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Productivity measurement and resource allocation in the operation of an electric utility

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PRODUCTIVITY MEASUREMENT AND RESOURCE ALLOCATION IN THE OPERATION OF AN ELECTRIC UTILITY

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Productivity measurement and resource allocation in the operation of an electric utility

by

David Wing-Hung Mo

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I. INTRODUCTION

During the past decade, there has been a great deal of concern about the performance of the American economy, particularly about productivity. There is no doubt that the problems of productivity are of the greatest importance, for John W. Kendrick (1961, p. 3), one of the pioneers in productivity research, has aptly put it:

> The story of productivity, the ratio of output to input, is at heart the record of man's efforts to raise himself from poverty.

The Joint Economic Committee of Congress (Boulden, 1979) could not agree with him more, as the Committee warned recently that the average American was likely to see his standard of living drastically reduced in the 1980s, unless productivity growth is accelerated. The impacts of productivity slowdown have been unfavorable. At the economy level it has aggravated inflationary tendencies, contributed to balance of trade and payments problems, and retarded the rate of increase in real individual wages and incomes. In the regulated industries, such as electric utilities, slower productivity growth coupled with accelerated inflation has resulted in profit squeeze, more frequent rate cases and rate increases and more widespread, vocal public resistance to such increases.

Understandably, this concern for the level of productivity is shared by government and industry. Individuals representing many disciplines, including management, engineering and economics, have begun to study this problem as part of large effort to attack our economic stagnation. The National Center for Productivity and Quality of Working Life was established in 1974 by the government to help increase the productivity of the American economy and improve the morale and quality of work of American workers. Another independent organization, the American Productivity Center (APC), was founded in early 1977 to assist companies with productivity improvement programs. The APC is a non-profit, privately funded and operated center created to accomplish these objectives (Hamlin, 1978):

1. To improve productivity,
2. To improve the quality of working life, and
3. To preserve and strengthen the private enterprise system.

These strong efforts in productivity improvement and the growing interest in measuring the productivity of resource utilization can be felt in every sector of economy. Such measurement, if applied and interpreted correctly, becomes a useful indicator of economic activity and a company's well-being.

The electric power industry has grown from an insignificant sector in the late nineteenth century to one of the largest and most important industries in the United States today. Until recently, the electric utility industry could be regarded as a model of progress. Over the period 1948-1966, total factor productivity in electric and gas utilities increased at an average rate of nearly 5 percent a year. Kendrick (1975) noted that this was well above the 2.5 percent rate of the private domestic business economy as a whole.

The general stagnation of the power industry since the 1960s has been reflected in the rates collected from users. One of the most important factors influencing mechanization and automation of American industry, and thus the improvement of productivity, has been the fact that the cost of electricity per kilowatt hour (kWH) to the so-called large power users, i.e., the large commercial and industrial customers, declined steadily throughout the century. The decline came to a halt in the 1960s and, after 1968 when they reached their low point, rates began to rise. As Table 1.1 shows, the increase has caused the price of electrical energy to increase by about 2.57 times between 1968 and 1977. Consequently, the average annual productivity rate decreased from 5.2 percent between 1948-1965 to -1.1 percent between 1973-1978 (Table 1.2).

To cope with the productivity retardation and other related problems, increased attention has been paid to the analysis of technological change, economies of scale and efficiency in operation with the hope of finding various steps to take to promote productivity advance. However, most productivity studies are at the industry or regional level. There are only a small number of studies, for example, Kendrick and Creamer (1965), Craig and Harris (1973), Taylor and Davis (1978), and Sumanth and Hassan (1980), that focus on productivity measures at the firm level. Besides, all of them deal with the manufacturing companies. Accordingly, productivity analysis at the firm level of an electric utility company was deemed to be an appropriate and worthwhile subject for investigation.

Table 1.1. Revenues per kWH for large light and power users, 1958-1977 (Morgan, 1980)

Year	Cost (Cents/kWH)	Year	Cost (Cents/kWH)
1958	1.12	1968	0.98
1959	1.10	1969	0.99
1960	1.11	1970	1.03
1961	1.11	1971	1.11
1962	1.08	1972	1.17
1963	1.04	1973	1.26
1964	1.02	1974	1.70
1965	1.00	1975	2.09
1966	0.99	1976	2.23
1967	0.99	1977	2.52

Table 1.2. Changes in total-factor productivity, 1948-78 (Meanley, 1980)

Sector	Average Annual Rates of Change		
	1948-65	1965-73	1973-78
Private Domestic Business	3.0	2.1	0.2
Public Utilities	5.2	1.7	-1.1

In order to improve productivity, some measuring mechanism must be identified and defined before the task can proceed. Although the traditional definition of output divided by input is straightforward and uncomplicated, evaluation of it remains elusive because of a lack of definitive theoretical work, mainly, at the firm level. This may be, as Kendrick and Creamer (1965) suggested, due to the difficulty of measuring productivity for a particular firm and the involvement of numerous definitional and statistical problems. Or perhaps, such studies are undertaken but do not appear in the literature because of the proprietary nature of the results, as suggested by Hines (1978).

This research developed a measuring scheme which is theoretically sound and easily applicable to an electric utility company. Based on this theoretical framework, the multi-factor productivity (MFP) and partial factor productivity indexes are derived. These indexes can be used as diagnostic measures of a company's performance. They help decision-makers understand the relationship between the output and input variables. This enables them to have a better forecast of demand; an efficient allocation in limited resources such as capital, fuel, labor, materials, etc.; and a sound plan for capital investment needs. However, partial productivity measures, such as labor productivity indexes or any other partial factor productivity indexes, should not be used alone, because these measures do not tell the whole story. Their indiscriminate use can lead to serious misunderstandings and erroneous conclusions.

Efficient utilization of input resources determines the relative productivity growth of a company, whether it is a manufacturing firm or an electric utility company. One way, or perhaps the only way which can assure this efficient allocation of the input resources is through the utilization of mathematical modeling techniques, the fundamental characteristic of operations research. These techniques have proved to be a powerful and effective approach for solving management problems. With today's computer technology, a large model of input allocation can be solved quite readily and inexpensively.

Goal programming, a technique more flexible than the linear programming, can solve problems with multiple goals. It is of particular value if these goals are conflicting with each other because of its capacity to resolve these conflicts by satisfying the highest priority goals first, then the other less important ones next.

This study uses this technique to allocate the input resources of an electric utility in such a way that a certain percentage growth in productivity as well as the satisfaction of customers' demands are achieved first. Other constraints upon the electric power system and the input requirements associated with the productivity measures are also optimized to the fullest possible extent. This technique, incorporated with the productivity measures, can provide meaningful results which the management of an electric power company could review and consider in making critical decisions related to productivity.

II. LITERATURE REVIEW

Economists have always been concerned with productivity problems. Adam Smith discussed the role of productivity advance in national economic growth:

> The annual produce of the land and labor of any nation can be increased in its value by no other means, but by increasing either the number of its productive laborers, or the productive power of those laborers who had before been employed...in consequence either of some additions and improvement to those machines and instruments which facilitate and abridge labor, or of a more proper division and distribution of employment (Smith, 1937, p. 326).

Since the beginning of the modern technological era, the effects of the technological advance on economic development have been closely studied. As a result of trying to measure and interpret this technological advance, different techniques have been developed, most of which are nothing more than productivity measures. Based on this expression: productivity a ratio of output to inputs, there lies the theory of production.

It was, however, not until the late 1920s and early 1930s, that the concept of production function was established and numerous studies involving theoretical as well as empirical investigations were conducted. In 1928, Charles W. Cobb and Paul H. Douglas (1928) developed a well-known production function, today known as the Cobb-Douglas production function, which was the first published empirical production function fitted to the time series for American manufacturing industries over the period 1899-1922. Their function was

$$Y = b\, L^{\alpha}\, K^{1-\alpha} \tag{2.1}$$

where Y was total value product; L was total labor employed in the industry; K was total fixed capital available for the industry; and b and α were constants. Brown (1968) claimed that their production function was, perhaps, the most famous one indigenous to economics. In his review on this function, Samuelson (1979) remarked that if Nobel prizes had been awarded in economics after 1901, Paul H. Douglas would probably have received one before World War I. This production function has received thousands of citations in present-day economics. And, many productivity indexes are based on this function.

A. Productivity Indexes and Methodological Development

There are two types of productivity indexes. One refers to partial productivity indexes, such as labor productivity index or capital productivity index. The other refers to total or multi-factor productivity index. The former indexes are simply the output divided by labor or capital, while total factor productivity index is defined as output per unit of labor and capital combined. Only two input factors are considered. Symbolically, these indexes are:

a) Partial factor productivity indexes:

$$AP_L = Y/L; \; AP_K = Y/K \tag{2.2}$$

b) Total factor productivity indexes:

$$A = Y/(aL + bK) \tag{2.3}$$

where Y, L and K are the aggregate level of output, labor and capital inputs, and a and b are appropriate weighting terms.

Prior to World War II, all productivity indexes estimated were of the simple output-per-worker, or per-hour variety (Kendrick and Vaccara, 1980). Beginning in the 1880s, occasional studies of output per unit of labor input were prepared in the Bureau of Labor and its successor agency, the Bureau of Labor Statistics (BLS). However, the current government estimates of productivity are still confined to measures of output per labor hour (except of estimates of multi-factor productivity in farming, which are prepared by the U.S. Department of Agriculture) (National Research Council, 1979). Most work on multi-factor productivity has been done by private investigators in universities and research institutes beginning in the 1940s.

Christensen et al. (1980) pointed out that the first empirical attempt to measure total factor productivity was made by Jan Tinbergen (1959) in a notable but neglected article in which estimates were presented for France, Germany, the United Kingdom and the United States for the period 1870-1914. The concept of total factor productivity (TFP) was further elaborated on by John Kendrick (1954) at a 1951 income and wealth conference, and he used it as the framework for his subsequent National Bureau of Economic Research study of total and partial productivity trends in the United States private domestic economy (Kendrick, 1961). Kendrick's total factor productivity index is defined as (Domar, 1962):

$$A^* = \frac{Y_i/Y_o}{\alpha_o(L_i/L_o) + \beta_o(K_i/K_o)} \tag{2.4}$$

where

A^* = the total factor productivity index.

Y_i = output of an industry in physical or value terms in the ith year.

L_i = labor input in ith year (in physcial units).

K_i = capital input in ith year (in physical units).

α_o = share of labor in the value of output in the base period.

β_o = share of capital in the value of output in the base period.

Walters (1963) and Baird (1977) named this index as "arithmetic index" because of its arithmetic combination of labor and capital. Domar (1962) referred to it as "Kendrick's index," and questioned Kendrick's method in the choice of production equation, and the variables and their weights in carrying out his empirical study. And, Baird (1977) remarked that the formula was not suited to measure the rate of technological advance, unless the capital-labor ratio and the ratio of input prices remain constant. Despite the above-mentioned criticism, Kendrick (1973) used the same methodology, with some clarification, to continue the U.S. postwar productivity trends analysis. Others (Stevenson, 1975, Sumanth and Hassan, 1980) still find Kendrick's TFP applicable for their use.

The second version of total factor productivity is R. Solow's geometric index (Solow, 1957) which is frequently cited in the economic literature. His measure was based on the Cobb-Douglas production function with constant returns to scale and neutral disembodied technological change. The resulting index is as follows:

$$\frac{dA}{A} = \frac{dY}{Y} - (\alpha \frac{dL}{L} + \beta \frac{dK}{K}) \tag{2.5}$$

where α and β are the shares of labor and capital and dY, dL and dK are the time derivatives of Y, L and K. Solow simplifies the expression still further, letting

$Y/L = q$

$K/L = k$

and

$\alpha = 1 - \beta$

He derives

$$\frac{dA}{A} = \frac{dq}{q} - \beta \frac{dk}{k} \tag{2.6}$$

where

q is the output per manhour,

k is the capital per manhour.

In order to find dA/A, one only needs a series of data over a period of time for output per manhour, capital per manhour, and the share of capital. Brown (1968) wondered what would happen if nonneutral technological change did exist in the data aside from assuming constant returns to scale. There is no way of treating this phenomenon unless it is assumed away.

Avoiding the problem of deriving a production function and its pattern of shifts over time, Barzel (1963) developed the output-per-unit-of-input technique:

$$Q_{12} = \frac{Y_2 \Sigma I_{i1} P_{i1}}{Y_1 \Sigma I_{i2} P_{i1}} \tag{2.7}$$

where

Y_i is output quantity in the ith year,

I_{i1} is the ith input quantity at year 1, and

P_{i1} is the ith input price at year 1.

However, Equation 2.7 was also derived under very restrictive conditions - of no economies of scale, of competition, and of no change in the marginal productivity of the inputs between the two years compared. He applied this equation to the electric power industry over the period 1929-1955 and concluded that the technique of measuring productivity change was not appropriate.

Consequently, some other production functions, such as generalized Cobb-Douglas (Diewert, 1973), translog production function (Christensen et al. 1973), etc. have been developed in order to have an appropriate production function for the industry under study.

The definition of technology has also been the source of much controversy in the literature. Because technological change cannot be measured by any conventional yardstick, its effect is commonly deduced by first accounting for everything else in the production function. The effect of technology will therefore be included in any discrepancy between what is accounted for by the known inputs and the actual output. Because of this, the rate of technological advance is often referred to variously as the "residual" (Domar, 1961), "technical change" (Solow, 1957), and "measure of our ignorance" (Abramovitz, 1956). Consequently, Nadiri (1970) pointed out that any misspecification or errors in estimating the parameters of aggregate production function, errors in measuring the variables, or errors due to omission of relevant inputs will spill over into the measure of total factor productivity.

In an effort to minimize the errors in measuring the variable, and thus minimizing the residual, Edward F. Denison (1974) updated and refined his initial work (1962) by:

a) Including in his labor input measure estimates of the effect of increased education, shortened hours of work, the change of age-sex composition of the labor force, and other factors that changed the quality of labor over time, and

b) Quantifying the contributions to growth of all major factors other than advances of knowledge, so that his final residual would primarily reflect the impact of that basic dynamic element.

Following Denison, attempts at making quality adjustments for input variables have been made by Jorgenson and Griliches (1967) and Kendrick (1976) as well.

Using Kendrick's (1973) estimate of productivity growth and following his definitions of input, output and productivity, Terleckyj (1974) explored further the effect of the variable, research and development, on economic growth, thus further reducing "our ignorance" concerning sources of productivity growth. Hoping to minimize the errors due to omission of relevant inputs, Barzel (1963) introduced another major input variable, i.e., fuel, for the conventional two-input model, and Stevenson (1975) introduced two more input variables: purchased power, and materials and supplies, in his productivity study in electric power industry.

In order to avoid errors due to misspecification of the form of the function, other production functions more generalized and flexible and fewer prior restrictions, have been developed. The constant elasticity of substitution (CES) was derived independently by two groups, one consisting of Arrow, Chenery, Minhas and Solow (1961), and the other of Brown and deCani (1963). The transcendental logarithmic function (TLOG) was introduced by Christensen et al. (1973). The generalized Cobb-Douglas function was proposed by Diewert (1973) and quadratic production function was worked out by Lau (1974). Heady and Dillon (1961) generated production functions for the agricultural sector.

Review articles by Kennedy and Thirlwall (1972), Nadiri (1970) and Walters (1963) present a broad perspective in the selection of the production function as a means of evaluating productivity and estimating technological change.

B. Productivity Measurement of Electric Utilities

The electric power industry has for many years been probed by economists interested in technological change and economies of scale. Indexes of productivity were developed as one way to measure the efficiency with which the resources entered the production process.

The indexes compiled by Gould (1946) were, perhaps, the earliest attempt to measure the growth of electric utility from the year 1889 to 1942. He constructed indexes of output and partial productivity indexes of input variables: fuel, labor and capital. Fabricant (1946) commented that Gould refrained from combining these measures, i.e., fuel, labor and capital, into a single index of total resources input per unit of product, partly because he was unable to measure each type of input in all aspects, and partly becuase of the theoretical difficulties involved.

Kendrick (1961) made use in part of Gould's data to compile his total factor productivity in electric utility industry. Kendrick utilized his own methodology, which was discussed in the previous section, to aggregate labor and capital input variables into a single index. In his analysis, however, he omitted a major input variable, fuel, which Barzel (1963) claimed as the main raw material in the electric power industry. Barzel argued that if fuel was excluded from the productivity measure, the shift from steam to hydro power, as a result of relative price change, would appear as a fall in productivity. Moreover, if fuel were saved as a consequence of productivity increases, it would not be captured by the productivity measure which would be biased downwards. Consequently, he included fuel explicitly in computing the productivity index in his study of productivity in the electric power industry from 1929 to 1955. Nevertheless, his "output-per-unit-input" technique was also a very restrictive method as a measure of productivity change, because of his predetermined assumptions: constant return to scale and no monopoly effect. However, quite a few studies, such as those done by Komiya (1962), Nerlove (1963), Barzel (1964) and Boyes (1976), etc., proved that the effect of economies of scale was of great importance for this industry.

Stevenson (1975) broke the traditional three-input-variable convention by adding two more input factors, i.e., purchased power and materials and supplies, in his productivity analysis between the period 1951 to 1973. However, his method of handling the capital reconstruction to reflect the current capital investment needed improvement.

Many papers have been devoted to the estimation of technological change and economies of scale in the electric power industry. References to these studies are Komiya (1962), Nerlove (1963), Barzel (1964), Cowing (1974), and Christensen and Greene (1976). From their analyses, insights into the electric utility industry are fully provided.

But, all of these analyses in productivity measurements, technological change and economies to scale are considered on an industry-wide level. Very little has been accomplished in working with particular firms.

C. Productivity and the Industrial Engineer

According to the Industrial Engineering Handbook (Maynard, 1963):

> Industrial engineering is concerned with the design, improvement, and installation of integrated systems of men, materials and equipments; drawing upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such system.

From this definition, it is no surprise that industrial engineers, traditionally have been involved in various efforts to improve manufacturing effectiveness. In fact, productivity has always been of utmost importance to the industrial engineer.

As early as 1900, Frederick W. Taylor (1911) originated the time study to seek a "fair day's work for a fair day's pay." This study technique had the effect of raising the efficiency of the individual labor in many instances. His scientific management technique required only 140 men to do the same amount of work in the yards as was formerly done by 400 to 600, observed Copley (1923). Thus, the productivity of labor was increased by a factor of 3 or 4.

Gilbreth (1911) developed the techniques of motion study which were used to improve manual operations. This search for the "one best way" by the technique of motion study demonstrated that output per man per hour could be increased as much as threefold in the brick-laying routine (Taylor Society, 1926).

In labor management, industrial engineers utilized the ideas of Maslow's (1954) Hierachy of Needs, Drucker's (1954) Management by Objectives, McGregor's (1960) Theory Y, and many other new theories and techniques so as to understand and manage people in order to raise the labor productivity in full extent.

Industrial engineers' involvement in plant layout gives rise to the productivity improvement, virtually in all related input factors, based on the major objectives of a good plant layout listed by Moore (1962). A remarkable growth in the size and complexity of organizations hastens industrial engineers to adopt the techniques of operations research, which have the characteristic of attempting to find the best or optimal solution to the problem under consideration (Hillier and Lieberman, 1974). With today's computer technology, these mathematical models of operations research further facilitate productivity improvement.

Essentially, industrial engineering techniques can be described as tools for productivity improvement. However, there are not many references available, which are related to the productivity measurement at firm level. Even those measurements developed by Taylor and Davis (1978), Sumanth and Hassan (1980) lack a strong theoretical framework to support their measures. Hines (1978) pointed out the typical industrial engineering educational background, including economics, accounting, engineering economy and measurement, can be used to develop a productivity measurement. He further suggested that an emphasis on manufacturing productivity at the firm level should be considered as a prime area for development in the practice of industrial engineering. Productivity measurement should be investigated as it is a prelude to enhancing it (Mundel, 1978).

III. OBJECTIVES

Many economists and engineers believe that productivity improvement can ease the vicious effects of the various economic woes, such as inflation and stagnation facing this nation. Just a decade or so ago, the electric utility industry had an impressive productivity growth record. Unfortunately, it, too, in recent years has encountered the same problem as other segments of the economy: a general decline in productivity. Thus, the analysis of the extent and the causes of productivity gains in an electric power firm is of importance. Most of the previous productivity investigations cited in the literature review were carried out at the industry or regional level. Yet, it is at the firm level that regulatory directives and rules are imposed and investment decisions are made. In addition to this, each firm has a different technological level and managerial policy. Consequently, the productivity growth rate will not be the same for each company. Comparing the current productivity growth rate of a company with those of previous years, or with those of other companies, ought to be helpful to the decision-makers. Hence, productivity analysis at the firm level is a significant topic to be examined. In this perspective, the objectives of this study can be formulated in the following manner:

1. To develop a productivity measurement scheme at the firm level, which is theoretically correct as well as readily applicable. This will be accomplished by adopting a classical

economic production function upon which to base the model and to test the scheme's applicability in a case study.

