of a minimum number of man-hour observations at various quantities. Because most of the available data were in lot form, it was impossible to control fully the number of units which were used to estimate the time reduction curve slope. In twenty-two of the twenty-eight cases it was possible to obtain a relatively accurate forecast of the applicable slope from three lot values. Four lot values were used in three cases, and the remaining three cases required five man-hour values. The average error in the slope estimate, based on minimum production quantities, for all twenty-eight cases is 1.8 per-cent.

To determine the effect that these errors in slope would have on estimates of required man-hours, forecasts were made for various quantities for which actual data were available. Comparison of the estimated and actual man-hours was made, and the error in estimate computed.

Computations were made for 28 products. Because the size and the direction of error varied at different quantities, the error in estimate was computed in fifty-four cases. An error in estimate of less than 7 per-cent was obtained in 72.3 per-cent of cases. In 90.8 per-cent of cases the error was less than 13 per-cent. However, in 7.4 per-cent of the cases the error in estimate range is from 20 to 25 per-cent.

The number of factors which affect the time reduction curve is large. There appears to be a need for a study of the major factors which affect time reduction. At present, the best approach seems to be to consider each individual case separately and take into account the expected influences. Here the historical shape of an individual firm's improvement curve may be helpful. A past time reduction curve of an individual firm may be expected to contain a multitude of factors which may well be expected to continue. In other words, although we cannot make an objective determination of the various factors that affect the slope of time reduction, a historical curve may have the majority of these factors already incorporated.

In the final analysis, management can, to a large extent, control the negative influence of the many factors that affect the rate of improvement once the factors that are expected to cause production inefficiencies become known. As yet, empirical evidence does not indicate that all the factors that affect the slope of time reduction or position of the time reduction curve are known.

Significant changes which are introduced when the product is being manufactured may upset the original man-hour consumption forecast. It has been suggested by some that the problem of changes has served as a deterrent to broader adaptation of the time reduction curve technique.

A number of airframe firms were contacted to determine the present methods used in dealing with problems of change. All of the ten companies, whose methods were reviewed, project the changed pattern of the work separately and then add the man-hours for new work to the man-hours for unchanged part of the unit. A considerable amount of variation in practice was evident. Most of the firms use either a detailed estimate of the time required for the changed part of the unit, or estimate the weight of the changed part. These are projected from unit number one. In most cases a contingency or disruption factor is added. A method of adjusting for changes, which is similar to methods now being used has been presented in this thesis. The proposed method may be used to estimate the effect of a change on the original estimate, and to determine at what point the effects of a change will be overcome.

Conclusions

Despite the many unsolved problems related to the time reduction curve, some positive conclusions can be drawn. Evidence based on empirical data for fifty-four time reduction functions indicates that the following conclusions are in order:

1. Empirical data strongly suggests that the existence of the time reduction curve phenomenon is not predicated on the use of the curve for purposes of planning and control of man-hour requirements in manufacturing situations.

2. The time reduction curve in its linear form is found to be reliable and useful within stated confidence ranges. In all but three cases, the data plotted on double logarithmic scales resulted in a close approximation of a linear function on double logarithmic scales. The average index of correlation for all cases is greater than .95. In 84 per-cent of cases estimates based on the linear curve were found to be highly reliable, i.e. less than 4 per-cent standard error of estimate.

3. It is concluded that there is no universal rate of time reduction, and the tendency to assume that there is a basic uniformity in slope of time reduction curves for an industry is unwarranted. In the airframe industry the 80 per-cent time reduction curve has been erroneously accepted by some as the generally applicable slope of time reduction. Analysis of the computed slope characteristic of fifty-four time reduction curves and World War II bomber airframe production indicates that the curve slope tends to vary widely among firms manufacturing similar products, non-similar products manufactured by one firm, and also models of a basic product type manufactured by one firm. In every one of the above categories the variation

in slope is in excess of 6 per-cent. This amount of variation in the curve slope is judged to be excessive for the purpose of forecasting direct man-hour requirements.