2. To devise a procedure which would give management advice on the optimal allocation of production inputs so that a desired rate of productivity growth might be attained. A goal programming model, a technique in operations research, will be utilized to accomplish this objective.
3. To construct a highly accurate forecasting model for year demand. In order to assure a certain percentage growth in productivity, the developed productivity equation has to be incorporated in the mathematical model as one of the objectives or goals to be satisfied. This requires the following year's demand quantity which, thus, must be forecasted.

The following chapter, Chapter IV, deals with the development of productivity measurement at a firm level and provides a case study with brief discussion of the results. Chapter V gives a brief description of mathematical modeling related to electric utilities and contains a goal programming model for an electric utility company. A comparison of two forecasting techniques for times series data of monthly electricity sales is the primary concern of Chapter VI. Chapter VII presents a case study of the goal programming model developed in Chapter IV to illustrate its applicability and capability. As is customary, the final chapter consists of sections dealing with summary, conclusions and recommendations for further study.

IV. PRODUCTIVITY MEASUREMENT OF AN ELECTRIC UTILITY COMPANY

The term "productivity" is generally used to denote a relationship between output and the related inputs used in the production process. The basic objective of productivity measures is to obtain at least rough estimates of the impact on production of the investments and other variables that advance knowledge, improve technology and organization, and otherwise enhance the productive efficiency of the factors of production.

The meaning of productivity measures depends on the definitions accorded to output and inputs, the methodology by which the concepts are statistically implemented, including the weighting patterns used to combine unlike units of outputs and inputs, and the manner in which outputs are related to the inputs.

Consider an electric utility company whose output, say Y, is equal to the sum of amount of kilowatt hours (kWh) sold to the ultimate customers and the sales for resales. The input variables, say X_i's, are labor, capital, amount of energy consumed, purchased power and miscellaneous materials, which are required to produce Y.

The quantities of these Y's and X_i's for any two periods, T-1 and T, can be tabulated as follows:

Period T-1 $Y_{T-1}, X_{1,T-1}, X_{2,T-1}, \ldots, X_{5,T-1}$

Period T $Y_T, X_{1,T}, X_{2,T}, \ldots, X_{5,T}$

The percentage change in output between these two periods can be determined by comparing Y_T and Y_{T-1}. In order to know what happened to inputs as a whole, the values $X_{1,T}/X_{1,T-1}$, $X_{2,T}/X_{2,T-1}, \cdots, X_{5,T}/X_{5,T-1}$ have to be weighted suitably. To get these weights, one has to know how the inputs X_i's relate with each other to produce Y. This relationship is described by the "production function," which is the organizing principle behind the measurement of productivity relationship (Kendrick 1973).

A. Production Function Theory

The production function is the basic concept in the theory of production. It is the expression of the relationship between the maximum quantity of output and the inputs required to produce it, and the relationship between the inputs themselves (Brown, 1968). These relationships between output and inputs and between the inputs themselves are determined by the technology that rules at any given time. The technology is embedded in the production function and can be expressed in terms of it. So, given a level of technology, a production function provides information concerning the quantity of output to be produced, per unit of time, when a particular quantity of input is employed. Since several inputs are involved, there are usually many possible combinations of resources to be used. A producer then chooses a combination that is the least-cost combination for a given quantity of output.

Production functions can be represented by mathematical terminology, such as for a two-factors production function,

$$Y = f(L, K) \tag{4.1}$$

where

Y = output

L = labor

K = capital

They can also be represented by specific algebraic forms, and graphically by a set of curves, isoquants, each denoting various combinations of inputs which produce a given output. Figure 4.1 shows graphically a general production function which specifies the dependence of a given output, Y, on two factors of production, labor, L, and capital, K.

It should be noted that the producer does not control or alter the production function. The producer can move along on the production function or choose to operate on an alternate one. In the short run, producers will operate with some resources in fixed supply. In the long run, there is sufficient time to enable the producers to vary the quantities of resources.

There are four characteristics of a production function, which are known as an abstract technology collectively (Brown, 1968). These four characteristics, based on two-factors production, are discussed as follows.

1. The efficiency of the technology

For given inputs, and given the other characteristics of an abstract technology, the efficiency characteristic determines the output that

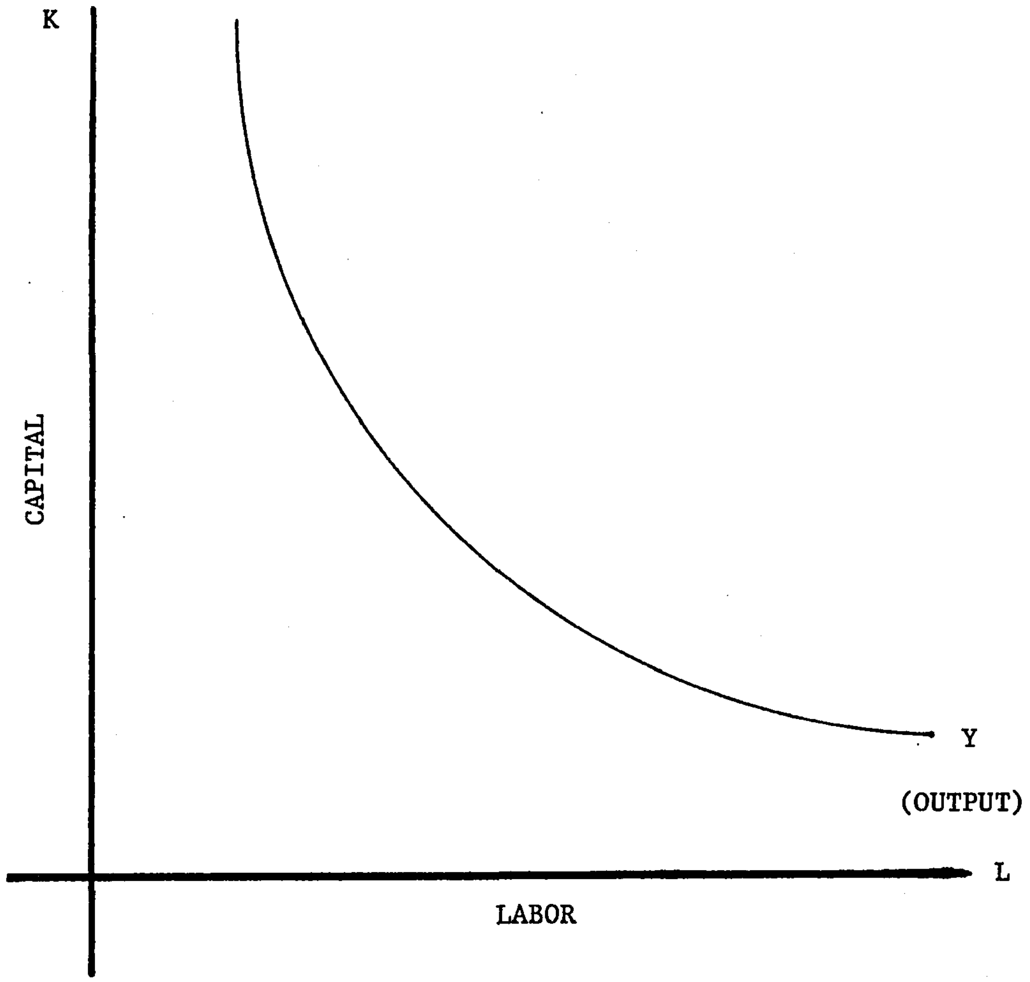


Figure 4.1. Two factors production function

results. If it is large, then the output is large, irrespective of the plant and equipment and the labor employed, etc. The efficiency characteristic can be thought of as a scale transformation of inputs into output.

2. The degree of economies of scale

Economies of scale are defined as follows: for a given proportional increase in all inputs, if output is increased by a large proportion, the firm enjoys increasing returns, or economies of scale; if output is increased by the same proportion, there are constant returns to scale; and if output is increased by a smaller proportion, decrease returns result or diseconomies of scale.

3. The degree of capital intensity of a technology

The usual definition of capital intensity is expressed in terms of the quantity of capital relative to the quantity of labor used in the production process. For example, comparing two firms, the one which has the larger capital-labor ratio is more capital intensive than the other. This definition focuses on the labor and capital variables only. But the larger capital-output ratio could have been produced by one of two ways. Either a larger amount of capital was supplied to the firm relative to the amount of labor, or it could have been due to the fact that the technology of that firm required a larger amount of capital relative to the amount of labor for given levels of input supplies.

4. The ease with which capital is substituted for labor

For two factors of production, labor, L, and capital, K, the elasticity of substitution is represented symbolically by

$$\sigma = \frac{(K/L)\ d(L/K)}{(f_L/f_K)\ d(f_K/f_L)} \qquad (4.2)$$

where

f_L = $\partial Y/\partial L$, the marginal product of labor

f_K = $\partial Y/\partial K$, the marginal product of capital

Y = the output quantity

The ratio of the marginal product of capital to the marginal product of labor is the marginal rate of substitution of labor for capital. The elasticity of substitution as defined in the formula relates the proportional change in the relative factor inputs to a proportional change in the marginal rate of substitution between labor and capital. Intuitively, it can be thought of as a measure of the ease of substitution of labor for capital.

The elasticity of substitution can take on any value between zero and infinity, always being positive. In Figure 4.2(a), it is zero, whereas in Figure 4.2(b), it is infinity. In the latter instance, the factors are to all purposes identical. From the graphs, it can be inferred that σ is related to the curvature of the isoquants; in fact, the larger the curvature of the isoquants, the smaller the elasticity of substitution.

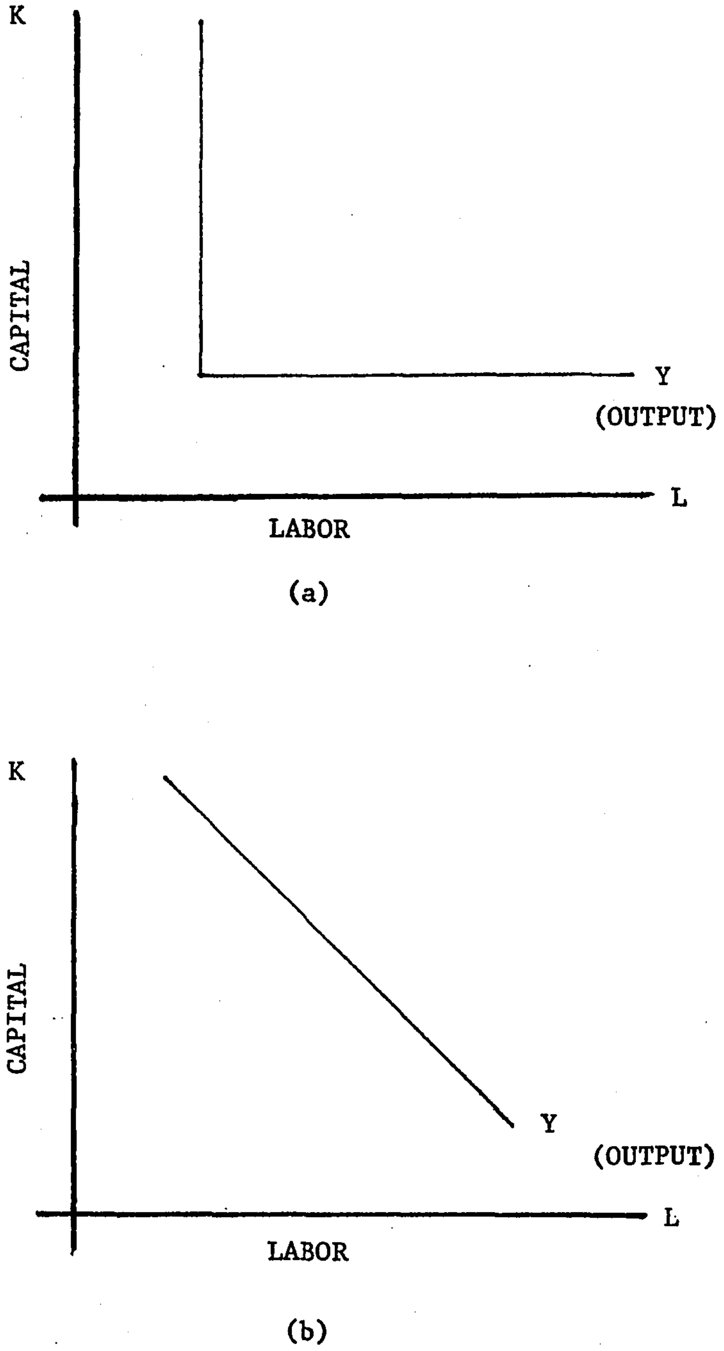


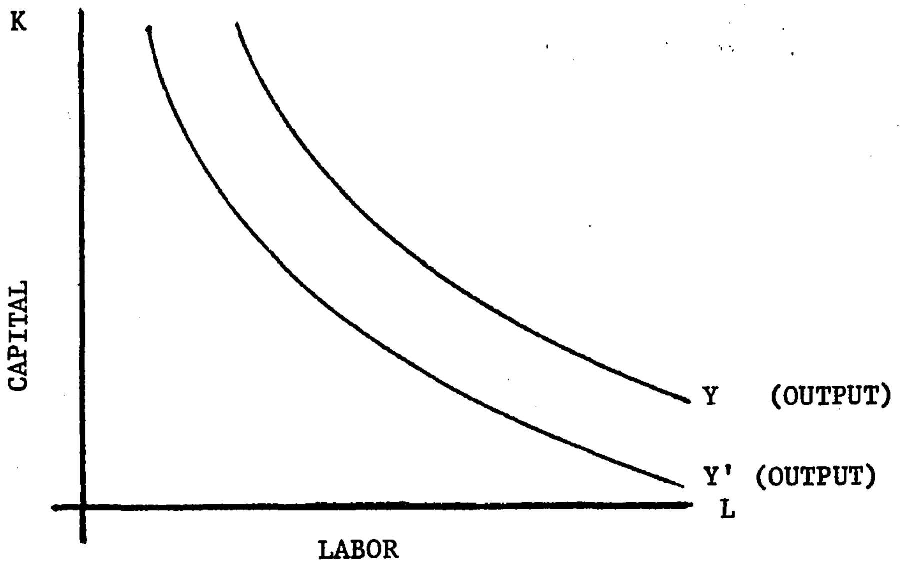
Figure 4.2. Extreme values of the elasticity of substitution

B. Technological Change and Production Function

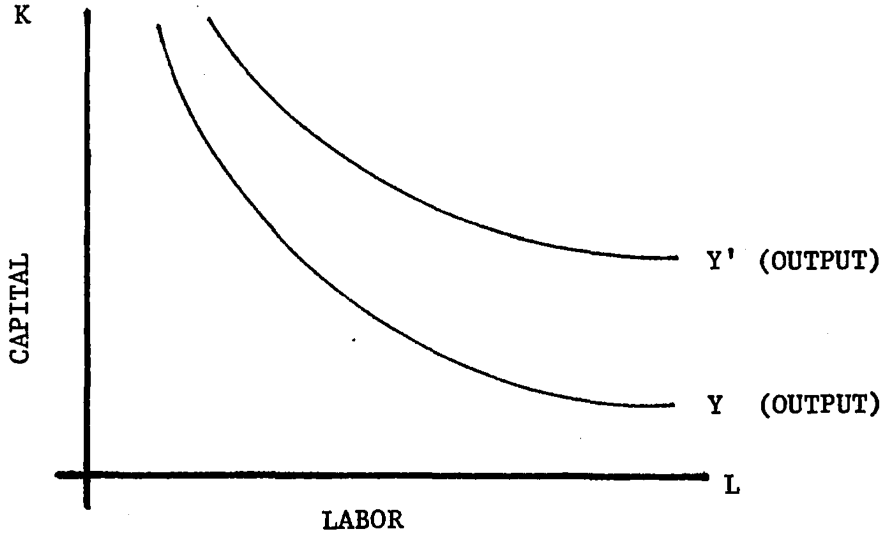
For any production function, there is a given state of technology. The producer cannot change his production function but he can shift to an alternative one by adopting a different technology, even though the same quantities of resources are employed. The producer will adopt a different technology only if the new production function is higher than the former one. This means that using the same quantity of resources will result in greater output.

There are two general types of technological change, neutral and nonneutral. A neutral change neither saves nor uses labor; it is one which produces a variation in the production relation itself, but does not affect the marginal rate of substitution of labor and capital. In Figure 4.3(a), a neutral technological change has been graphed. The outputs Y and Y' have the same value. They differ in that Y' is to be produced under a new technology. Here is the case where more output is produced with the same levels of inputs. The marginal rate of substitution of labor for capital remains unchanged at each combination of labor and capital. This type of technological progress simply alters the scale of the axes. Thus, changes in the efficiency of a technology and economies of scale -- two characteristics of an abstract -- are neutral technological change.

A nonneutral technological change alters the production function and can be either labor-saving (capital-using) or capital-saving (labor-



a) A neutral technological change



b) A nonneutral technological change

Figure 4.3. Graphs of technological change

using). If the production function is altered such that the marginal product of capital rises relative to the marginal product of labor for each combination of capital and labor, there is said to occur a capital-using (labor-saving) technological change. A capital-saving technological change occurs when the marginal rate of substitution of labor for capital is lowered at every combination of capital and labor. In Figure 4.3(b), the isoquant labor Y' represents a technology which saves labor relative to the isoquant labeled Y. The pivoting or twisting of an isoquant is characteristic of a nonneutral technological change. In Figure 4.3(b), Y' can differ from Y for two reasons: the capital intensities and/or the elasticities of substitution of two technologies can differ.

C. Partial Factor Productivity and Multi-Factor Productivity

In this study, partial factor productivity indexes (PFPI) and multi-factor productivity indexes (sometimes known as total factor productivity indexes) (MFPI) are studied and developed. The partial factor productivities are ratios of gross output to individual classes of inputs, and can be defined mathematically as follows:

$$PFP_{i,T} = \frac{Y_T}{X_{i,T}} \qquad (4.3)$$

where

$i = 1, 2, \cdots, n$

Y_T = the output produced at time T

$X_{i,T}$ = the ith input required at time T to produce Y_T

n = the number of input variables at time T required to produce Y_T

T = a time period

The partial factor productivity indexes are the ratios of the partial factor productivities, one of which is used as the base factor. Mathematically, it can be written as:

$$PFPI_{i,T} = \frac{Y_T/Y_1}{X_{i,T}/X_{i,1}} = \frac{PFP_{i,T}}{PFP_{i,1}} \qquad (4.4)$$

where

Y_1, $X_{i,1}$ and $PFP_{i,1}$ are the base factor, when T = 1 is used as the base period.

Historically, the partial factor productivity indexes, particularly ratios of output to the associated labor inputs, were the first type of productivity measures to be developed. Beginning in the nineteenth century, occasional studies of output per unit of labor input were prepared in the Burear of Labor and its successor agency, the Bureau of Labor Statistics (BLS). In the 1930s, extensive studies of labor productivity were undertaken by the National Bureau of Economic Research.

Individual partial factor productivity ratios can be used to show the saving achieved in specific inputs per unit of output as a result of efficiency changes plus factor substitution. But, it would be unwise to use any one of these partial factor productivity measures as the sole yardstick for efficiency improvement, such as "labor productivity." They do not measure changes in the efficiency of a particular resource nor changes in productive efficiency generally. Although they are informative, they are incomplete indexes of productivity.

The multi-factor productivity index is developed in order to have a better measure of efficiency than those based on partial factor productivity indexes alone. It is necessary to relate output to all associated inputs so as to have the correct measure of the net saving in factor inputs, and thus the increase in overall productive efficiency. The multi-factor productivity index is derived as the ratio of output to all associated classes of inputs. Algebraically, it can be defined as follows:

$$MFP_T = \frac{Y_T}{g_T(\cdot)} \qquad (4.5)$$

where

MFP_T = multi-factor productivity at time T

Y_T = the output produced at time T

$g_T(\cdot) = g_T(X_{1,T}, X_{2,T}, \cdots, X_{n,T})$

= a function of input aggregate at time T

The multi-factor productivity index is a ratio of these two measures, one of which is used as a reference:

$$MFPI_T = \frac{Y_T/Y_1}{g_T(\cdot)/g_1(\cdot)}$$

$$= \frac{MFP_T}{MFP_1} \qquad (4.6)$$

where MFP_1 is used as the base factor when T = 1.

The aggregated-input structure can be revealed by the production function approach which is used to derive the multi-factor productivity index. The weighting scheme is also to be considered in the aggregated-input structure so as to indicate the relative importance of the aggregated inputs. As Kendrick (1973) pointed out, with the changing input proportions, the extent or even the direction of productivity change cannot be determined without the appropriate weights. The share of each input in total cost will be used as the appropriate weight in this research.