4. Estimating the applicable slope on the basis of a limited number of units produced results in a relatively close approximation of the actual curve slope attained in production. The average error in the slope estimate for all cases is 1.3 per-cent. Man-hour forecasts based on the estimated slope were made and appear to be moderately reliable. In 72.3 per-cent of the cases the error in estimated man-hours is less than 7 per-cent. In 90.8 per-cent of the cases the error in estimate is less than 13 per-cent. However, in 7.4 per-cent of the cases the error ranges from 20 to 25 per-cent.

5. When the time reduction curve slope is estimated on the basis of a limited production quantity, it appears desirable to report the man-hour observations on basis of units or small lots. This would make possible an earlier estimate of applicable slope than would be the case if man-hours were reported on the basis of large lots.

6. It appears that the time reduction curve is of limited usefulness in cases where the total quantity to be produced is small, and where the index of correlation between man-hours per unit and total units produced is low in the first part of the run. Under those circumstances it would be difficult to predict the applicable slope percentage sufficiently early to be of value in forecasting.

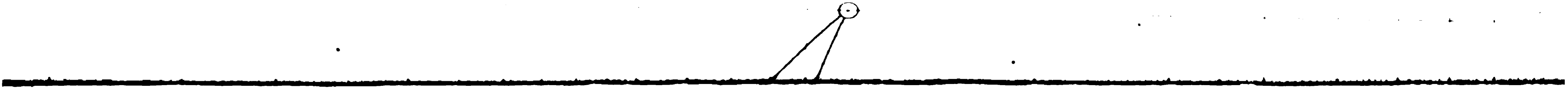
7. It is concluded that in spite of the fact that the time reduction curve relationship is highly reliable, it is of very limited usefulness in forecasting direct man-hours required in the production of a product before a number of units of that product have been manufactured. This condition exists because of the inability to estimate the applicable time reduction curve slope before the start of production. It may be that future research of slope determinants will make possible somewhat more accurate curve slope estimating ahead of actual production. However, this study indicates that the time reduction curve is with certain limitations, a useful tool for forecasting direct man-hours required in production after a limited quantity of a product has been manufactured. Whether forecasting results will be of desired accuracy will depend on the requirements of a specific situation. Indeed, before a decision is reached as to whether the time reduction curve should be used in a specific situation, it must first be determined whether the benefits derived justify the administrative cost involved.

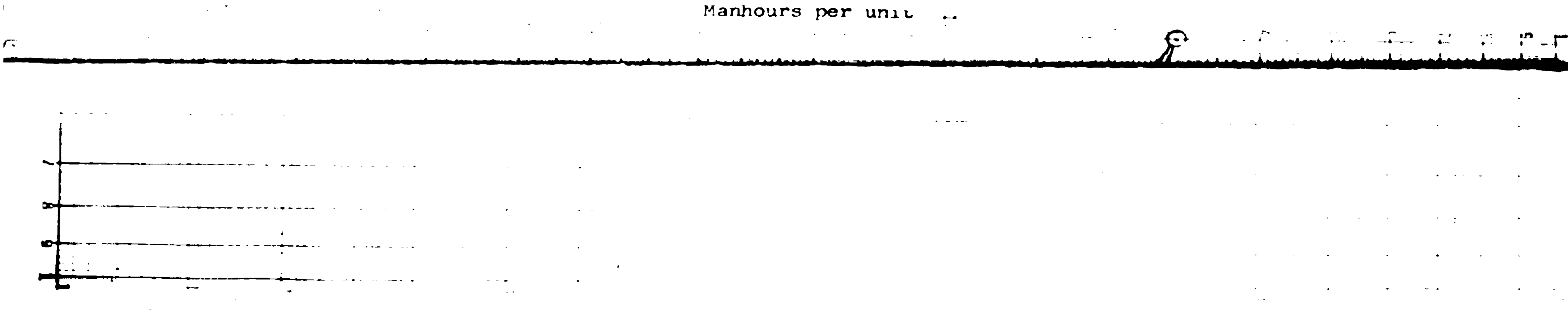
The conclusionsof this study are limited by the fact that data used in the primary analysis was obtained from only three manufacturers, although that was supplemented by certain other data reported in the airframe industry. The data in the primary analysis, however, did include man-hours actually used in five production programs and the manufacture of fifty-four products.

APPENDIX A

FIFTY-FOUR EMPIRICAL TIME REDUCTION CURVES

Manhours per unit

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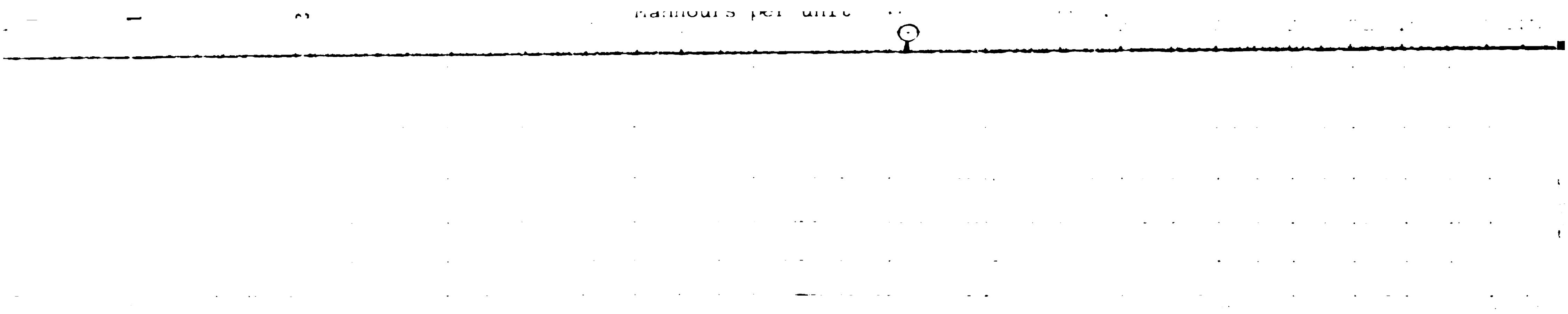
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