D. Methodology in Derivation of Productivity Indexes

The efficient transformation of a vector of inputs X into an output Y can be represented by an implicit production function, which is the basic framework productivity measurement:

$$Y = f(X_1, X_2, \cdots, X_n, T) \qquad (4.7)$$

where

Y = the output

X_i = the ith input factor

$i = 1, 2, \cdots, n$

T = the time period

By totally differentiating Equation 4.7 with respect to time T, the basic growth equation is derived:

$$\frac{dY}{dT} = \frac{\partial Y}{\partial X_1}\frac{dX_1}{dT} + \frac{\partial Y}{\partial X_2}\frac{dX_2}{dT} + \cdots + \frac{\partial Y}{\partial X_n}\frac{dX_n}{dT} + \frac{\partial Y}{\partial T}$$

$$= \sum_{i=1}^{n} \frac{\partial Y}{\partial X_i}\frac{dX_i}{dT} + \frac{\partial Y}{\partial T} \qquad (4.8)$$

A more formal basic growth equation, which underlies most multifactor productivity studies, can be derived by dividing Equation 4.8 by Y on both sides of the equation and rewriting it in logarithmic form:

$$\frac{d \ln Y}{dT} = \sum_{i=1}^{n} \frac{\partial \ln Y}{\partial \ln X_i}\frac{d \ln X_i}{dT} + \frac{\partial \ln Y}{\partial T}$$

$$= \sum_{i=1}^{n} e_i \frac{d \ln X_i}{dT} + \frac{\partial \ln Y}{\partial T} \qquad (4.9)$$

where

$(d\ln Y)/dT = (dY/dT)/Y$

= the total growth in output Y

$e_i = \partial \ln Y/\partial \ln X_i$

$= (X_i/Y)\ (\partial Y/\partial X_i)$

= output elasticity with respect to X_i[1]

---

[1] It denotes the percentage change in output attributable to a percentage change in X_i, keeping others constant.

$$(d\ln X_i)/dT = (dX_i/dT)/X_i$$

$$= \text{growth rate of input } X_i$$

$$(\partial \ln Y)/\partial T = \text{technological change}^1$$

When the quantity, $\sum_{i=1}^{n} s_i \, (d\ln X_i/dT)$ is subtracted from both sides of Equation 4.9, it becomes

$$d\ln Y/dT - \sum_{i=1}^{n} s_i \, (d\ln X_i/dT) \doteq \sum_{i=1}^{n} (s_i - e_i) \, (d\ln X_i/dT) + (\partial \ln Y)/\partial T \qquad (4.10)$$

where

$$s_i = P_i \, X_i / \sum_{i=1}^{n} P_i \, X_i$$

$$P_i = \text{the price of input } X_i$$

$$\sum_{i=1}^{n} X_i \, P_i = \text{the total expenditure of all inputs}$$

The left-hand side of Equation 4.10 is measurable. In fact, it is a Divisia index of the growth in total factor productivity (Jorgenson and Griliches, 1967). Let G_T be the expression

$$G_T = d\ln Y/dT - \sum_{i=1}^{n} s_i \, (d\ln X_i/dT) \qquad (4.11)$$

This productivity growth, G_T, depends on changes in input levels, deviations between output elasticities and cost shares, and technological

---

[1] A change in any of the characteristics of the abstract technology that is embedded in the production function, which is discussed in the previous section of this chapter.

change. However, Equation 4.11 is formulated in a continuous time fashion. Since data take the form of observations at discrete points in time, a model formulated in discrete time is required. Hulten (1973) showed that Equation 4.11 could be approximated by the following equation:

$$\overline{G}_T = (\ln Y_T - \ln Y_{T-1}) - \sum_{i=1}^{n} \overline{s}_i (\ln X_{i,T} - \ln X_{i,T-1}) \qquad (4.12)$$

where

$\overline{G}_T$ = the average rate of productivity growth between T-1 and T

$\overline{s}_i = \frac{1}{2} (s_{i,T} + s_{i,T-1})$

= the average cost share of X_i at T-1 and T

This is a desirable procedure which is capable of representing a diversity of possible production structures, i.e., one which is free of a priori restrictions. This approach avoids restrictive assumptions, such as constant returns to scale, predetermined elasticities of substitution and transformation, etc.

From this average productivity growth rate, $\overline{G}_T$, between T-1 and T, the multi-factor productivity index ($MFPI_T$) at time T can be derived. Equation 4.12 can be rearranged in the following fashion:

$$\overline{G}_T = \ln (Y_T/Y_{T-1}) - \sum_{i=1}^{n} \ln (X_{i,T}/X_{i,T-1})^{\overline{s}_i}$$

$$= \ln (Y_T/Y_{T-1}) - \ln \prod_{i=1}^{n} (X_{i,T}/X_{i,T-1})^{\overline{s}_i}$$

$$= \ln \left[\frac{Y_T/Y_{T-1}}{\prod_{i=1}^{n} (X_{i,T}/X_{i,T-1})^{\bar{s}_i}} \right]$$

or

$$\exp(\bar{G}_T) = \frac{Y_T / \prod_{i=1}^{n} \left(X_{i,T}\right)^{\bar{s}_i}}{Y_{T-1} / \prod_{i=1}^{n} \left(X_{i,T-1}\right)^{\bar{s}_i}}$$

$$= \frac{MFP_T}{MFP_{T-1}}$$

or

$$MFP_T = MFP_{T-1} \exp(\bar{G}_T) \tag{4.13}$$

where

$\exp(\bar{G}_T)$ = the growth rate between T-1 and T

$\prod_{i=1}^{n} (X_{i,T})^{\bar{s}_i} = g_T(\cdot)$

= the aggregate function of inputs at time T

Y_T/Y_{T-1} = the output quantity index between T-1 and T

$X_{i,T}/X_{i,T-1}$ = the X_i input quantity index between T-1 and T

Consequently, the multi-factor productivity index can be derived from Equation 4.13:

$$MFPI_i = MFPI_{i-1} \exp(\bar{G}_i) \tag{4.14}$$

where

i = 2, ···, T

$MFPI_1$ = 100

= the base index

T = the number of periods (years) under study

The partial factor productivity indexes for various input factors can also be developed, as well.

E. A Case Study: Productivity Measurement

The Iowa Electric Light and Power Company is utilized to illustrate the applicability of the developed productivity measurement model. Data for the study are derived primarily from the company's annual reports (1974-1979) to the Federal Energy Regulatory Commission (FERC).

Construction of the multi-factor productivity index (MFPI) and partial factor productivity indexes (PFPI) requires the formation of an output quantity measure and the aggregation of the input quantities, together with their associated cost shares.

In order to show the sensitivity of this productivity measurement, two different methods of capital acquisition are performed, whereas the other input factors remained the same. In another perspective, it illustrates the danger of miscalculation of the input quantity, which will result in the misinterpretation of the productivity measurement.

1. Data base of output

The output measure used in this research was defined as total kilowatt hours (kWh) of electricity sold to the ultimate customers and sales for resale. Sales to ultimate customers included all direct sales by the company to residential, rural, commercial, industrial and governmental customers. Sales for resale included both sales to publicly-owned utilities and to privately-owned companies. The quantities of output component are listed in Table A.1 of Appendix A.

2. Data base of inputs

Five input factors were considered in this study: (1) labor, (2) fuel consumption, (3) capital service, (4) purchased power, and (5) miscellaneous materials (a residual from the operation and maintenance expense). In this research, each input quantity was required and its related expenditure was denominated in constant (1976) dollar terms.

a. Labor The Iowa Electric Light and Power Company's annual reports did not provide sufficient detail with which to distinguish between the various categories of laborers. Consequently, no contribution to economic growth by the changing composition of the firm's labor force has to be assumed. Labor input was the sum of full-time employees plus one-half the number of reported part-time laborers. The labor expenditure was calculated by multiplying the total number of employees by the 1976 average wage and benefit payment, which was about $15,319/employee. These statistics are reported in Table. A.2 of Appendix A.

b. Fuel consumption The total amount of Btu's consumed by the company was derived as follows:

$$\text{Total Btu consumed} = \text{Fuel expenditure} \div \text{Average cost}/10^6 \text{ Btu}$$

Fuel expenditure was given in the Annual Report of the company, and the average cost of fuel/10^6 Btu for that company could be found in Moody's Public Utility Manual (Hanson, 1974-1979). Then, the fuel expenditure of any year was converted to 1976 dollars by multiplying the quantity derived by the 1976 average cost. Fuel statistics are shown in Table A.3 of Appendix A.

c. Purchased power Not all electric utility companies generate sufficient power to meet their customer's needs. Quite often, it is more economical to purchase power from other utility firms than to generate power by running an uneconomical plant. Sometimes the company must buy power because of an unforeseen outage. The amount of purchased power is equal to the total power received from the other firms. The expenditure for the purchased power in 1976 dollars for any given year was calculated by the total purchased amount times the 1976 average unit cost of purchased power which was about $0.026/kWh. The purchased power statistics are reported in Table A.4 of Appendix A.

d. Miscellaneous materials The expenditure for this category was computed as the difference between the reported total operating and maintenance expenses, and the sum of fuel, labor and purchased power payments. This factor was a heterogeneous mixture of costs. The wholesale price index for intermediate materials, supplies and components (net of intermediate materials for food and manufactured animal feeds), U.S. Department of Labor, Bureau of Labor Statistics, 1974-1980) was used to deflate the expenditure into 1976 constant dollars. Consequently, the quantity index is also derived from the deflated expenses. These statistics are also reported in Table A.5 of Appendix A.

e. Capital In a strict economic sense, Stevenson (1975) stated that the cost of the capital component should reflect the opportunity cost of the investment in capital assets and the physical depreciation or depletion of the capital equipment maintained and utilized by the utility company.

The opportunity cost of capital is estimated by the return on capital times the value of utility plant and equipment (net of depreciation). Whereas, the depreciation charge is essentially an installment payment designed to recoup the investor's capital by the end of the expected life of the capital equipment.

The capital investment of a utility at any point in time is not homogenous. It represents a stream of net additions over time and includes a variety of items reflecting then-current construction and equipment costs at the time of purchase. To be compatible with other input factor variables in this research, a reconstruction of capital investment on a 1976 price basis was required.

There are several methods to reconstruct the capital investment: the perpetual inventory method proposed by Christensen and Jorgenson (1969), Stevenson's method (1975), and the Iowa type survivor curve approach. In this research, the latter two methods are considered and results are compared and discussed.

1) Method I: Stevenson's method in reconstruction capital investment An adjusted Hardy-Whitman index is used to deflate the annual net investment of capital in service. The total investment in that portion of the electric utility which is in service is reconstructed on a 1976 basis in the following manner:

$$CS_i = CS_{i-1} + NI_i/HW_i \qquad (i = 1975,\cdots, 1979) \quad (4.15)$$

$$CS_{1974} = ACS_{1974}/\sum_{k=1}^{15} (k/\sum_{i=1}^{15} i)\ HW_j \qquad (j = 1959 + k) \quad (4.16)$$

where

CS_i = reconstructed capital service in year i

ACS_i = actual (unconstructed) capital service in year i

NI_i = $ACS_i - ACS_{i-1}$

= actual net investment in year i

$HW_{i,j}$ = adjusted Handy-Whitman index for year, i, j

The Handy-Whitman index (Whitman, Requardt and Associates, 1979) is constructed on a geographic basis for fossil production, nuclear production, transmission and distribution capital components and is constructed with the year 1949 = 100. The index used in this study is a weighted average over these four capital components of the North Central geographic region.

The quantity index for capital is constructed by means of data from the reconstructed capital investment. Whereas, the capital expenditure is estimated as follows:

$$\begin{aligned}\text{Capital expenditure} &= \text{Depreciation} + \text{Opportunity cost}\\ &= (1/\text{investment life})\ (CS_i) + (1\text{-depreciation reserve})\ (\text{rate of return on capital})\ (CS_i)\end{aligned} \tag{4.17}$$

where

$$\text{rate of return on capital} = \frac{\text{total return on capital}}{\text{total capitalization}}$$

total return on capital = net profit + taxes on income + interest payment + depreciation

total capitalization = common equity + cumulative preferred stock + cumulative preference stock + long-term debt

The investment life of the major plants was estimated to be 30.71 years and the rate of return on capital was calculated to be 16.84 percent. The depreciation reserve was recorded to be 25.4 percent in Moody's Public Utility Manual (Hanson, 1978). These calculations and the reconstruction of capital investment as well as its expenditure are listed in Table A.6 and Table A.7 respectively in Appendix A.

2) Method II: Iowa type survivor curve There are situations where the age distribution of the capital investment is known. Often times, the property records of the firm are not kept in

sufficient detail to determine the age distribution of the surviving plant. Only gross additions and gross retirements and the balances of each property account for each year are available. For example, the company may have recorded the balances in the following fashion:

$$Bal_i = Bal_{i-1} + (Add_i - Ret_i) \tag{4.18}$$

where

i = the i calendar year ($i = 1974, \cdots, 1979$)
Bal_{i-1} = balance beginning of the year i
Bal_i = balance end of the year i
Add_i = the additions (in current dollars) for the year i
Ret_i = the retirements (in current dollars) for the year i

From Equation 4.18, the capital investment consists of the present addition plus the survival of the previous yearly invested units (in monetary value). If the yearly gross additions are available and the retirement frequencies are known, an estimate of the amount of surviving units at each age as of any year can be calculated. The Iowa type survivor curves provide the retirement frequency data needed if the proper type curve can be identified. In order to have a whole picture of the reconstruction method using Iowa type survivor curves, some related definitions, according to Winfrey (1967), are stated below:

1. An original group is a group of like units installed in service at the same time or at least during the same accounting interval. Thus, they become a like-age group since all units are of the same age.

2. The age of a unit of property is the lapsed time from the data of installation to the data of observation. For a group of units, the average age is the average of the ages of the separate units.
3. The service life of a unit is that period of time (or service) extending from the data of its installation to the date of its retirement from service.
4. The average service life of a group of individual units is the quotient obtained by dividing the sum of the service lives of all the units by the number of units.
5. Retirements are those property units which are taken out of service for any reasons whatsoever.
6. Installations are new units placed in service, not as replacement units, but as additions to the property.
7. Survivor curves show the number of units of a given group which are surviving in service at given ages. The ordinates to the curve give, at any particular age, the percentage (or the actual number) of the original number which are yet surviving in service.
8. The mode is defined as the point on the frequency curve having the highest ordinate.

Literature related to Iowa type survivor curves can be founded in many references, for example, Cowles (1979), Fitch et al. (1975), Marston et al. (1970), and Winfrey (1967). Actually, the families of Iowa type curve system resulted from studies of the survivor characteristics of many types of industrial and utility properties. The purpose of these studies was to generalize the attrition of units of physical properties in the form of retirement frequency curves representing expected experience. These curves were grouped together according to the location of the mode of the frequency curves with respect to the mean of the distribution. If they accrued at an age less than the mean retirement age (average service life), the curve was designated an L-type. An R-type curve was one in which the modal age was greater than the mean. For symmetrical distribution, the symbol S was used. A number subscript to the letter indicated the variance observed. The larger the subscript, the smaller the variation of the retirement ages about the average service life. Figure 4.4 shows the R_2-Iowa type curve in a survivor curve format for various average service lives.

The capital reconstruction method can best be described through an example listed in Table 4.1. The input data required are the yearly gross additions, the actual book balances (end of the year) and the knowledge of which Iowa type survivor curve to use. Knowing the Iowa type survivor curve, say R_3-8, the percent surviving can be worked out, which is listed in column 2 of Table 4.1. The simulated balance of 1975 is obtained by summing up the values in column 3. The deviation of the simulated balance and the actual one is spread out according to the weights for each year. The purpose of doing so is to have the simulated balance matched up with the actual one, which has the value 21200. The adjusted simulated balance under column 5 is then converted to constant

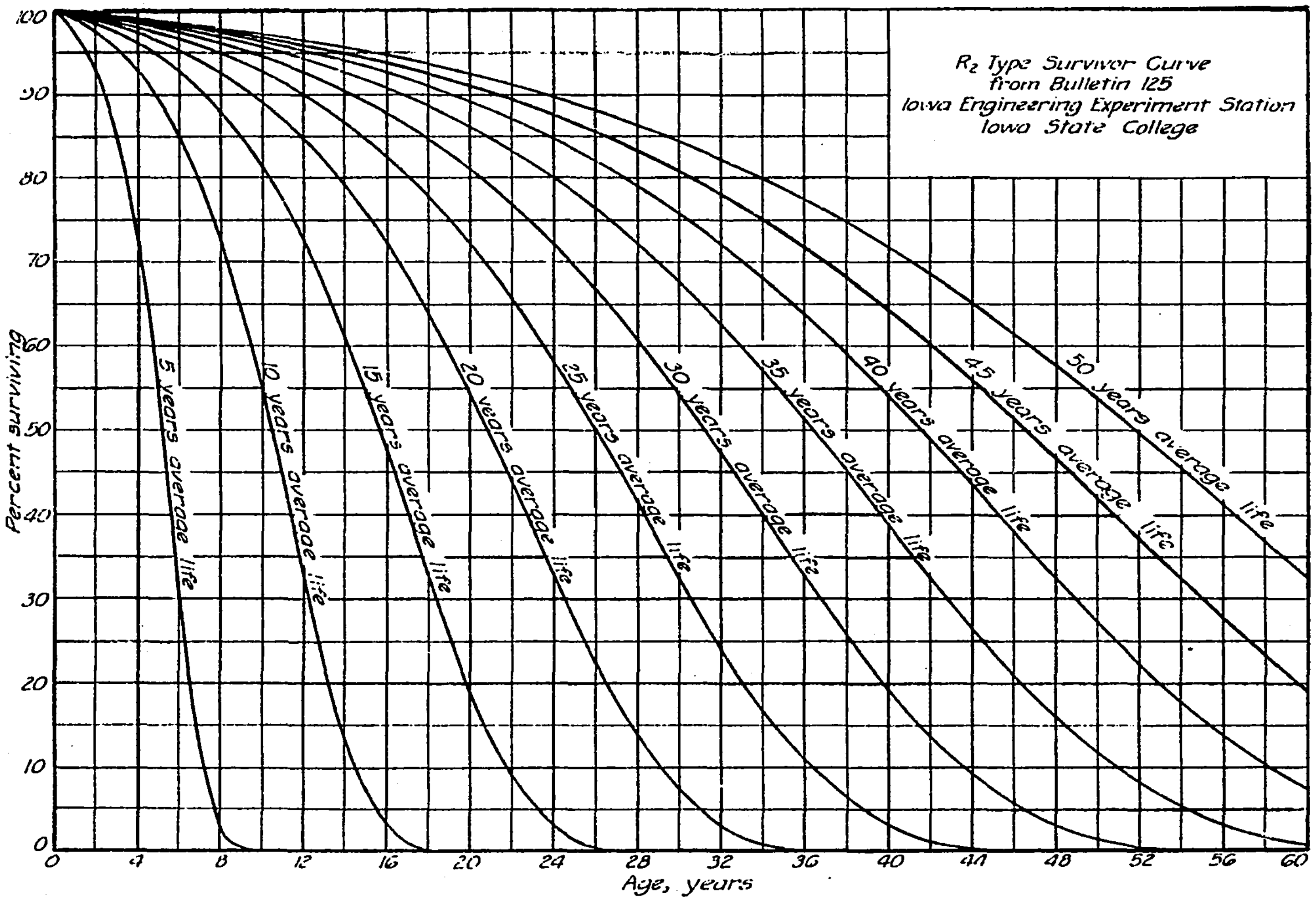


Figure 4.4. R_2 type survivor curve

Table 4.1. Calculation of reconstructed capital investment from actual balances using an R_3-8 Iowa type curve

Year	Gross Addition (1)	Percent Surviving[a] (2)	Simulated Balance of 1975 (1)x(2) (3)	Weights[b] {(3) ÷ 21099.} (4)	Adjusted Simulated Balance {(4) x 101. + (3)} (5)	Handy-Whitman Index (1976=100) (6)	Deflated Balance (5) ÷ (6) x 100. (7)
1960	2150	--	--	--	--	39.6	--
1961	1200	--	--	--	--	38.6	--
1962	900	.0	0	0	0	38.8	--
1963	950	.4	4	0.000	4	38.6	10.4
1964	1400	3.4	48	0.003	48	40.1	119.7
1965	1000	12.0	120	0.006	121	42.2	286.7
1966	1850	26.2	485	0.023	487	43.7	1114.4
1967	750	45.8	344	0.016	346	45.8	755.5
1968	1600	62.9	1006	0.048	1011	47.3	2137.4
1969	1900	77.1	1465	0.069	1472	51.9	2836.2
1970	2350	86.1	2023	0.096	2033	56.8	3579.2
1971	2700	92.4	2495	0.118	2507	60.7	4130.1
1972	2850	96.1	2739	0.130	2752	61.7	4460.3
1973	3200	98.3	3146	0.149	3160	66.1	4780.6
1974	3700	99.4	3678	0.174	3695	81.7	4522.6
1975	3550	99.9	3548	0.168	3564	95.6	3728.0

Total simulated balance............21,099

Book balance.......................21,200

Deviation (Difference).............101

Adjusted total simulated balance....21,200

The reconstructed capital investment for 1975 (in 1976 constant dollar)...32,461.1

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[a] Derived from Iowa type R_3-8 curve and applicable to gross additions.