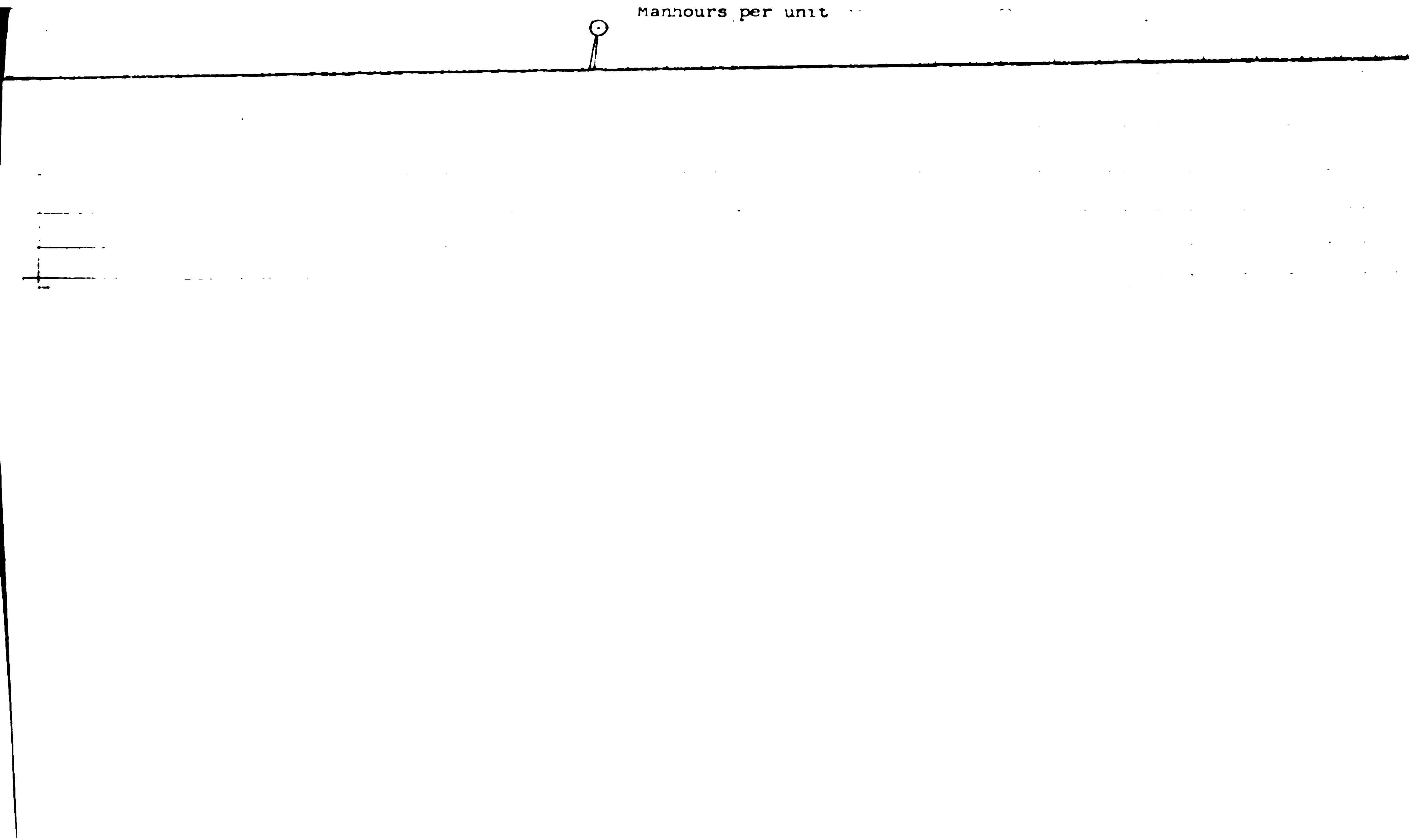
Manhours per unit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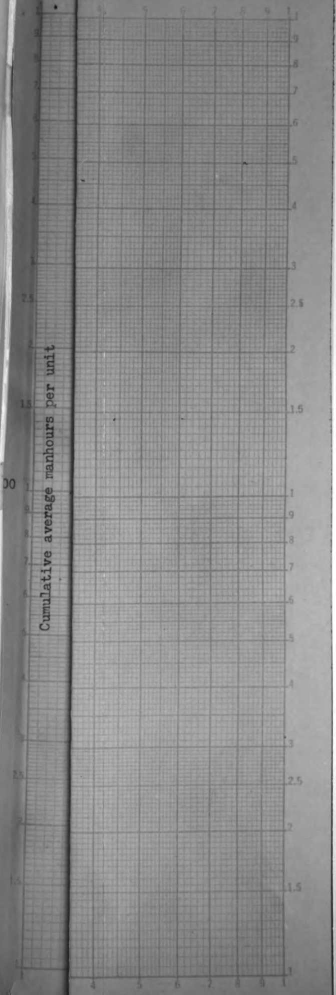
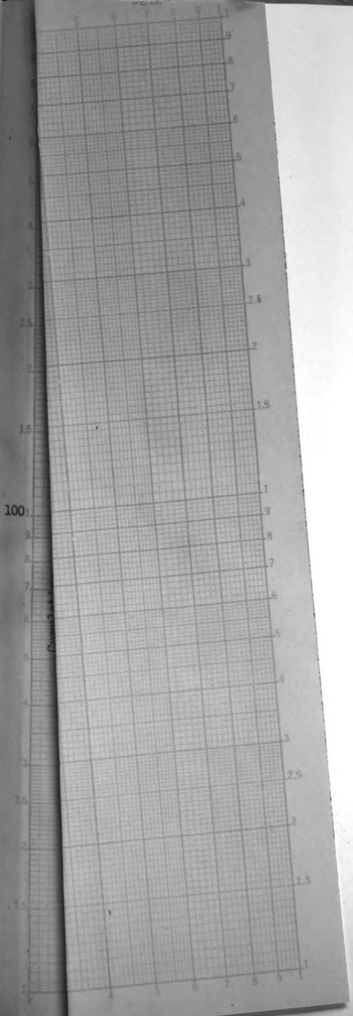