[b] Based on the values of simulated balance of 1975.

(1976) dollars, using the Handy-Whitman index. The reconstructed capital investment that reflects the "real" capital input for 1975 is the accrued values through those surviving values in constant (1976) dollars.

Applying the procedure depicted above, the capital investment, which can be segregated into the component parts of generation, transmission and distribution, is able to be reconstructed if the frequencies of survival for these three major components are known. According to A Survey of Depreciation Statistics (LeVee, 1979), most steam generation, transmission and distribution plants have retirement characteristics of Iowa R_2 type curves. With the availability of average service lives, yearly gross additions and the balances for each component, the simulated balances from the year 1974 to the year 1979 for each component were calculated and summarized in Table A.8 of Appendix A. Accordingly, the total reconstructed capital investment, reflecting the "real" capital input, for each year was computed and recorded in Table A.9 in Appendix A.

3. Results and discussion

The estimation of multi-factor productivity (MFP) indexes requires the computation of the log-differences of the output and the input factors, which can be interpreted as the growth rates of the output and input factors. The quantity indexes of output and input factors, listed in Table 4.2, are used to derive the growth rates of the corresponding factors, recorded in Table 4.3 and Table 4.4. Using the figures in

Table 4.5, the cost shares and, consequently, the average cost shares for each input factor are computed and recorded in Table 4.6. The average rate of productivity growth, $\overline{G}_T$, was deduced from the values in Table 4.5 and Table 4.6, and listed in Table 4.4.

The selection of a base year, a reference year for computing the productivity indexes, should reflect the normal operation of the company during that period (Craig and Harris, 1973). In other words, a normal base year is one in which no serious deviations from average production occurred. The company does not experience a strike of some duration or any change in complexion, such as acquisition or merger. The year 1974 was chosen as the base year, which appeared to be a normal operating year for the Iowa Electric Light Power Company.

By setting the $MFP_{1974} = 100$ and $\exp(\overline{G}_{1974}) = 1$, the MFP indexes can be calculated as follows:

$$MFP_T = (MFP_{T-1}) \times \exp(\overline{G}_T) \qquad (4.19)$$

where

$T = 1975, \cdots, 1979$

The values of MFP indexes (1974 = 100), using two different methods to evaluate capital input, are tabulated in Table 4.7, together with the partial factor productivity (PFP) indexes. Their corresponding curves are shown in Figures 4.5-4.8.

Table 4.2. Output and input quantity indexes

Year	Output Indexes	Input Indexes					
		KI[a]	KS	L	F	M	P
1974	88.0	98.1	95.1	103.4	82.2	124.2	155.2
1975	95.3	98.6	96.9	100.4	92.7	120.5	127.0
1976	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1977	105.7	100.3	101.6	103.6	109.5	252.9	58.1
1978	112.0	102.4	106.1	105.7	85.5	231.1	461.2
1979	113.6	104.6	110.7	110.6	92.0	458.7	276.4

[a] In the following tables of this chapter, KI = capital investment reconstructed by Iowa type survivor curve, KS = capital investment reconstructed by Stevenson's method, L = labor, F = fuel consumption, M = miscellaneous materials, and P = purchased power.

Table 4.3. Growth rate of inputs

Year	KI	KS	L	F	M	P
1975	0.00565	0.01903	-0.02975	0.12030	-0.02963	-0.20046
1976	0.01372	0.03116	-0.00356	0.07611	-0.18675	-0.23913
1977	0.00301	0.01588	0.03503	0.09059	0.92773	-0.54258
1978	0.02076	0.04320	0.02044	-0.24776	-0.08980	2.07138
1979	0.02164	0.04226	0.04533	0.07353	0.68461	-0.51203

Table 4.4. Output, aggregate input growth rates and their corresponding annual average growth rates

Year	Output	Aggregate Input Using Iowa Type Curve	$\overline{G}_T$ Iowa Type	Aggregate Input Using Stevenson Method	$\overline{G}_T$ Stevenson Method
1974	--	--	1.000	--	1.000
1975	0.08209	0.00291	1.080	0.01099	1.072
1976	0.04769	0.00292	1.046	0.01299	1.035
1977	0.05555	0.03243	1.023	0.04368	1.012
1978	0.05774	0.19490	0.872	0.22268	0.848
1979	0.01435	-0.00906	1.024	-0.00942	1.024

Table 4.5. Input expenditures in 1976 constant dollars ($1000)

Year	KI	KS	L	F	M	P	Total Expense Using Iowa Type Curve	Total Expense Using Stevenson's Method
1974	129422	105857	17770	23885	4899	14112	190088	166523
1975	130155	107891	17249	26938	4756	11549	190647	168383
1976	131952	111306	17188	29070	3946	9093	191249	170603
1977	132350	113087	17801	31825	9978	5285	197239	177976
1978	135126	118079	18169	24840	9121	41940	229196	212149
1979	138082	123176	19011	26736	18087	25134	227050	212144

Table 4.6. Cost share (and average cost shares in parentheses) of input factors. 1st line is according to Iowa type survivor curves; 2nd line is according to Stevenson's method

Year	K		L		F		M		P	
1974	0.681	--	0.093	--	0.126	--	0.026	--	0.074	--
	0.636	--	0.107	--	0.143	--	0.029	--	0.085	--
1975	0.683	(0.6820)	0.090	(0.0915)	0.141	(0.1335)	0.025	(0.0255)	0.061	(0.0675)
	0.641	(0.6385)	0.102	(0.1045)	0.160	(0.1515)	0.028	(0.0285)	0.169	(0.0770)
1976	0.690	(0.6865)	0.090	(0.0900)	0.152	(0.1465)	0.021	(0.0230)	0.048	(0.0545)
	0.652	(0.6465)	0.101	(0.1015)	0.170	(0.1650)	0.023	(0.0255)	0.053	(0.0610)
1977	0.671	(0.6805)	0.090	(0.0900)	0.161	(0.1565)	0.051	(0.0360)	0.027	(0.0375)
	0.635	(0.6435)	0.100	(0.1005)	0.179	(0.1745)	0.056	(0.0395)	0.030	(0.0415)
1978	0.590	(0.6305)	0.079	(0.0845)	0.108	(0.1345)	0.040	(0.0455)	0.183	(0.1050)
	0.557	(0.5960)	0.087	(0.0935)	0.117	(0.1480)	0.043	(0.0495)	0.198	(0.1140)
1979	0.608	(0.5990)	0.084	(0.0815)	0.118	(0.1130)	0.080	(0.060)	0.111	(0.1470)
	0.581	(0.5690)	0.090	(0.0885)	0.126	(0.1215)	0.085	(0.064)	0.118	(0.1580)

Table 4.7. Productivity indexes

Year	MFP Index (Iowa Method)	MFP Index (Stevenson Method)	PFP Indexes					
			KI	KS	L	F	M	P
1974	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1975	108.0	107.2	107.7	106.3	111.5	96.0	111.6	132.3
1976	113.0	110.9	111.5	108.1	117.5	93.4	141.1	176.4
1977	115.6	112.3	117.5	112.4	116.8	90.2	59.0	320.0
1978	100.8	95.2	121.9	114.1	124.5	122.4	68.4	42.8
1979	103.2	97.5	121.1	110.9	120.7	115.3	35.0	72.5
Average Annual Rate of Growth (Percent)	0.53	-0.42	3.24	1.74	3.19	2.40	-16.1	-5.22

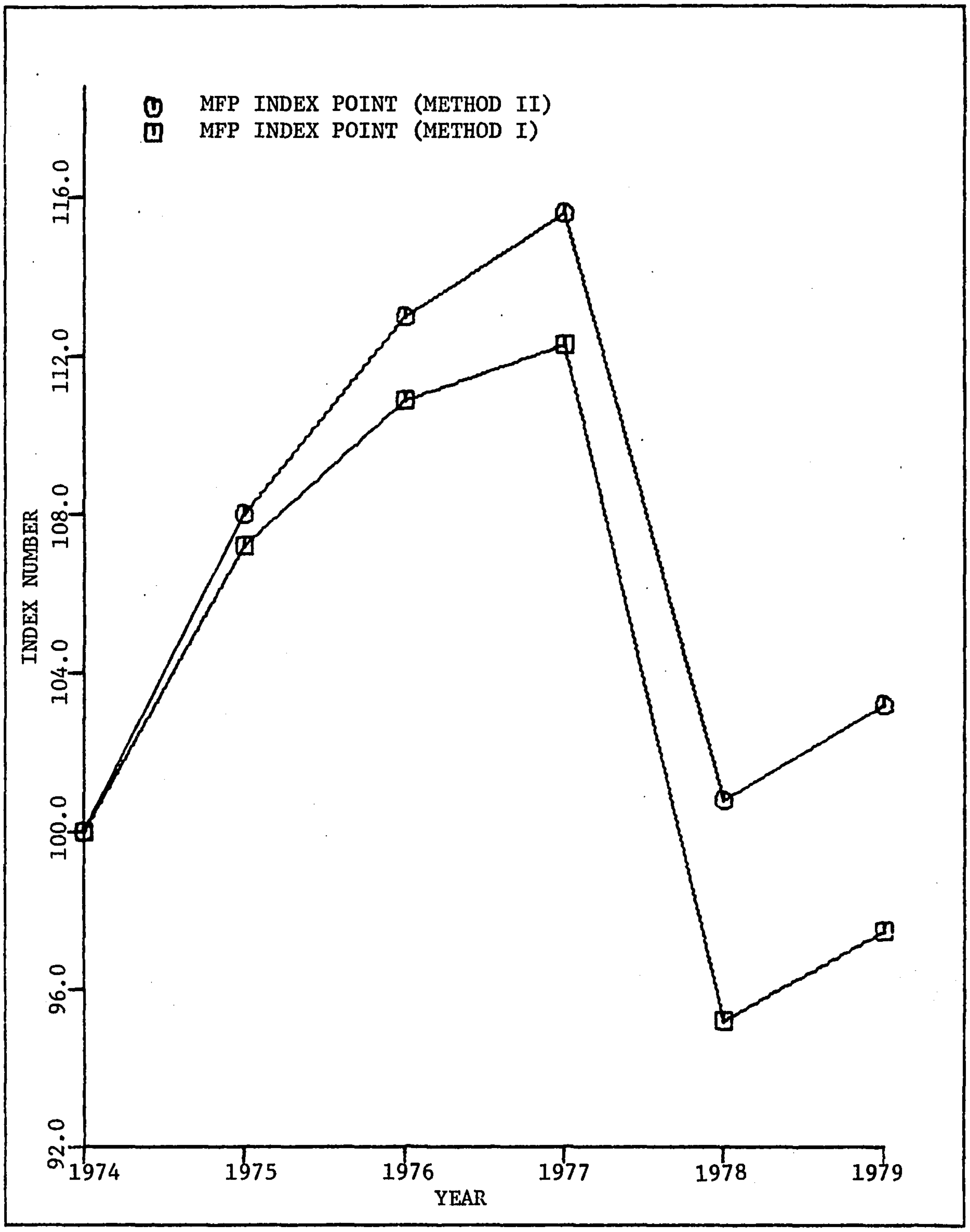

Figure 4.5. Multi-factor productivity indexes

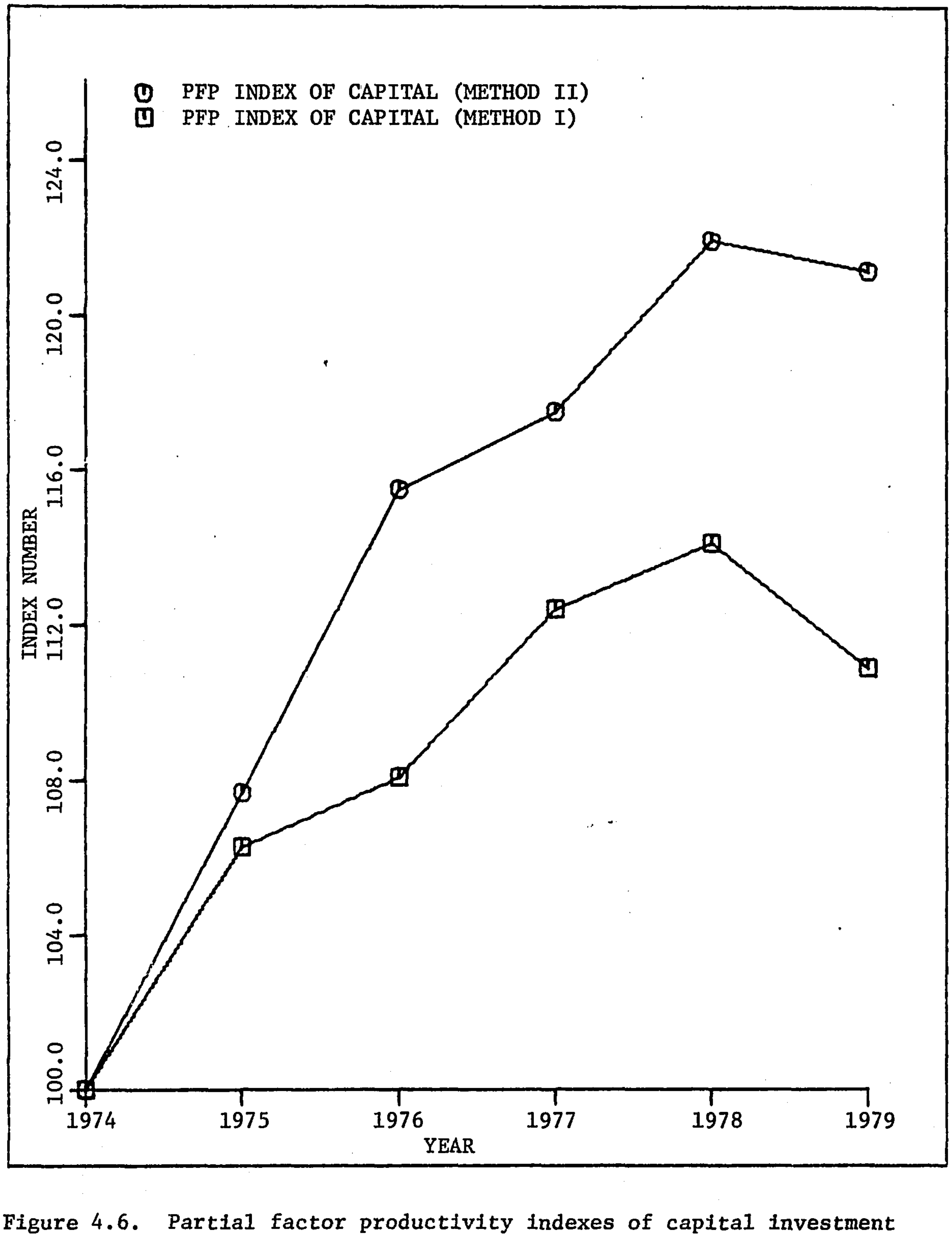

Figure 4.6. Partial factor productivity indexes of capital investment

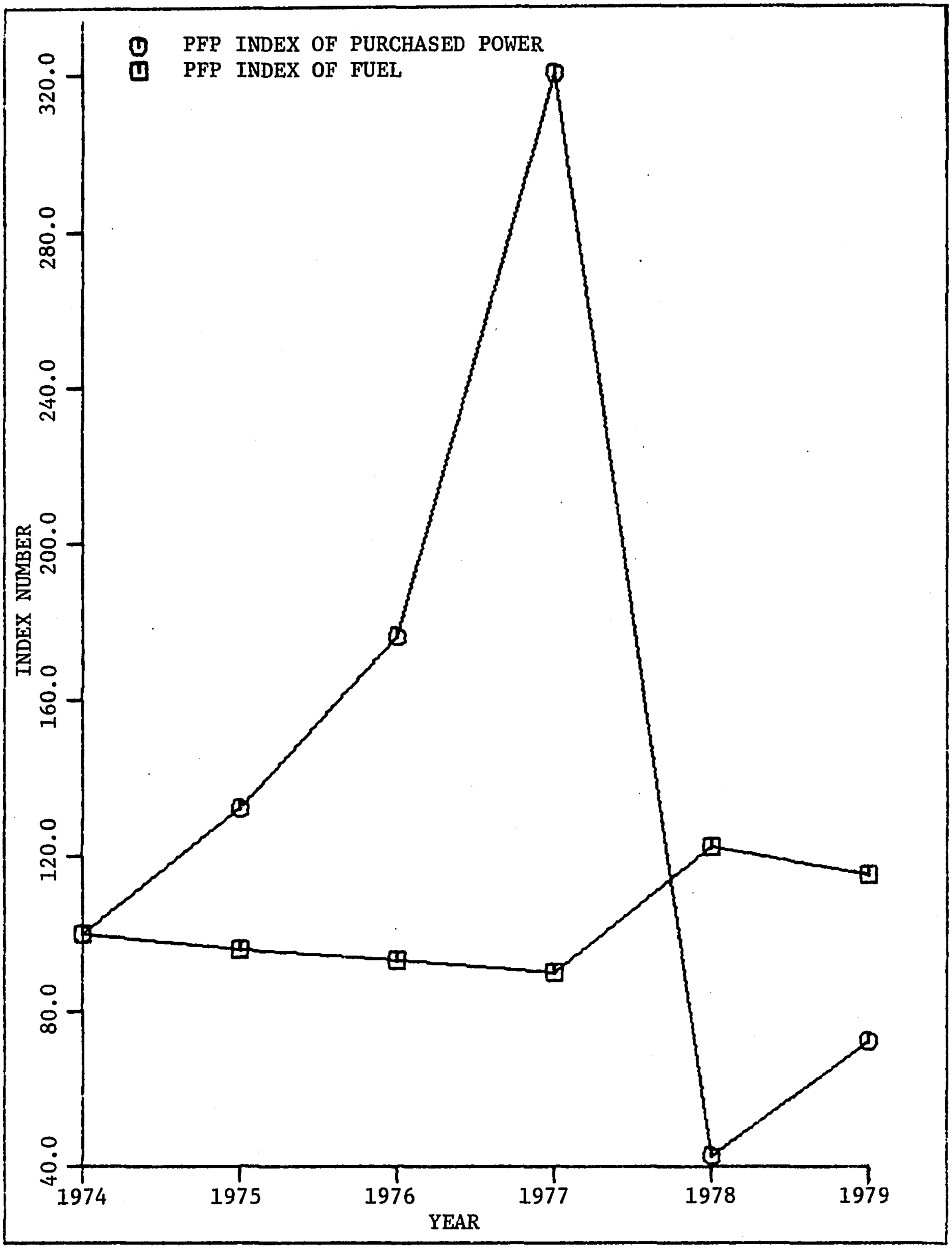

Figure 4.7. PFP indexes of purchased power and fuel

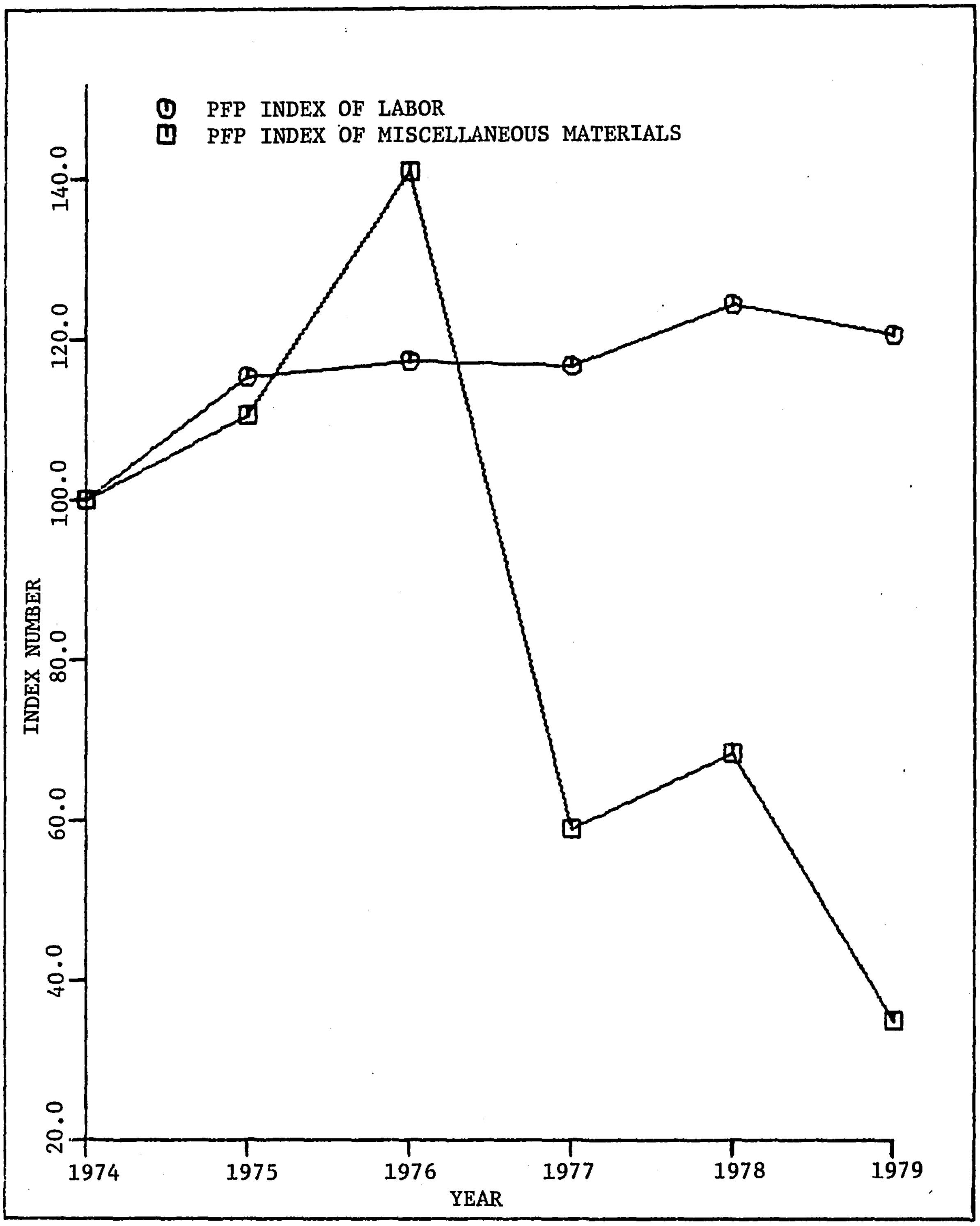

Figure 4.8. Partial factor productivity indexes of labor and miscellaneous materials

From the results derived, the company had an annual growth rate of 0.53 % in the period 1974-1979 (-0.42 % using Method I). However, between years 1974 and 1977, the company had enjoyed an annual growth rate of 3.69 % (2.90 % using Method I), which was higher than the figure, -1.10 % (Table 1.2) between years 1973 to 1978, tabulated by the American Productivity Center (Meanley, 1980).

The setback in 1978 seemed to be the result of purchasing a large amount of power from the other utility companies[1]. Even though there were savings in fuel consumption and miscellaneous materials, it could not help much. Nevertheless, the cause should be studied closely and other reasons, such as the deviations between output elasticities and cost shares and technological change, could not be overlooked, as these reasons were factors that the MFP indexes depended upon. Moreover, the inter-relationship between input factors inhibited the blaming of a particular input factor on the grounds that the low productivity growth of one input factor might help the outlook of the other. An example of this kind would be the case of fuel consumption and purchased power, which showed this kind of relationship clearly in Figure 4.7. Gould (1946) brought up another instance in increase in the efficiency of fuel consumption, which might be attributed almost entirely to improvements in various kinds of capital equipment. An increase in labor productivity might be caused by the labor-saving equipment. In other words, any use

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[1] The Iowa Electric Light and Power Company experienced an extended outage of a nuclear generating plant from June 1978 to March 1979. As a result, a large amount of electrical energy was purchased to ensure the customer's demand.

of a particular series of PFP indexes might jump to the wrong conclusion. When these productivity measures utilized inclusively, the management would be able to identify problem areas, contemplate alternatives improvement and determine what should be done with the limited resources in order to raise the performance of the entire company.

Another consideration in the interpretation of the variation in MFP measures developed in this research is recognition of the measurement biases. In addition to the actual errors in measuring the input factors, the method of evaluating the input factors should be research thoroughly. For example, different methods of reconstructing the capital investment did result in a small disturbance in the MFP indexes. But, a closer look at these two methods, the one using Iowa type survivor curve, appears to have a better estimation, as it attempts to reflect the actual capital service from the oldest installation to the most recent additions. Stevenson's method only dates back to the previous fifteen years and tries to reconstruct the major different component of capital investment using the average Handy-Whitman indexes. Consequently, the Iowa type survivor method appears to refine the estimation of capital cost over that produced by Stevenson's method. In the work that follows, any estimates related to capital investment and the productivity measurement will be those made using Iowa type survivor curve approach (Method II) unless they are stated otherwise.

V. MATHEMATICAL MODEL OF INPUT RESOURCES ALLOCATION UNDER THE CONSIDERATION OF A PRODUCTIVITY CONSTRAINT

Industrial engineering techniques, such as time study, material handling, engineering economy, operations research, just to mention a few, are ways available to management to use to raise its company's productivity. Stearns (1978) listed a table of the need, application and possible results of productivity improvement when industrial engineering techniques were employed.

To look at the whole operating system of an electric utility, operations research techniques seem to be appropriate and attractive as a management diagnostic tool in productivity improvement analysis. This is due to their unusually wide breadth of application and the characteristic of finding the best, or optimal solution, to the problem under consideration. It has proved time and again to be a powerful and effective approach for solving critical management problems.

This chapter consists of a brief description of the capability of operations research, a summary review of related mathematical models for the electrical power system and the development of mathematical model associated with the electric power company. The main topics of the model structure are the incorporation of a productivity constraint and the constraints generated by the input variables. The other operating policies of the electric utility plant are also included.

A. Applicability of Operations Research

The term "operations research" came into prominence around World War II. Because of the requirement of the war effort, there was an urgent need to allocate resources to the various military operations, and to the activities within each operation, in an effective manner. Today, the operations research is being applied to solution of allocation problems in complex, dynamic and specialized organizations.

Operations research can be defined as a scientific approach to decision making that involves the operations of organizational system (Hillier and Lieberman, 1974). It helps executive management in problem-solving. An application of operations research involves:

1. Constructing mathematical, economic and statistical descriptions or models of decision and controlling problems to treat situations of complexity and uncertainty.
2. Analyzing the relationships that determine the probable future consequences of decision choices, and devising appropriate measures of effectiveness in order to evaluate the relative merit of alternative actions.

Because of their characteristics of scientific approach to problem-solving and an attempt of finding the best or optimal solution to the problem under study, the operations research techniques have the following advantages, as noted by Wagner (1975):

1. Better decisions are featured to provide actions that do improve on intuitive decision-making.
2. Better coordination is formulated to bring order out of chaos.
3. Better control is provided to supervise the routine decision for the executives, who can thereby devote their attention to more pressing matters.
4. Better systems are established to analyze a decision problem.

Owing to these advantages, the diversity of application to problem-solving is tremendous. Hillier and Lieberman (1974) illustrate some problems solved by particular techniques of operations research. Linear programming has been used successfully in the solution of problems concerned with assignment of personnel, blending of materials, distribution and transportation, and investment portfolios. Dynamic programming has been successfully applied to such areas as planning advertising expenditures, distributing sales effort, and production scheduling. Queueing theory has had application in solving problems concerning with traffic congestions, servicing machines subject to breakdown, determining the level of a service force, air traffic scheduling, design of dams, production scheduling, and hospital operation. Goal programming, an extension of linear programming, gains its popularity because of flexibility and capability in solving problems with multiple conflicting objectives. It has been applied to academic resource allocation and other areas. Other techniques of operations research, such as inventory theory, game theory and simulation, also have been successfully applied in a variety of situations.

The management and researchers of electric power industry do not hesitate to utilize various mathematical models to analyze the investments, expansion, generation, transmission, distribution and other related networks. The following section explores some related references in handling these kinds of problems using mathematical models.

B. Some Mathematical Models Related to Electric Utilities

Masse and Gibrat (1957) could be considered as the pioneers in the use of linear programming models to solve the problems related to the production cost of the electric power system. Since then, the literature has expanded rapidly.

The general state-of-the-art of mathematical models for electric power system planning and operation has been summarized by Anderson (1972). His review was, perhaps, the most widely referenced due to his elaborate coverage of the major types of models. The general orientation of his work was toward economic planning policy.

Fanshel and Lynes (1964) used linear programming techniques to build production cost models and computed the minimum cost of operating this system to meet a particular set of demands. In this deterministic framework, loads were assumed known and forced outages did not occur.

By adding a Monte-Carlo component to the deterministic simulation model, Baldwin, Garver and Hoffman (1959) assumed that demand could fluctuate and forced outage could occur radomly. Sager et al. (1972) and Booth (1972) applied probabilistic production cost simulation models which provided information on the production cost, as well as system "security" or loss of load probability.

Apart from these production cost models, Galloway and Garver (1964) developed capacity expansion simulation providing for expansion of the system according to some a priori determined plan or by a "one-year-at-a-time" optimization algorithm. However, these simulation models did not guarantee a global solution. The capacity expansion mathematical models, which did yield global optima, were the first work done by Masse and Gibrat's linear programming models. Other early references using a linear programming framework include Masse (1962) and Bessiere and Masse (1964). The advantage of these linear programming models for electric power system analysis was that operating constraints and transmission network links could be explicitly written out. The drawback was that they could not accommodate nonlinear cost function and still achieve a global solution. In general, the linear programming models minimized (linear) capacity and operating cost subject to demand (load) constraints. Resources were simply required to be a certain percentage of total demands. Losses were assumed linear with power transmitted.

Le (1977) formulated a chance-constrained linear programming model to determine the optimal expansion over a nine-year planning horizon. Petersen (1973) tackled the same problem with a dynamic programming model, which could easily accommodate all forms of nonlinearity that linear programming failed. However, the number of constraints for which dynamic programming is computationally feasible is very small. This means that all possible installed capacity states of the system generation and transmission equipment must be explicitly enumerated and precosted before the solution is obtained. Scherer (1977) utilized mixed-integer models so that the approximated concave costs could be incorporated. Other mixed-integer models had been proposed by Gately (1970), Manne (1971) and Fernandez et al. (1973).

Thompson et al. (1977) developed a linear programming model of electric power production to evaluate the important substitution possibilities in power production, fuel use, input water treatment, waste use, investment capital use, wastewater treatment, air emission control and solid waste management.

Cherniavsky (1974), Cazalet (1977) and Manne (1976) also constructed large scale generation expansion models. Cherniavsky's generation expansion was obtained through static optimalization at the national aggregation level. Cazalet and Manne achieved their optimal generation expansion process through dynamic programming, where the former, Cazalet, at the regional level and the latter, Manne, at the national level of aggregation. Because of their primary interest in interfuel substitution, they tended to focus on generation and use of fuels in the industry and neglected transmission and distribution.

Baughman et al. (1979) introduced a model, known as the Regionalized Electricity Model (REM), which had been utilized to examine the effects of a wide range of public policies on the demand and supply of electricity and the utilization of fuels by the electric utility industrial over the next twenty-five years.

Poock (1979) established a goal programming framework to study the tradeoff between timing of investments and replacements, versus maintaining dividends at a constant rate for electricity utility planning. In conclusion, he noted that goal programming was a desirable technique for a regulated industry facing conflicting objectives to examine the tradeoffs explicitly.

C. Formulation of Mathematical Model for a Electric Utility Company

From the brief review presented in the previous section, mathematical models, from a simple linear programming model to the most intricate dynamic programming method, have been developed for use in the electric utility industry. The problems involved and solved are broad, ranging from a small network system to the complete planning of a company or the entire nation.

The management uses these mathematical models to maximize the profits or minimize the costs of its company in the planning process, which is regarded in classical economic theory as the sole purpose of the business firm. But, in today's dynamic business environment, it is not always the only objective. In fact, business firms quite frequently place higher priorities on noneconomic goals than on profit maximization or cost minimization.

For example, meeting the customer's demand in electrical energy may be considered as the top priority goal for the electric utility company. Thus, the utility has to keep a high level of reserve to assure the sufficient flow of electricity. The utility may have to purchase power from other electric utilities at whatever the cost required in order to satisfy the customer's demand in the event of an unforseen breakdown of a major generator. Besides, being operated under a regulated situation, the utility must meet the regulated requirements before it can consider other objectives, such as minimization of costs or maximization of the rate of return. Hence, the problem of multiple conflicting objectives is real, not only in business, the public sector and the nonprofit organizations, but also in the regulated industry, namely the electric utility. And, these problems cannot be easily solved by traditional techniques using only one predominant objective criterion. In other words, the conventional numerical objective function approach (e.g., linear programming) for today's complex decision problems is apparently not capable of producing acceptable solutions to problems that involve highly abstract objective criteria, such as consumer satisfactions, public health and community image of the firm (Lee, 1976). Consequently, the only alternate method to the numerical approach for problems involving multiple conflicting objective criteria is the ordinal solution approach. Goal programming, based on the ordinal solution approach, appears to be the most appropriate, flexible and power technique for these complex decision problems involving multiple conflicting objectives.

1. The goal programming approach

The concept of goal programming was initially introduced by Charnes and Cooper (1961) as a tool to resolve linear programming problems by minimizing the sum of the absolute values of the deviation from such goals included as constraints. This technique had been further refined by Ijiri (1965), Lee (1972) and others. However, the notation used by those involved in goal programming was, by no means, standardized.

The following general goal mathematical model is adopted from Ignizio's set-up (1978):

$$\text{Find } \overline{x} = x_1, \cdots, x_j, \cdots, x_J, \text{ so as to minimize}$$

$$\overline{a} = \{g_1\ (\overline{n}, \overline{p}), \cdots, g_k\ (\overline{n}, \overline{p}), \cdots, g_K\ (\overline{n}, \overline{p})\} \tag{5.1}$$

such that

$$f_i(\overline{x}) + n_i - p_i = b_i \text{ for all } i = 1, \cdots, m \tag{5.2}$$

and

$$\bar{x}, \bar{n}, \bar{p} \geq \bar{0}$$

where

x_j is the jth decision variable,

$\bar{a}$ is denoted as the achievement function, a row vector measure of the attainment of the objectives, or constraints at each priority level,

$g_k(\bar{n}, \bar{p})$ is a function of the deviation variables associated with the objectives or constraints at priority level k,

K is the total number of priority level in the model,

b_i is the right-hand side constant for goal (or constraint) i,

$f_i(\bar{x})$ is the left-hand side of the linear goal or constraint i.

Under such a formulation, given any type of goal or constraint, the minimization of specific deviation variables results in minimizing the nonachievement of that goal or constraint. Table 5.1 summarizes the approach taken to accomplish this task.

Table 5.1. Model formulation

Goal or Constraint Type	Processed Goal or Constraint	Deviation Variables to be Minimized
$f_i(\bar{x}) \geq b_i$	$f_i(\bar{x}) + n_i - p_i = b_i$	p_i
$f_i(\bar{x}) \leq b_i$	$f_i(\bar{x}) + n_i - p_i = b_i$	n_i
$f_i(\bar{x}) = b_i$	$f_i(\bar{x}) + n_i - p_i = b_i$	$n_i + p_i$

The deviation variables at each priority level, k, are included in the function $g_k(\overline{n},\overline{p})$ and ordered, in the achievement vector $\overline{\overline{a}}$, according to their respective priority. These priorities are under the preemptive ordering or ordinal ranking structure, developed by Ijiri (1965), which separates the objective function into different levels by degrees of relative importance of the goals.

The ordinal ranking can be represented by the following notation:

$$P_k >>> nP_{k+1}$$

which implies that the multiplication of P_{k+1} by n cannot make P_{k+1} greater than or equal to P_k. Therefore, the kth decision-making goal must be achieved as much as possible before an attempt is made to satisfy the goal associated with P_{k+1} priority factor.

Another consideration in the goal programming model formulation is that deviational variables of the goals on the same level must be commensurable, i.e., they are measured on the same unit basis, although deviations that are on different priority levels need not be commensurable.

From the above formulation of goal programming model, instead of trying to maximize or minimize the objective function directly as in the linear programming, the deviations between the desired goals are attempted to be minimized, within the given set of constraints. The goal programming model possesses the flexibility that is lacking in linear programming. In linear programming, the objective function is unidimensional (Lee, 1972), which is expressed in terms of the same units. The optimal solution must satisfy all constraints, which have equal importance in solving the problem. Furthermore, infeasibility occurs when there are conflicting constraints or goals, whereas goal programming is of greatest value when the goals are conflicting. The ranking structure of goal programming enables the management to assign priorities to different goals according to their relative importance. Furthermore, in goal programming, the objective function tries to satisfy the constraint set, which may be composed of any quantifiable measurements.

In general, Lee (1976) summarizes three types of analysis performed by a goal programming model: 1) it determines the input requirements to achieve a set of goals; 2) it determines the degree of attainment of defined goals with given resources; and 3) it provides the optimum solution under the varying inputs and goal structures. Thus, goal programming can be applied to almost unlimited managerial and administration decision areas. Allocation, planning and scheduling and policy analysis are the most readily applicable areas of goal programming.

2. Mathematical model of input resources allocation

From the brief review above, it was shown that mathematical models have been used to find optimal solutions in allocation of resources, budget and investment planning for the electricity supply system.

In the present study, the mathematical model was utilized in a different perspective, one which dealt with the problems not only involving allocation of limited resources, minimization of resources costs and other operations requirements, but also the problems relating to the efficient and effective use of the input resources. In other words, given a set of constraints used to solve the traditional problems, the productivity constraint (or goal) is also introduced. This brings in an additional idea on how to allocate resources so as to satisfy both major constraints, in minimizing the cost and meeting the requirement of a constant productivity growth. These constraints may be complementary, but often times they are conflicting, which depends on the growth rate of the output and other constraints (goals). These conflicting multiple constraints can best be solved by the goal programming technique, a special extension of linear programming (Lee, 1976), which has been discussed in the previous section.

Figure 5.1 describes the general production system of an electric utility being studied. The input resources, namely capital, labor, fuel, miscellaneous materials and purchased power, are introduced into this production system, which consists of three power plants and four substations. During the production process, electricity is generated, transmitted and distributed to the different classes of customers, according to their demand which varies throughout the day and throughout the year, as seen in Figure 5.2(a). The operating costs are the area under this curve weighted at each time interval u(t) by the fuel costs