Cumulative average manhours per unit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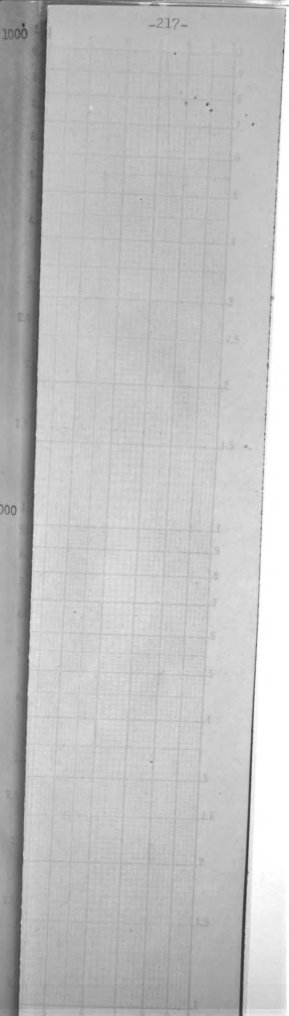

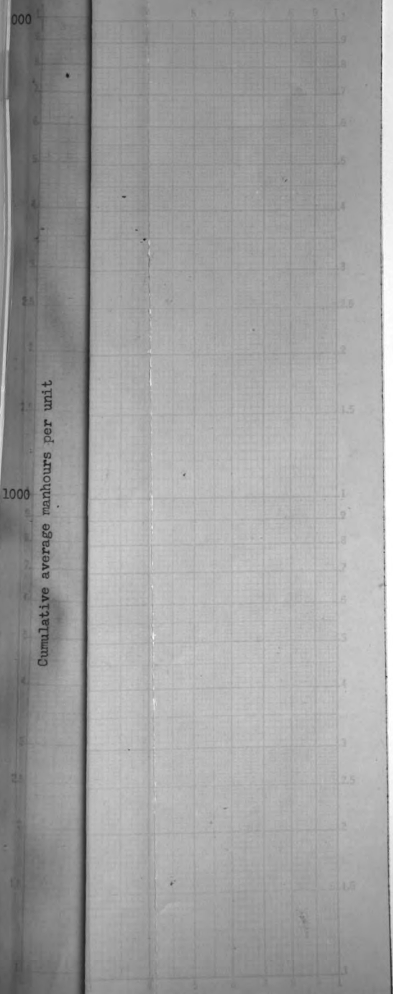
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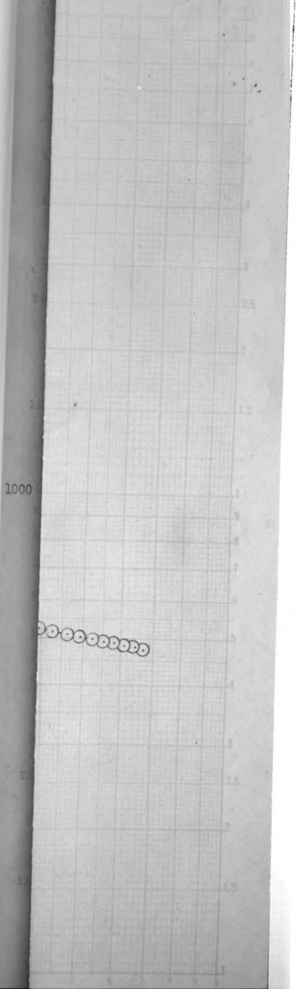
Cumulative average manhours per unit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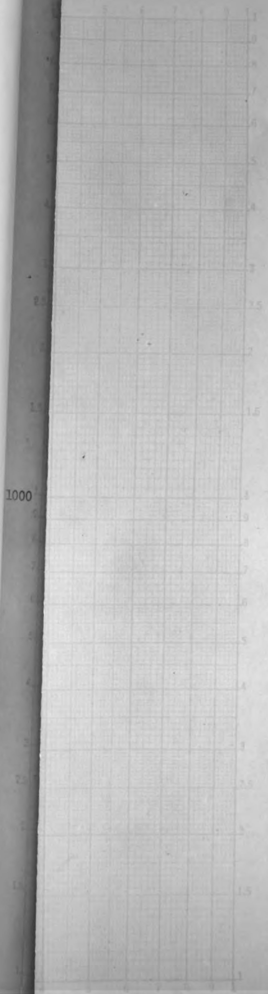