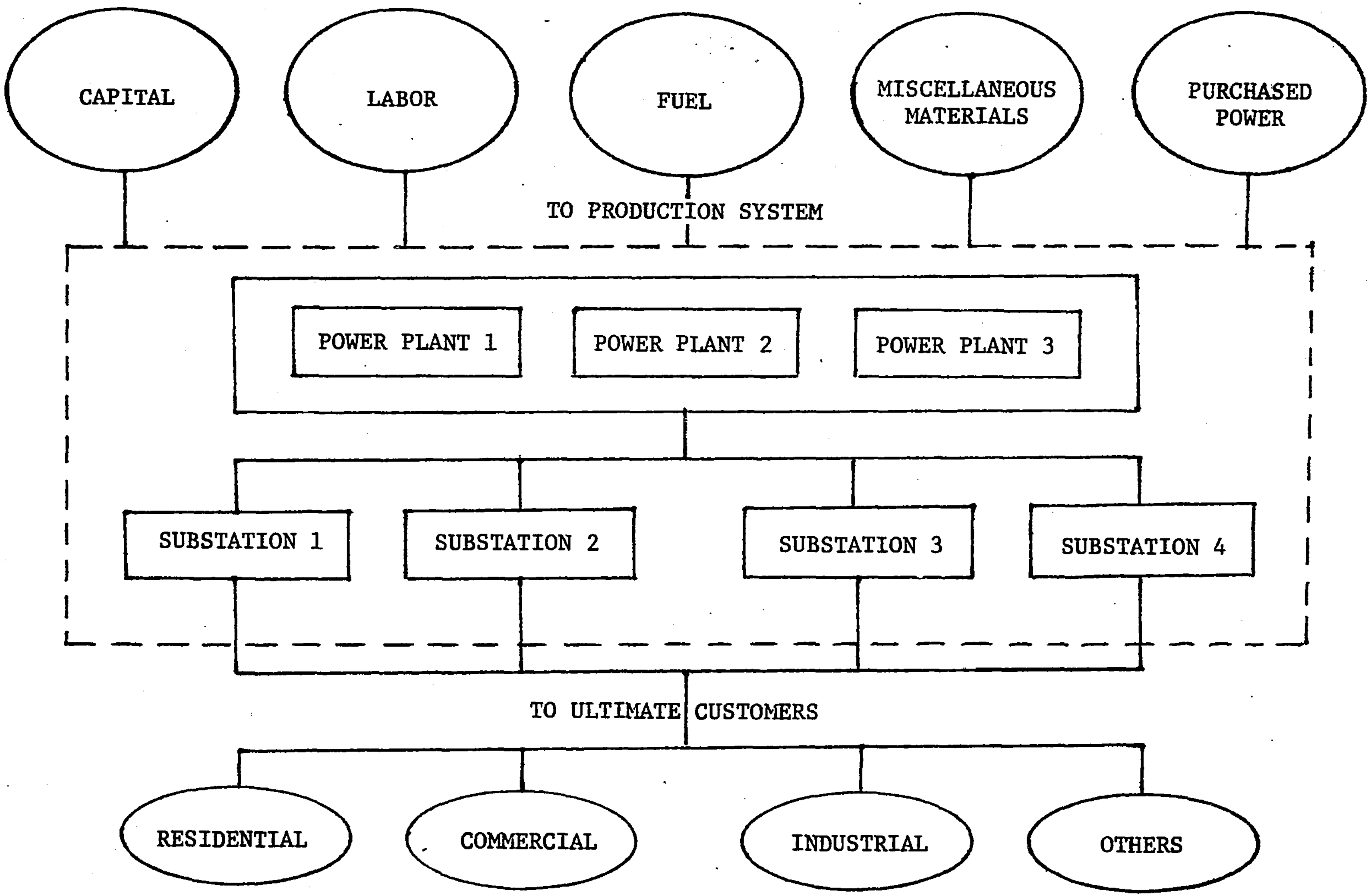
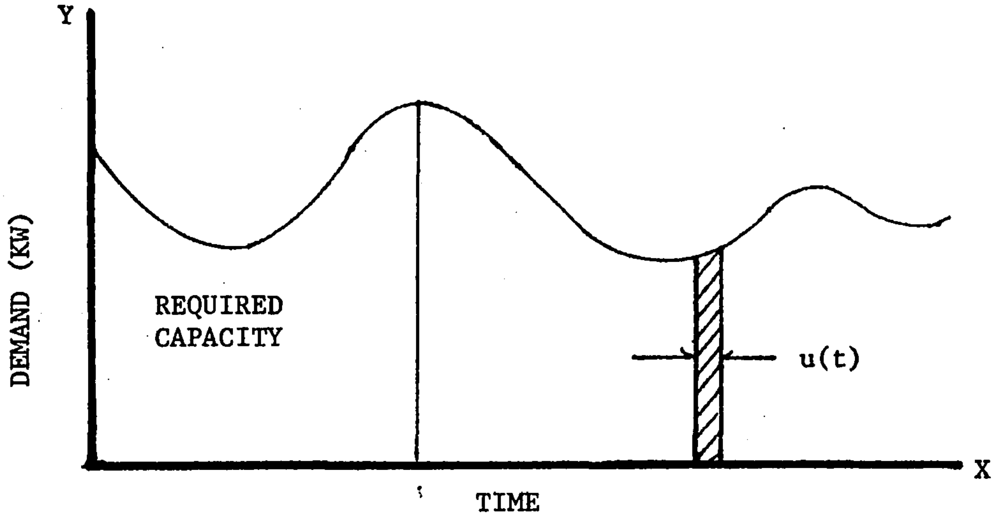
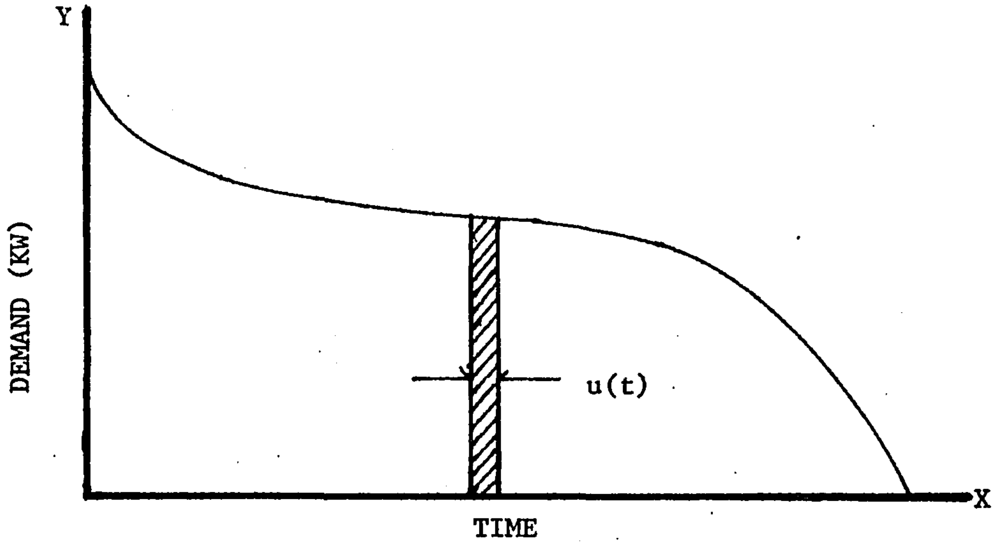


Figure 5.1. The production system of an electric utility



a) Variability of power demand



b) Load duration curve

Figure 5.2. Demand curve of an electric utility

and the outputs of the plant in that interval. In order to simplify the calculation of operating costs, it is usual to construct a curve known as the load duration curve (Anderson, 1972). This curve is constructed from the above demand curve, Figure 5.2(a), by rearranging each load for each time interval u(t) to occur in descending order of magnitude, as shown in Figure 5.2(b). This load duration curve makes integration of costs less difficult because it can be represented by simpler functions than the curve of Figure 5.2(a).

In the following section, constraints were formulated in regard to the productivity growth, input variables and general operating policies of an electric utility company. A glossary of symbols was also included to depict the terms used in the model.

a. Glossary of symbols The subscripts (lower case) and decision variables (upper case) used in this model are as follows:

c = type of customer ($c = 1, 2, \cdots, C$)

p = type of plant ($p = 1, 2, \cdots, P$)

f = type of fuel ($f = 1, 2, \cdots, F$)

y = years in study ($y = 1, 2, \cdots, Y$)

s = each year y is subdivided into s subperiods (seasons) ($s = 1, 2, \cdots, S$)

n = number of substations ($n = 1, 2, \cdots, N$)

m = type of transformers ($m = 1, 2, \cdots, M$)

v = vintage of a plant or a transformer ($v = 0, 1, \cdots, y$)

t = duration period segment within s, which is constructed by a load duration curve divided into t segments (t = 1, 2,•••, T)

w = type of a polluted waste (w = 1, 2,•••, w)

PS = size of a power plant (MW)

OC = operating capability of a power plant (MW)

GO = generating output of a power plant (MW)

TC = transmission capacity of a power plant (MW)

FC = fuel consumption at a power plant (MBTU)

FTLA = full-time employees

PTLA = part-time employees

PPO = purchased power (MWh = 1000 kWh)

PPOI = purchased power through interchange (MWh)

MM = miscellaneous materials (constant dollars)

PRODIN = generation investment (constant dollars)

TRANIN = transmission investment (constant dollars)

DISTIN = distribution investment (constant dollars)

TRC = transformer capacity (MVA)

X(i,y) = ith input variable at year y (i = 1,•••, t)

The combined meaning of these subscripts and decision variables is, for an example, as follows:

GO(p, v, n, t, s, y) - the quantity of generated power from plant p, vintage v, received by the substation n, vintage v, at time segment t, season s and year y.

Some other variable names may also be defined separately in the course of model development.

The input data to be provided by the company are listed as follows:

a = annual multi-factor productivity growth rate (constant value)

b(y) = the reserve in terms of total demand at year y (percent of demand)

r(y) = reserve percentage of a plant at year y ($0 < r(y) < 1$)

h(y) = transmission safety factor at year y ($0 < h(y) < 1$)

u(t) = width of time interval of segment t on the load duration curve

df = pollution waste discharge factor (particles/MBTU)

EP = environmental pollution waste limit (particle)

FL = fuel availability (MBTU)

CD = customers' demand (MWh)

PS = plant size (MW)

ACS(i,y) = average cost share of ith input variable ($i = 1, 2, \cdots 5$)

$\alpha(y)$ = the range percentage of previous year employment ($0 < \alpha(y) < 1$)

MAXPPO(y) = maximum amount of purchased power bought at year y (MBTU)

MINPPO(y) = minimum amount of purchased power required at year y (MBTU)

MAXP(y) = the allocated budget for generation investment at year y (constant dollars)

MAXT(y) = the allocated budget for transmission investment at year y (constant dollars)

MAXD(y) = the allocated budget for distribution investment at year y (constant dollars)

MAXMM(y) = the maximum funding for miscellaneous materials at year y (constant dollars)

All the variables with subscript, y-1, are considered to be known values.

b. Productivity related constraint A minimum growth rate, say a percent, should be attained. From Equation 4.13 in Chapter IV, the following productivity constraint could be implemented:

$$\frac{Y_T/Y_{T-1}}{\prod_{i=1}^{n} (X_{i,T}/X_{i,T-1})^{\bar{s}_i}} \geq (1 + a)$$

or

$$\prod_{i=1}^{n} (X_{i,T}/X_{i,T-1})^{\bar{s}_i} \leq [1/(1 + a)]\ (Y_T/Y_{T-1})^{\bar{s}_i} \tag{5.3}$$

where

Y_{T-1}, Y_T = the outputs at periods T-1 and T

$X_{i,T-1}$, $X_{i,T}$ = the X_i input variable at periods T-1 and T

$\bar{s}_i$ = the average cost shares of X_i at periods T-1 and T

n = the number of input variables

Owing to the properties of linear goal programming, the geometric mean, i.e., $\prod_{i=1}^{n} (X_{i,T}/X_{i,T-1})^{\bar{s}_i}$, should be converted to arithmetic mean in order to be compatible with the linearity assumption. Beckenback and Bellman (1961) showed their relationship as follows:

$$\sum_{i=1}^{n} \bar{s}_i \, (X_{i,T}/X_{i,T-1}) \geq \prod_{i=1}^{n} (X_{i,T}/X_{i,T-1})^{\bar{s}_i} \qquad (5.4)$$

where

$$\sum_{i=1}^{n} \bar{s}_i = 1$$

and

$$(X_{i,T}/X_{i,T-1})$$

is nonnegative for every *i*.

This productivity constraint, therefore, could be expressed follows:

$$\sum_{i=1}^{n} \bar{s}_i \, (X_{i,T}/X_{i,T-1}) \leq [1/(1 + a)] \, (Y_T/Y_{T-1}) \qquad (5.5)$$

In order to be compatible with the notation used for this model, the following formulation was adopted:

$$\sum_{i=1}^{5} \mathrm{ACS}(i,y) \, [X\,(i,y)/X(i,y-1)] \leq [1/(1 + a)][\mathrm{CD}(y)/\mathrm{CD}(y-1)] \quad \text{for } y = 1,\cdots, Y \qquad (5.6)$$

where

ACS(i,y) = average cost share of X(i,y) and X(i,y-1) at year y

X(1,y) = total capital investment at year y
= TCIN(y)

X(2,y) = total number of employees at year y
= TNLA(y)

X(3,y) = total amount of fuel consumption at year y

= FC(y)

X(4,y) = total amount of miscellaneous materials at year y

= MM(y)

X(5,y) = total amount of purchased power bought at year 6

= PPO(y)

CD(y) = total amount of demand (load) at year y

$$= \sum_{c}^{C} \sum_{t}^{T} \sum_{s}^{S} CD(c,t,s,y)$$

c. Capital investment constraints The capital investment for a utility can be segregated into three main components of generation, transmission and distribution. The generation and transmission investments are closely related to the generated output and demand load, respectively. Consequently, the amount of these two investments can be ascertained once the generated output and demand load are known. Whereas, the investment in distribution, as pointed out by Turvey (1968), is nothing but the sum of a very large number of individual schemes, each determined either by the prospect of load in relation to distribution capacity in a particular locality, or by a need to replace a particular unsafe or obsolete piece of equipment. Accordingly, distribution investment was estimated independently. And, the constraints of capital investment could be treated separately as follows:

1. The investment in each component must be greater than or equal to the previous year's investment value. In other words, the additions in that year must be, at least, equal

to the accumulated value of retirements. However, the investment must be within the allocated budget.

$$\sum_{p}^{P} \mathrm{PRODIN}(p,y) \geq \sum_{p}^{P} \mathrm{PRODIN}(p,y-1) \tag{5.7}$$

$$\sum_{n}^{N} \mathrm{TRANIN}(n,y) \geq \sum_{n}^{N} \mathrm{TRANIN}(p,y-1) \tag{5.8}$$

$$\mathrm{DISTIN}(y) \geq \mathrm{DISTIN}(y-1) \tag{5.9}$$

$$\sum_{p}^{P} \mathrm{PRODIN}(p,y) \leq \mathrm{MAXP}(y) \tag{5.10}$$

$$\sum_{n}^{N} \mathrm{TRANIN}(n,y) \leq \mathrm{MAXT}(y) \tag{5.11}$$

$$\mathrm{DISTIN}(y) \leq \mathrm{MAXD}(y) \tag{5.12}$$

2. Total amount of capital investment at year y is the sum of capital investments in generation, transmission and distribution.

$$\mathrm{TCIN}(y) = \sum_{p}^{P} \mathrm{PRODIN}(y) + \sum_{n}^{N} \mathrm{TRANIN}(y) + \mathrm{DISTIN}(y) \tag{5.13}$$

d. Labor related constraints The availability of labor depends on the job market and the attractiveness of wages and benefits. The number of employees needed also depends on the growth of the company. Consequently, the following assumptions were made:

1. The number of full-time employees should be greater or equal to the number of full-time employees previously employed.

$$\sum_{p}^{P} FTLA(p,y) \geq \sum_{p}^{P} FTLA(p,y-1) \qquad (5.14)$$

$$\text{for } y = 1,\cdots, Y$$

2. The total number of fulltime and parttime employees should be within a certain range, say $\alpha(y)$ percent of the previous year employment.

$$TNLA(y) \geq [1 - \alpha(y)]\ TNLA(y-1) \qquad (5.15)$$

$$TNLA(y) \leq [1 + \alpha(y)]\ TNLA(y-1) \qquad (5.16)$$

$$TNLA(y) = \sum_{p}^{P} FTLA(p,y) + \sum_{p}^{P} PTLA(p,y) \qquad (5.17)$$

$$\text{for } y = 1,\cdots, Y$$

$$0 < \alpha(y) < 1$$

e. Fuel consumption related constraints   When fuels, such as coal, oil, gas, and nuclear fuel, are consumed to generate electricity, the following constraints must be considered:

1) Availability of fuels   The increasing demand for energy in all sectors and the need for the environment clean fuel to comply with the emission standards under the Clean Air Act have created a serious shortage of low-sulfur oil, low-sulfur coal and natural gas. Consequently, the amount of fuel f consumed should be less or equal to the availability of each fuel f supply for periods u(t), s and year y.

For u(t):

$$\sum_{v}^{y} \sum_{p}^{P} FC(f,p,v,t,s,y) \leq FL(f,t,s,y) \qquad (5.18)$$

$$\text{for } f = 1,\cdots, F$$

$$t = 1,\cdots, T$$

$$s = 1,\cdots, S$$

$$y = 1,\cdots, Y)$$

For period s:

$$\sum_{t}^{T} \sum_{v}^{y} \sum_{p}^{P} FC(f,p,v,t,s,y) \leq \sum_{t}^{T} FL(f,t,s,y) \qquad (5.19)$$

$$\text{for } f = 1,\cdots, F$$

$$s = 1,\cdots, S$$

$$y = 1,\cdots, Y$$

For year y:

$$\sum_{s}^{S} \sum_{t}^{T} \sum_{y}^{y} \sum_{p}^{P} FC(f,p,v,t,s,y) \leq \sum_{s}^{S} \sum_{t}^{T} FL(f,t,s,y) \qquad (5.20)$$

$$\text{for } f = 1,\cdots, F$$

$$y = 1,\cdots, Y$$

2) Fuel related pollution When fuels are burned to generate electricity, their related pollutants, such as particulates, sulfur oxides, etc., are also produced. In 1971, the Environmental Protection Agency (EPA) issued national ambient air quality standards which specified the maximum allowable average three-hour, daily and annual concentrations of pollutants which could be discharged. The following constraints were constructed so that the pollutant emissions should be less than the upper limit imposed by the EPA during periods u(t), s, and y.

For u(t):

$$\sum_{v}^{y} \sum_{p}^{P} \sum_{f}^{F} FC(f,p,v,t,s,y)\ df(f,w,p,v,t,s,y) < EP(w,t,s,y) \qquad (5.21)$$

$$\text{for } w = 1,\cdots, W$$
$$t = 1,\cdots, T$$
$$s = 1,\cdots, S$$
$$y = 1,\cdots, Y$$

For period s:

$$\sum_{v}^{y} \sum_{p}^{P} \sum_{f}^{F} \sum_{t}^{T} FC(f,p,v,t,s,y)\ df(f,w,p,v,t,s,y) < \sum_{t}^{T} EP(w,t,s,y) \qquad (5.22)$$

$$\text{for } w = 1,\cdots, W$$
$$s = 1,\cdots, S$$
$$y = 1,\cdots, Y$$

For year y:

$$\sum_{v}^{y} \sum_{p}^{P} \sum_{f}^{F} \sum_{t}^{T} \sum_{s}^{S} FC(f,p,v,t,s,y)\ df(f,w,p,v,t,s,y) < \sum_{s}^{S} \sum_{t}^{T} EP(w,t,s,y) \qquad (5.23)$$

$$\text{for } w = 1,\cdots, W$$
$$y = 1,\cdots, Y$$

3) Fuel conversion factors Each fuel has a different conversion factor which depends on the fuel consumed and the efficiency of an electric power plant's operation, known as "heat rate," that is, the number of Btus of fuel heating value required to produce one kWh of electricity. The constraints were that the generated output should be less than the conversion of fuel into electrical energy.

$$\sum_{f}^{F} e(f,p,v)\ FC(f,p,v,t,s,y) - \sum_{n}^{N} GO(p,v,t,n,s,y)\ u(t) \geq 0 \qquad (5.24)$$

$$\begin{aligned} \text{for } p &= 1,\cdots, P \\ v &= 1,\cdots, y \\ t &= 1,\cdots, T \\ s &= 1,\cdots, S \\ y &= 1,\cdots, Y \end{aligned}$$

The total quantity of fuel consumption at year y is:

$$FC(y) = \sum_{f}^{F} \sum_{p}^{P} \sum_{v}^{y} \sum_{t}^{T} \sum_{s}^{S} FC(f,p,v,t,s,y) \qquad (5.25)$$

$$\text{for } y = 1,\cdots, Y$$

f. Miscellaneous materials related constraints Basically, this is a residual component, which is the difference between the total expenses in operating and maintenance and the sum of fuel, labor and purchased power payments. The constraint for this category could be constructed as follows.

The allocation funding for this category should be as much as the previous one.

$$\sum_{p}^{P}\sum_{n}^{N} MM(p,n,y) \geq \sum_{p}^{P}\sum_{n}^{N} MM(p,n,y-1) \qquad (5.26)$$

$$\text{for } y = 2,\cdots, Y$$

The expense for this input variable should not exceed the budgeted funds.

$$\sum_{p}^{P}\sum_{n}^{N} MM(p,n,y) \leq MAXMM(y) \qquad (5.27)$$

$$\text{for } y = 1,\cdots, Y$$

Tthe total amount of miscellaneous materials required at year y is:

$$MM(y) = \sum_{p}^{P}\sum_{n}^{N} MM(p,n,y) \qquad (5.28)$$

$$\text{for } y = 1,\cdots, Y$$

g. Purchased power related constraints Not all electric utility companies generate sufficient power to meet their systems' loads (demands). Often times, it is more economical to purchase power from other companies than to generate by their own relatively high-cost oil-fired or gas-fired generators. Sometimes, it is a must to do so due to a forced outage of a major generator. It may become a policy for the company to have a contract with other utility firms for the amount of purchased power at a reasonable price. The constraints related to the purchased power were formulated as follows:

1. The purchased power and the generated one should be matched up with the customers loads with a reserve margin, say b %.

$$PPO(t,s,y) + PPOI(t,s,y) + \sum_{p}^{P} \sum_{v}^{y} \sum_{n}^{N} GO(p,v,n,t,s,y)\ u(t) \geq (1+b) \sum_{c}^{C} CD(c,t,s,y) \qquad (5.29)$$

for $t = 1,\cdots, T$

$s = 1,\cdots, S$

$y = 1,\cdots, Y$

2. Due to the contract requirement and the policy of the company, ranges of purchased power were set in such a way that the expenses for purchased power was minimized and the minimum contracted load had to be met.

$$\sum_{t}^{T} \sum_{s}^{S} PPO(t,s,y) + \sum_{t}^{T} \sum_{s}^{S} PPOI(t,s,y) \leq MAXPPO(y) \qquad (5.30)$$

$$\sum_{t}^{T} \sum_{s}^{S} PPOI(t,s,y) \geq MINPPO(y) \qquad (5.31)$$

for $y = 1,\cdots, Y$

3. The total amount of purchased power at year y is:

$$PPO(y) = \sum_{t}^{T} \sum_{s}^{S} PPO(t,s,y) + \sum_{t}^{T} \sum_{s}^{S} PPOI(t,s,y) \qquad (5.32)$$

h. Some general operating policies of a utility company These policies, treated as constraints, are listed below in accordance with generation, transmission and distribution.

1) Generation The operating capability, a measure of generating ability, is defined as the maximum kilowatt output of available power sources under actual generating condition. It is thus a little lower than nameplace rating, known as capacity.

$$OC(p,v,y) \le PS(p,v) \tag{5.33}$$

$$\text{for } p = 1,\cdots, P$$
$$v = 1,\cdots, y$$
$$y = 1,\cdots, Y$$

As regarding reserve consideration, each generating unit, and sometimes the entire plant, will be routinely taken off line for scheduled maintenance. They may also be forced off (forced outage) due to equipment failure. A significant amount of generating capacity must be held in reserve so that demand also never exceeds available capacity. Reserve requirements may be determined by using simply probability methods to provide for a predetermined loss of load probability (LOLP), which is used as an index of system reliability. For this study, the reserve margin, r(y), was predetermined and incorporated into the generated capacity.

$$[1 + r(y)] \sum_{n}^{N} \sum_{v}^{y} \sum_{p}^{P} GO(p,v,n,t,s,y) \le \sum_{v}^{y} \sum_{p}^{P} OC(p,v,y) \tag{5.34}$$

$$\text{for } t = 1 \text{ (peak)}$$
$$s = 1,\cdots, S$$
$$y = 1,\cdots, Y$$
$$0 < r(y) < 1$$

2) <u>Transmission and distribution</u> The transmission and distribution system delivers electric power from the point of generation to the point of final consumption. It must have sufficient capacity to meet the peak demand of the customers it serves and, simultaneous, to satisfy local energy demand patterns within the service area. The constraints related to this section are listed as follows:

1. Transmission capacity between power plants and substitutions should be sufficient to carry peak load by a margin h(y) used as a safety factor for energy loss through transmitting process or sudden failure of some transmission unit.

$$\sum_{v}^{y} \sum_{p}^{P} TC(p,v,n) \geq [1 + h(y)] \sum_{v}^{y} \sum_{p}^{P} GO(p,v,n,t,s,y) \qquad (5.35)$$

$$\begin{aligned} \text{for } n &= 1,\cdots, N \\ t &= 1 \text{ (peak)} \\ s &= 1,\cdots, S \\ y &= 1,\cdots, Y \\ 0 &< h(y) < 1 \end{aligned}$$

2. Transformer capacity should be greater than the circuit loads at each substation,

$$\sum_{v}^{y} \sum_{n}^{N} \sum_{m}^{M} TRC(m,n,v,t,s,y) \geq CD(c,t,s,y) \qquad (5.36)$$

$$\begin{aligned} \text{for } c &= 1,\cdots, C \\ t &= 1,\cdots, T \\ s &= 1,\cdots, S \\ y &= 1,\cdots, Y \end{aligned}$$

The model developed in this section can be used to analyze how these input resources should be allocated so that certain rate of productivity rate could be achieve and other requirements could also be satisfied to the fullest extent.

Some of the goals of this particular model formulated for the electric utility may be stated as follows:

1. To meet the constant rate of productivity growth.
2. To satisfy the demand of customers.
3. To minimize the quantity of purchased power.
4. To maximize the utilization of its own efficient generation capacity.
5. To maintain a constant employment record.
6. To minimize the expenses of the other related input resources.
7. To minimize the under-utilization of capital investment.

Of course, the productivity and customers demand satisfaction would be the top priority goals under this study. However, the following requirements must be met before the goal programming model analysis is carried out:

1. The objective function constraints and goal relationship must all be linear.
2. It is a deterministic model in input resources allocation.
3. The operation of the company is in a normal condition.

VI. DEMAND FORECASTING FOR AN ELECTRIC POWER COMPANY

Every productivity measure, in some way or other, depends heavily on the output. It gives the decision-makers some leverage to manage the other input variables, such as capital investment, labor employment and so forth. In other words, a prospect of high demand (load) gives management more confidence in authorizing a large capital investment in generation, transmission and distribution facilities, some of which have a lead time of at least two to ten years for design and construction. This is the demand that "governs" the changes of input utilization, which is evident in the productivity measurement equation developed in Chapter IV.

Unfortunately, electric utilities are not like other manufacturing firms in that they are not able to stock output quantities. In fact, electric power cannot be economically stored in large quantities, and with few exceptions, must be supplied on demand. Because of this unique characteristic of a utility, forecasting goes on continually in both peak rate of supply (power demand) and volume (energy demand) for both long term investment decisions and short-term operation decisions. Consequently, a sound, accurate and manageable demand forecast is a must for the utility company, not only for the utility company to commit itself to a huge sum of capital investment, but also to shed light on the productivity evaluation.

This chapter consists of a brief look at the features of load forecasting, a general description of some forecasting techniques, a case study of a company's demand forecast with different methods, and finally, a short discussion of the results.

A. Features of Load Forecasting

Garver (1978) pointed out that load forecasting in electric utilities involves three distinct features: the forecasted quantity, the time period and the method used.

1. Quantity forecasted.
    - a. Megawatts of peak power demand in a day, season or year.
    - b. Shape of the demand curve in a day, week or year.
    - c. Megawatt-hours of energy in a day, month or year.
2. Time period.
    - a. Short term: one hour to several weeks ahead.
    - b. Long term: one season to many years into the future.
3. Forecasting methods used.
    - a. Same as a similar day or sequence of days.
    - b. A decomposition method.
    - c. Multiple regression analysis.
    - d. Moving average.
    - e. Exponential smoothing.

Forecasting is a critical input for some of the most important decisions' models in operations management, particularly those related to aggregate planning and scheduling. In an electric utility company, the financial departments forecast energy to estimate revenue, fuel expenses, etc., while the operating and planning departments forecast peak demand to schedule capacity changes. In this research, only energy demand (volume) forecast is considered, which is used to estimate the capital investment and the output growth incorporated to the constraints of goal programming model. As a result, only yearly demand is required, which, in turn, is the aggregate of monthly forecasts for that year.

The goal of a forecast is to be within an acceptable margin such as 3 %, and preferably to errors less than 2 %, suggested by Garver (1978). Nevertheless, in some cases, even a 2 % error in a yearly demand forecast is considered to be intolerable as the yearly demand growth may be less than 2 %. It is desirable, however, to have an error of a yearly forecast in the order of 1 %, which is the measurement error for demand metered at the generators (Sandiford et al., 1956), and thus, is a bound on the accuracy possible.

B. Investigation of Some Forecasting Techniques

Le (1977) investigated four forecasting techniques: time series analysis[1], stepwise multiple regression analysis, Box-Jenkins method of auto-regressive model, and exponential smoothing. In the Le case study, monthly sales (January 1970 - June 1975) of the Iowa Electric Light and Power Company were utilized. Le concluded that the time series analysis gave the best predictions in electricity demand forecast of these four methods studied. However, from his selection of variables in the multiple regression analysis[2], some improvement in this technique is possible if different variables are used. And, probably, it could prove to be a better forecasting technique than the Census II method. Accordingly, in this research, only the Census II decomposition method and multiple regression analysis were investigated and results were compared. A general description of these two techniques is presented in the following section.

1. Census II decomposition method

References concerning this method can be found in the literature, for instance, Shiskin (1967) and Makridakis and Wheelwright (1978).

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[1] Le used the Census II decomposition method in time series analysis.

[2] Only three variables were considered: 1) total electric utility output in the U.S., 2) total electric sales to ultimate customers, and 3) total electric sales to residential customers.

Decomposition methods, as the name implies, "break down" a time series[1] into four components - seasonality, trend, cycle and randomness - that frequently are present in sales time series. Furthermore, it is usually assumed that the relationship between these four components is multiplicative, as shown in Equation 6.1:

$$Y_t = S_t \times T_t \times C_t \times I_t \tag{6.1}$$

where

Y_t is an observed value of the variable of interest

S_t is the seasonal component

T_t is the trend component

C_t is the cyclical component

I_t is the irregular or erratic component

The above equation is known as the classical decomposition method. The Census II is another category of these decomposition methods. This Census II decomposition method, developed by Shiskin (1967) of the United States Census Bureau, had been used widely over the last twenty years by the Bureau, several other government agencies and recently by many business enterprises. In principle, Census II is similar to other decomposition methods, but is more elaborate. According to Makridakis

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[1] A time series is a sequence of values of some variable, or composite of variables, taken at successive time periods. The monthly sales volume of electricity of a utility firm is an example of this.

and Wheelwright (1978), there are three main differences between the Census II and the classical decomposition methods:

1. The Census II method calculates preliminary estimates of seasonality and trend-cycle and then final estimates. The result is that the influence of each component can be removed separately. Classical decomposition, on the other hand, attempts to decompose the series for more than one component at a time.
2. The Census II method removes outliers, i.e., values which are abnormally high or low, and smoothes out irregular fluctuations to a much greater extent than does classical decomposition.
3. The Census II method provides several measures, or tests, which allow the user to determine how well the process of decomposition has been achieved.

The equation evaluated by the Census II method is:

$$Y_t = (TC)_t \times S_t \times I_t \tag{6.2}$$

where

Y_t is the time series

$(TC)_t$ is the trend-cycle component

S_t denotes the seasonality

I_t denotes the irregularity

2. Multiple regression analysis

References to this multiple regression approach are numerous. Bowerman and O'Connell (1979), Draper and Smith (1966), and Snedecor and Cochran (1967) are some of them.

Multiple regression analysis can be a powerful tool for forecasting sales of electricity (demand) if the independent variables are correctly chosen. The general multiple regression model is:

$$Y_t = \beta_o + \beta_1 x_{t1} + \beta_2 x_{t2} + \cdots + \beta_p x_{tp} + \varepsilon_t \tag{6.3}$$

where

Y_t denotes the dependent variable in period t,

p represents the number of independent variables used in the model,

$x_{t1}, x_{t2}, \cdots, x_{tp}$ represent the values of those p independent variables in period t,

$\beta_o, \beta_1, \cdots \beta_p$ are unknown parameters relating the dependent variable y_t to the p independent variables $x_{t1}, x_{t2}, \cdots, x_{tp}$,

ε_t is a random error component that describes the influence on y_t of all factors other than the p independent variables $x_{t1}, x_{t2}, \cdots, x_{tp}$.

For the regression Equation 6.3 to be statistically correct, ε_t must have the following properties:

1. ε_t is a random variable with mean zero and variance σ^2 (unknown), that is,

$$E(\varepsilon_t) = 0$$

and

$$V(\varepsilon_t) = \sigma^2$$

2. ε_i and ε_j are uncorrelated, $i \neq j$, so that

$$\text{cov}\ (\varepsilon_i, \varepsilon_j) = 0$$

3. ε_t is a normally distributed random variable, with mean zero and variance σ^2 by (1), that is,

$$\varepsilon_t \sim N(0, \sigma^2)$$

These three properties or assumptions are named as inference assumptions because they are the assumptions that must be met if statistical inferences concerning regression models, for example, calculations of confidence intervals for y_t, are to be valid (Bowerman and O'Connell, 1979).

The exact multiple regression model for the electricity sales of the utility firm is discussed in the following section.

C. A Case Study: Electricity Sales Forecasting

To illustrate the capability of these two forecasting methods, monthly sales data were used to predict the future monthly (or yearly) demand. These data were provided by Iowa Electric Light and Power Company (1974 - 1980), an Iowa corporation, which is engaged primarily in the generation, transmission, distribution and sale of electric energy, and in the purchase, distribution and sale of natural gas in Iowa. Electric service is supplied in fifty-five counties in the State of Iowa, including 270 incorporated cities and 122 unincorporated communities.

The monthly, and thus the annual, sales data from January 1975 to December 1979 of Iowa Electric Light and Power Company were utilized to forecast the sales of the next twelve months in the year 1980. The actual 1980 monthly sales of electricity were used as test data to compare with the predicted ones using these two methods. Figure 6.1 shows the plot of monthly sales from January 1974 to December 1979, inclusively.

1. Forecasting using Census II decomposition method

Iowa State University has a set of interactive forecasting packages known as SIBYL/RUNNER stored in the VAX/VMS(Virtual Address Extension/Virtual Memory System) system. In the SIBYL/RUNNER package, there lies the Census II decomposition program. Once the input data were fed in, the outputs related to Census II method were provided in full detail. A portion of computer printouts are listed in Appendix B.

The forecasts for the next twelve months' demands are also provided and listed in Table 6.1, together with the percent error, calculated as follows:

$$\text{Percent Error} = \frac{(\text{Actual Demand} - \text{Predicted Demand})}{\text{Actual Demand}} \times 100\ \% \qquad (6.4)$$

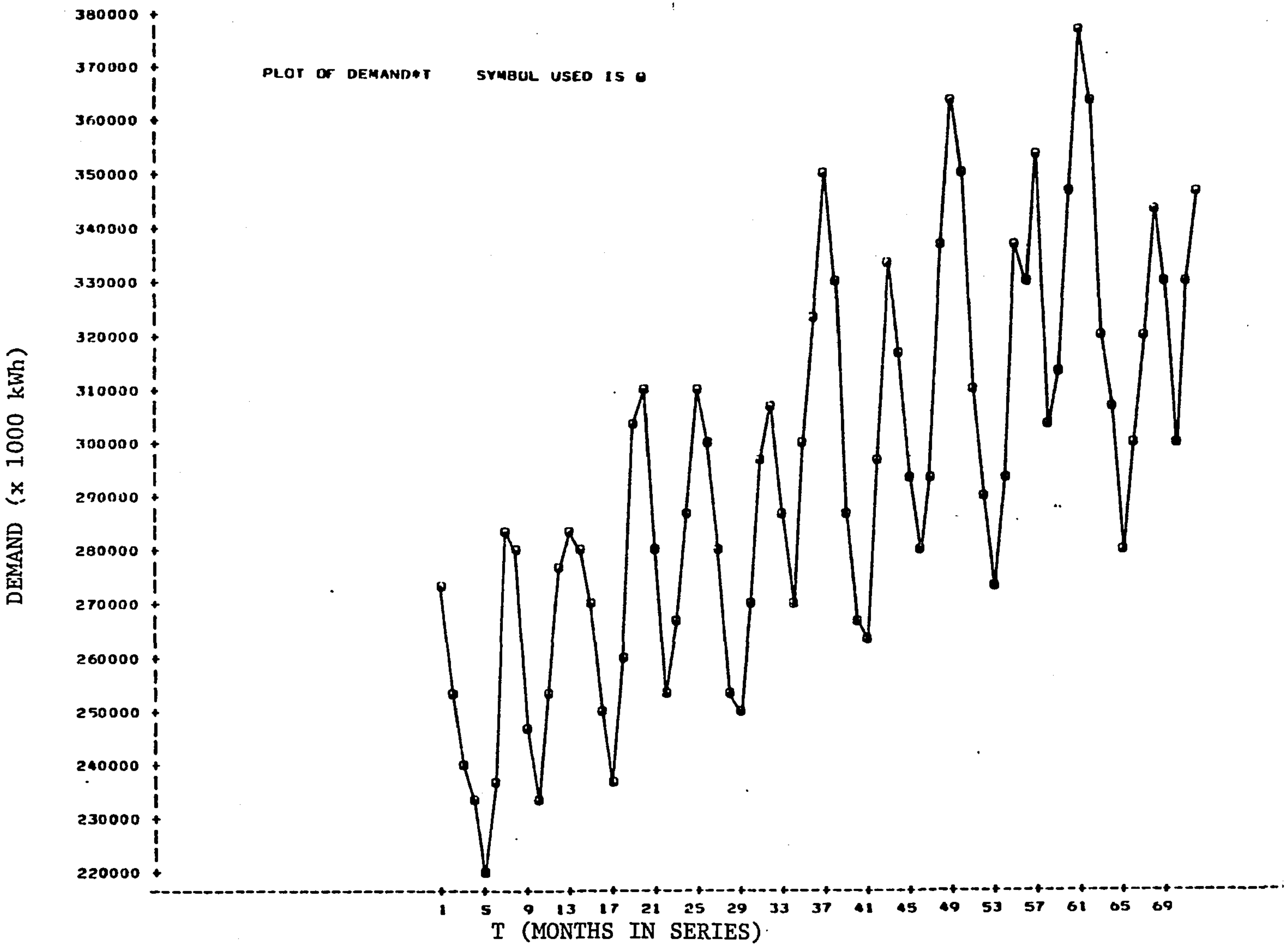

Figure 6.1. Monthly demands (January 1974 - December 1979)

Table 6.1. Forecasts for the 1980 monthly electricity demand (in 1000 kWh)

Months of 1980	Actual Demand	Predicted Demand (Census II)	Percent Error (%) (Census II)	Predicted Demand (Regression)	Percent Error (%) (Regression)
Jan	358796	384727	-4.44	353377	1.55
Feb	354071	371232	-4.85	351850	0.63
Mar	331298	329572	0.52	336359	-1.53
Apr	330904	310106	-3.06	300883	0.01
May	281361	296968	-5.55	285919	-1.62
Jun	305292	324850	-6.41	310005	-1.54
Jul	364599	362116	0.68	364484	0.03
Aug	373327	364778	2.29	367828	1.47
Sep	349314	360958	-3.33	337431	3.40
Oct	303912	326277	-7.36	313800	-3.25
Nov	321117	347631	-8.26	324628	-1.09
Dec	345112	381127	-10.44	--	--
Total	3989109	4160342	-4.29		

2. Forecasting using multiple regression model

The multiple regression model used for this study employed both causal variables and mathematical functions of time to forecast a time series. Figure 6.1 shows that the monthly demands follow a strong trend and that they have a seasonal pattern with upper peaks in January and July, and lower peaks in May and October in nearly every year. It also appears that the amount of seasonal variation is increasing with the level of the time series. According to Bowerman and O'Connell (1979), a log transformation can equalize the amount of seasonal variation over the range of the data. Consequently, the data were transformed and plotted in Figure 6.2.

From the 1979 annual report of Iowa Electric Light and Power Company, kilowatt-hour sales of electricity in 1979 showed the lowest increase in many years, only 1.4 % over the total for 1978. Kilowatt-hour sale growth has ranged between 3.3 % and 8.4 % in recent years. It was believed the declining growth rate was the customers' response to pleas for conservation and wise use of energy. Consequently, the trend was going to differ from that of previous years. In order to remedy this situation, a second trend was introduced to represent a slower growth rate.