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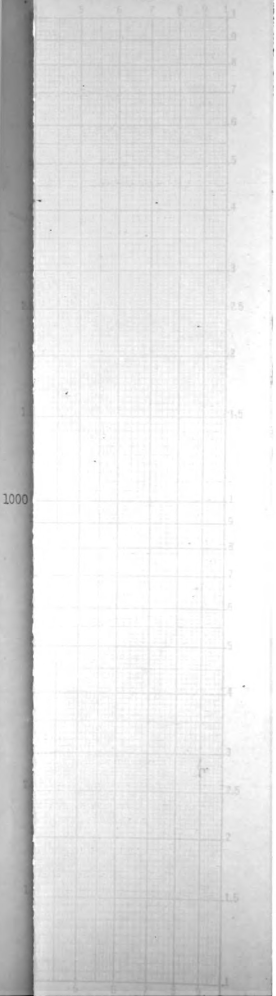
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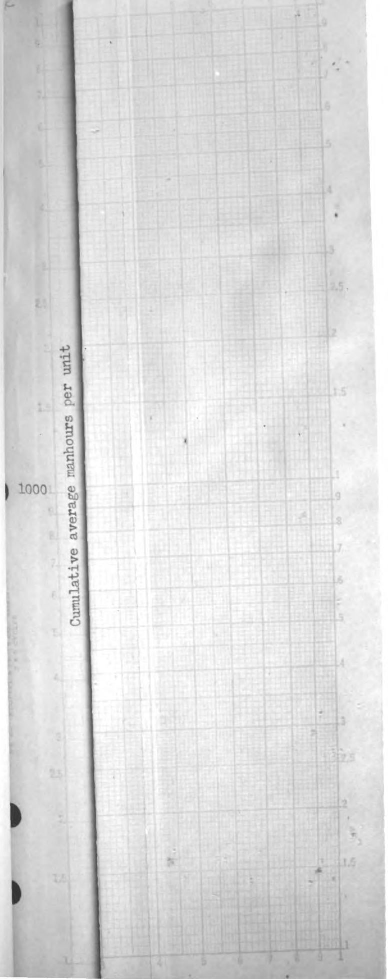
Cumulative average manhours per unit
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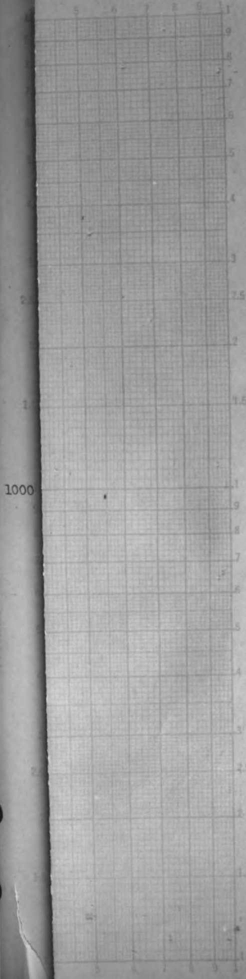
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