The causal variables, such as the heating degree days and cooling degree days both based on 65 °F, seem to have a significant effect on the sales of electricity. Accordingly, these two variables were

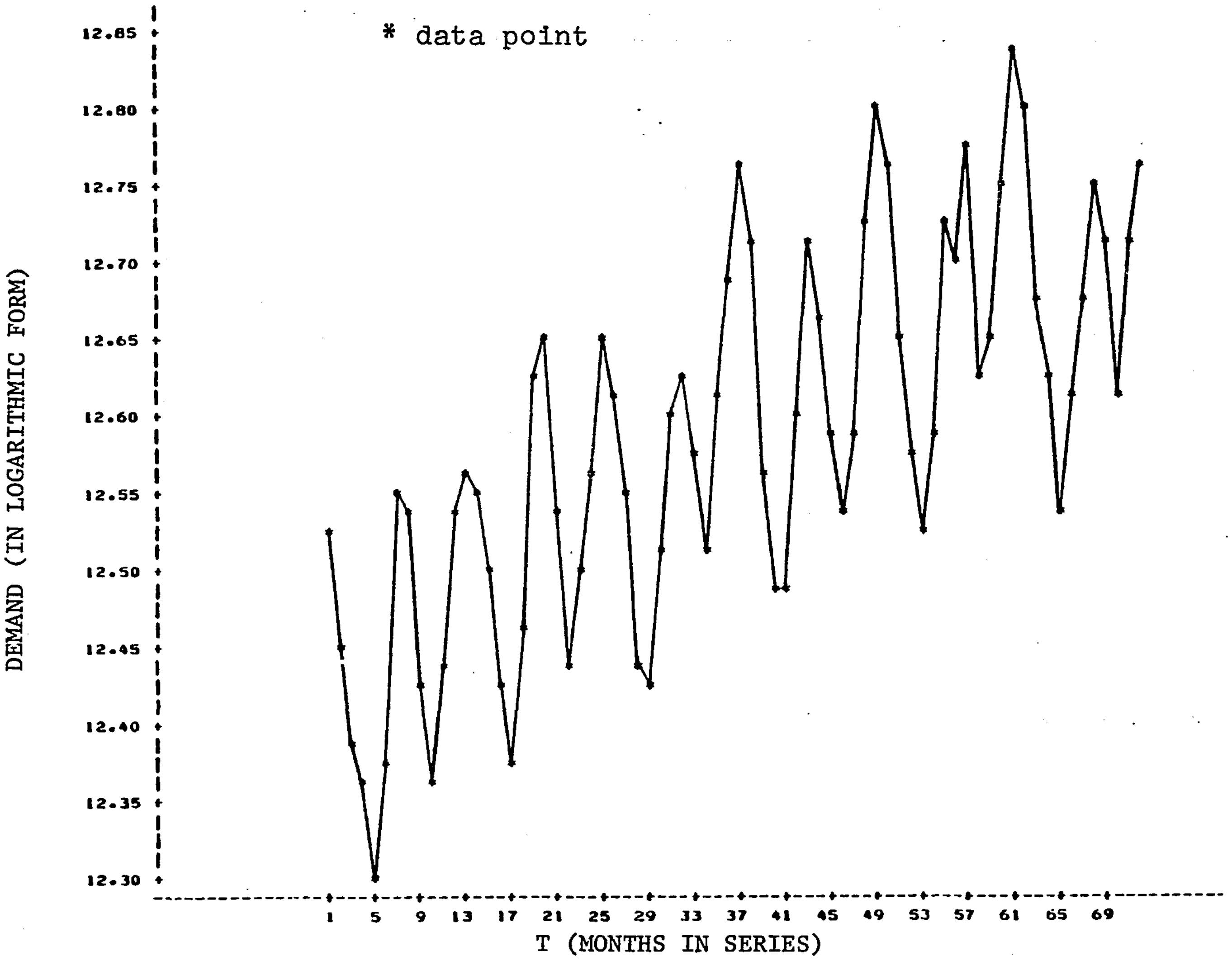

Figure 6.2. Monthly demands in logarithmic form

included in the model. The data of these two variables were taken from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (1974-1980). These data were averages of recorded values by the four stations located in Iowa.

$$y_t^* = \beta_0 + \sum_{i=1}^{12} \beta_{mi} x_{mi,t} + \beta_1 x_{t1} + \beta_2 x_{t2} + \beta_3 x_{t3} + \beta_4 x_{t4} + \varepsilon_t \quad (6.5)$$

where

y_t = the monthly demand at period t

y_t^* = the log transformation of y_t

β_0 = the interception

$$x_{mi,t} = \begin{cases} 1 \text{ if sales period t is month i} \\ 0 \text{ if otherwise} \end{cases}$$

x_{t1} = the first trend between years 1974 to 1978

x_{t2} = the second trend between years 1978 and 1979

x_{t3} = the heating degree days

x_{t4} = the cooling degree days

$\beta_{m1}, \cdots, \beta_{m12}, \beta_1, \cdots, \beta_4$ are parameters to be estimated

$$\sum_{i=1}^{12} \beta_{mi} = 0$$

ε_t the error term, a random variable distributed $N(0,\sigma^2)$

The input data and the actual and predicted values for this multiple regression model are listed in Appendix B. The estimates of the parameters are recorded in Table 6.2, together with related statistics. The Durbin-Watson D statistic had a value of 1.8291, which was very close

Table 6.2. Summary of the multiple regression analysis

```
MODEL:   MODEL01                 SSE      0.036103        F RATIO      107.04
                                 DFE            56        PROB>F       0.0001
DEP VAR: LND                     MSE    0.00064469        R-SQUARE     0.9663

DURBIN-WATSON D STATISTIC   =   1.8291
FIRST ORDER AUTOCORRELATION =   0.0822

                              PARAMETER      STANDARD
VARIABLE            DF         ESTIMATE         ERROR         T RATIO     PROB>|T|

INTERCEPT            1        12.273875      0.018684        656.9053       0.0001
M1                   1      0.001176945      0.028553          0.0412       0.9673
M2                   1         0.015875      0.019907          0.7975       0.4285
M3                   1        -0.036007      0.014754         -2.4404       0.0179
M4                   1        -0.042947      0.012997         -3.3045       0.0017
M5                   1        -0.078849      0.015050         -5.2390       0.0001
M6                   1        -0.034086      0.019720         -1.7285       0.0694
M7                   1      0.003258653      0.031411          0.1037       0.9177
M8                   1         0.070615      0.022603          3.1241       0.0028
M9                   1         0.079166      0.015838          4.9986       0.0001
M10                  1       -0.0096438      0.013371         -0.7212       0.4738
M11                  1      0.002412292      0.013906          0.1735       0.8629
T1                   1         0.054413   0.002389955         22.7672       0.0001
T2                   1         0.016903   0.009335047          1.8107       0.0755
HDD                  1     0.0001443127  .00002675987          5.3929       0.0001
CDD                  1     0.0005719486  0.0001100277          5.1982       0.0001
```

to 2, indicating that the error terms, ε_t, were independent with each other (Murphy, 1973). The low coefficient of autocorrelation further confirmed this statement. Furthermore, the residuals, ε_t, were normally distributed with mean 0 and variance 0.000508488, as indicated by the normal probability test and related statistics, shown in Figure 6.3 Consequently, the assumptions of this multiple regression model were satisfied and it was a valid model of the monthly demand forecast for the Iowa Electric Light and Power Company between years 1974 to 1979. The forecasts for the next twelve monthly demands of 1980 are also listed in Table 6.1.

3. Discussion

The better forecasting technique was the multiple regression analysis from the results of forecasts listed in Tables 6.1 and 6.3. the reasons can be as follows:

1. Time series components, such as seasonality and trend, can be easily introduced to the multiple regression model by means of dummy variables.
2. Apart from these time series components, other important causal variables can be employed in the regression model as long as they are related to the variables to be predicted and proven to be significant statistically.
3. When the trend shifts owing to changes in policy or other reasons, there are means available to incorporate this trend shift in the regression model.

```
VARIABLE=RESID          RESIDUALS

                  MOMENTS

N                   72      SUM WGTS            72
MEAN         2.316E-14      SUM          1.667E-12
STD DEV      0.0225497      VARIANCE .000508488
SKEWNESS     0.0140364      KURTOSIS 0.00672005
USS          0.0361026      CSS          0.0361026
CV           9.738E+13      STD MEAN     0.0026575
T:MEAN=0     8.713E-12      PROB>|T|             1
D:NORMAL     0.0797554      PROB>D           >0.15
```

```
                     NORMAL PROBABILITY PLOT
 0.0525+                                                 *
       |                                           * *
       |                                         * +
       |                                        *+
       |                                       ++
       |                                     ***
       |                                  ***
 0.0175+                                +*
       |                             *****
       |                           **+
       |                        ***+
       |                       *+
       |                     ***
       |                   ***
-0.0175+                 **
       |              +***
       |           ****
       |          *+
       |       * *
       |       +
       |     +
-0.0525+ *   *
        +----+----+----+----+----+----+----+----+----+----+
            -2        -1        +0        +1        +2
```

Figure 6.3. Normal probability plot of residuals and related statistics

Table 6.3. Yearly predicted demands

Year	Actual Demand[a]	Predicted Demand (Census II)[b]	Percent Error (%) (Census II)	Predicted Demand (Regression)[c]	Percent Error (%) (Regression)
1974	3033773	3089752	-1.85	3056081	-0.74
1975	3287272	3266142	0.64	3267867	0.59
1976	3447849	3442528	0.15	3430046	0.52
1977	3644804	3618915	0.71	3632489	0.34
1978	3861461	3795304	1.71	3883478	-0.57
1979	3917265	3971691	-1.39	3917258	0.00

[a] All demands are in 1000 kWh.

[b,c] Sums of the monthly predicted values under the Census II decomposition method and multiple regression model, respectively.

Accordingly, the multiple regression models are advantageous to utilize and allow management to evaluate the impact of various alternative policies. However, one disadvantage of this technique is that the ability to predict the dependent variable depends on the ability of the forecaster to accurately predict future values of the independent variables. Besides this, the parameters of the independent variables being estimated may not be statistically significant. Nevertheless, Brown (1963) argues that if there is a definite reason why one series is related to another, one can place one's confidence on a continuing relationship, even if the coefficients do not seem to be significant statistically.

The yearly predicted demands, which are the sum of monthly forecasts of that year, can be incorporated to the mathematical model of productivity analysis discussed in the previous chapter.

VII. A CASE STUDY OF THE GOAL PROGRAMMING MODEL

The model formulated in Chapter V was solved by the modified simplex procedure computer program developed by Lee (1976). It is an algorithmic procedure that employs an iterative process so that the optimal solution is achieved through progressive operations. Several cases with different priority combinations in resource allocation were considered, as well as other general policies of operation in the electric utility under study. The results are discussed and presented in the final section of this chapter.

A. Input Data

The model developed in Chapter V can be used for long-range planning of resource allocation with the objective of a certain percentage growth in productivity. However, for the sake of demonstration and manageability of the model, a reduction in size was accomplished by the following assumptions:

1. Only one year, i.e., the year of 1980, would be used as the planning period.
2. Seven major production plants served the different classes of customers.
3. Different varieties of customers were aggregated together as a single class.

4. There were four types of fuel (coal, oil, gas and nuclear fuel) available to generate electricity.
5. There was only one season in the year.
6. Environmental factors were eliminated.
7. The energy lost during the transmissing process was taken care of by the demand reserve as well.

With these assumptions, Equations 5.21, 5.22, 5.23, 5.34 and 5.36 were not required. As a result, the model contained only 28 constraints and 63 variables. Using this reduced model, some precision is bound to be lost. For example, the environmental factor constraints have an effect of monitoring the amount of fuel consumption. Elimination of these constraints results in relaxing the amount of fuel consumed. However, the productivity objective and fuel limitation will check over the activity of fuel consumption. As an illustrative example, this reduced model is valid to show the capability of goal programming technique in allocating resources. In real practice, nevertheless, a full model should be employed.

The historical data and the reconstructed capital investment in generation, transmission and distribution of the Iowa Electric Light and Power Company (1974-1979) were utilized for this study. Various relationships between the capital investment in three major plants (i.e., generation, transmission and distribution) with the yearly demands, generated outputs and/or time (in years) were evaluated by means of simple/multiple regression analyses. Summaries of these relationships are presented in Figures D.1 through D.4 of Appendix D. The yearly operation and maintenance expenses were also found to be related with the yearly demands and time, as shown in Figure D.5 of Appendix D. Accordingly, point estimates for various capital investments and other expenses were calculated. These values are recorded in Table 7.1.

The actual customers' demand for 1980 was 3,989,109 MWh (without the reserve consideration), which was a 1.83 % increase over the previous year. Based on this rate, another set of data was generated by increasing the 1979 input data by this growth percentage. The purpose was to select more appropriate values from these two sets to be utilized in the goal programming model. All related data are listed in Tables 7.1 and 7.2. The cost shares of the input variables in the productivity constraints were those from the previous year, 1979.

B. Priority Ranking of Objectives

There are many objectives (goals) to be sought by the management. Most of the time, objectives can only be achieved by means of trade-offs. In other words, the aspiration level of some objectives must be lowered in order to fulfill those of higher priority first. Seven major objectives (goals) were chosen to be investigated:

Table 7.1. Input resource data for the goal programming model, Part I

	Categories[a]	Point Estimation	1.83 % Increase of 1979 Record
1.	Total capital investment	821,254	888,960
2.	Transmission investment	147,510	152,719
3.	Distribution investment	259,088	258,915
4.	Generation investment (¢/kWh generated)	12	
5.	Total expenses for operations and maintenance ($1000 current dollars)	153,274	120,319
6.	Expenses for miscellaneous materials		18,418
7.	1980 demand (MWh)	3,989,109	
8.	1980 demand plus 10 % reserve (MWh)	4,388,020	
9.	Purchased power (forced) (MWh)		370,574
10.	Purchased power contracted (MWh)	350,000	
11.	Total purchased power (MWh)		967,604
12.	Labor (fulltime)		1,243
13.	Labor (parttime)		41
14.	Coal availability (x 10^9 Btu)		16,767
15.	Gas availability (x 10^9 Btu)		2,152
16.	Oil availability (x 10^9 Btu)		401
17.	Nuclear fuel availability (x 10^9 Btu)		22,343

[a] All values of investments and expenses are in thousands of constant (1976) dollars unless they are stated otherwise.

Table 7.2. Input data of generation plants for the goal programming model, Part II

Plant	Average Fuel Cost ($/$10^6$ Btu)[a]	Average Btu Per kWh Generated (Heat Rate)	Average kWh Generated Per 10^6 Btu	Normal Generating Capacity (MWh)
1	c - 1.665 g - 2.324	11,623	86.04	693,373
2	c - 1.726 o - 1.541 g - 2.399	16,137	61.97	38,339
3	c - 2.126 o - 3.405 g - 2.209	13,055	76.60	258,052
4	c - 2.057 o - 3.278 g - 2.269	10,639	93.99	517,898
5	c - 2.032 o - 2.598 g - 2.389	20,061	49.85	144,687
6	o - 3.340	14,601	68.49	28,031
7	n - 0.377	10,533	94.94	2,224,685

[a] c - coal, o - oil, g - gas and n - nuclear fuel.

1. An attainment of 5 % productivity growth rate (10 % in case 4).
2. A demand requirement of 4,388,020 MWh (which includes a 10 % reserve margin of the actual demand).
3. Total capital investment of \$888.96 in millions of dollars (cumulated investment balance).
4. Employment of 1,243 fulltime and 41 parttime employees.
5. Fuel consumption of 41,664 x 10^9 Btu.
6. Miscellaneous materials expenses of \$18,418,000.
7. Purchased power of 967,604 MWh.

Four cases to evaluate the effects of priority rankings among these objectives (goals) were studied. Table 7.3 lists the combinations that were considered in this research.

C. Discussion of the Results

All four cases were solved by Lee's (1976) modified simplex procedure computer program, as indicated previously. The required input data for case 1, according to Lee's format, are listed in Appendix E. Input data for the other three cases can be generated by changing the priority level accordingly, as shown in Table 7.3. The results are summarized and recorded in Table 7.4, corresponding with the format listed in Table 7.3.

Table 7.3. Four cases with seven priority levels

Priority Level (k)	Case			
	1	2	3	4[a]
1	Productivity Growth Rate	Productivity Growth Rate	Productivity Growth Rate	
2	Demand Requirement	Demand Requirement	Purchased Power	
3	Fuel Consumption	Fuel Consumption	Demand Requirement	
4	Labor Requirement	Labor Requirement	Capital Investment	
5	Miscellaneous Materials	Capital Investment	Labor Requirement	
6	Purchased Power	Miscellaneous Materials	Fuel Consumption	
7	Capital Investment	Purchased Power	Miscellaneous Materials	

[a] Iowa priority combination as case 3 except the productivity growth rate is 10 % instead of 5 %.

Table 7.4. Results of the studied cases[a]

Priority Level (k)	Case 1	Case 2	Case 3	Case 4
1	0	0	0	0
2	0	0	0	0
3	0	0	0	292,968
4	0	0	66,703	101,859
5	0	30,231	0	0
6	128,227	(1,320)	2,619	8,135
7	51,316	303,929	(762)	0

[a] A value of zero means achievement of the indicated objective (goal), i.e., both n_i and p_i approach zero, where n_i and p_i denote underachievement and overachievement of the ith objective, respectively; a number without parentheses represents underachievement of the ith objective (i.e., $n_i > 0$); and a number in parentheses denotes overachievement of the ith goal (i.e., $p_i > 0$).

This model was primarily designed for the resource allocation with high emphasis on the fulfillment of a certain percentage growth (5 % in cases 1, 2 and 3, and 10 % in case 4) in productivity and of customers' demand (with a 10 % reserve margin). Consequently, these two goals (objectives) had the top priority to be achieved first.

A zero value in Table 7.4 indicates that the utility company attains the exact assigned amount. For instance, the priority level 3 in case 1 represents fuel consumption (Table 7.3). The company consumes all 41,664 x 10^9 Btu of fuel to generate electricity. A number without parentheses in Table 7.4 reveals either the utility fails to meet the requirement or that amount of the particular resource is unnecessary. For example, the priority level 3 in case 4, which denotes the customers' demand requirement (Table 7.3), has a value of 292,968 (Table 7.4). This means that the company fails to achieve that goal of meeting customers' demand of 4,388,020 MWh by the amount of 292,968 MWh. A second example is priority level 6 in case 1 (Table 7.3) which represents the amount of purchased power requirement. The utility has assigned a level of acquiring 967,604 MWh of purchased power. However, only 839,378 MWh are needed. If that extra amount of 128,227 MWH, as shown in Table 7.4, was bought while other resources remained the same, then the goal of 5 % productivity growth rate would be violated.

A number in parentheses, as shown in Table 7.4, indicates an over-achievement of that goal (objective) or that extra amount of resource is required so as to satisfy the higher priority goals. A value of 762 at priority level 7 in case 3 (Table 7.4) represents the expense in miscellaneous materials (Table 7.3). The utility has to spend an extra sum of money (762 x 10^3) constant dollars) in order to meet the expenses of that category. Similar arguments can be made regarding each of the values listed in Table 7.4. Table 7.5 illustrates how various priority ranking can generate different combination of resource allocation. Actually, each case studied represents an alternative of resource allocation process by goal programming.

In all cases, the company achieved the productivity growth rate of 5 % (in cases 1 through 3) and of 10 % (in case 4). The labor employment was also satisfied to the minimum requirement of the predetermined level (i.e., an employment of 1,243 fulltime and 41 parttime employees).

The customers' demand was met in all cases except in case 4, which had a 10 % productivity growth rate objective. The case was probably due to the squeezing effect of the high productivity growth rate, which required less input resources to provide the same output quantity. This effect resulted in minimizing the miscellaneous materials expenses, reducing the fuel consumption and thus utilizing less capital investment, as shown in cases 3 and 4 in Table 7.5. Accordingly, with these limited resources, the company failed to generate enough electricity to satisfy the 4,388,020 MWh demand by an amount of 292,268 MWh.

Table 7.5. Resource allocations according to the four studied cases

	Case			
Category	1	2	3	4
Productivity goal attained	yes	yes	yes	yes
Demand satisfied (MWh)	4,388,020	4,388,020	4,388,020	4,095,052
Total capital investment ($1000 constant dollars)	837,644	858,728	822,257	787,101
Total employment[a]	1,264	1,264	1,264	1,264
Fulltime employee	1,243	1,243	1,243	1,243
parttime employee	41	41	41	41
Fuel requirement (10^9 Btu)	41,664	41,664	39,044	33,528
Miscellaneous materials expenses (in $1000 constant dollars)	18,418	19,738	19,180	18,418
Purchased power required	839,378	663,678	967,604	967,604

[a] Total employment = fulltime employee + ½ (parttime employee).

The effect of a different priority ranking scheme on the allocation of resources was very apparent in these cases. In cases 1 and 2, the first four objectives (goals) had the same priority ranking. Whereas, the last three objectives were ranked differently. For example, purchased power had a priority level 6 in cases 1, but 7 in case 2 (Table 7.3). Consequently, a different value was allocated for each of these three resources in cases 1 and 2 (Table 7.5).

Furthermore, the complementary effect can be noted for fuel consumption and purchased power. In case 2, when fuel consumption goal of 41,664 x 10^9 Btu was achieved fully to generate electricity to meet the objective demand of 4,388,020 MWh, power purchased from other utilities was lower (only 663,676 MWh). Whereas, in case 3, it was just the opposite: 967,604 MWh of electricity was bought when only 39,044 x 10^9 Btu of fuel were burned to meet the same demand in both cases 2 and 3.

From these four studied cases, the tradeoffs among resources utilized to meet the productivity goal as well as customers' demand are very apparent. Actually, the results generated by each case specify a combination of allocated resources. For example, in case 1, the company should employ 1,243 fulltime and 41 parttime employees, invest no more than $838 millions of dollars (constant dollars) in capital (cumulated book balance), spend about $18.42 millions of dollars (constant dollars) in miscellaneous materials, consume 41,664 x 10^9 Btu of fuel, and purchase electricity in the amount of 839,378 MWh from other utilities. While operating with this allocation of resources, the company is certain to meet the customers' demand and achieve a 5 % rate of productivity growth as well. Different alternatives in resource allocation are also possible by changing priority assignments of the various goals according to the managerial decisions on what is the best for the well-being of the company.

VIII. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter consists of three sections: a summary of what has been accomplished, a discussion of conclusions regarding the results of this research, and some recommendations for further study on this topic.

A. Summary

In this research, productivity indexes, partial factor productivity (PFP) and multi-factor productivity (MFP), were developed to measure an overall performance of an electric utility. Based upon the classical economic production function approach, a five-input-variable productivity model was established. These five input variables were capital, labor, fuel, miscellaneous materials and purchased. The output was total amount of electricity sold to various customers. Cost shares of each input variable were used as weights in aggregating these variables. Productivity indexes of a utility company, between the period: 1974 - 1979, were calculated with the year 1974 as the base year.

Productivity gains can be improved in many ways. One certain route is to impose this objective in the input resource allocation problem solved by a linear goal programming technique. The goal programming model requires priority rankings for each goal. Seven major goals were assumed to be appropriately investigated. Five of them had to do with the requirements for the input variable. The other two were:

1. Productivity growth rate.
2. Customers' demand (with a 10 % reserve margin).

Four cases of different combinations of priority ranking for those objectives were considered. Each of these cases did provide useful information on resource allocation alternative according to the priority ranking scheme.

B. Conclusions

In regard to the results generated by this research, the productivity indexes just established were valid and theoretically sound. They can be applied to measure the overall performance of an electric utility. From the results of the productivity measurement case study, these indexes did spot the good performing years, as well as the ineffective ones, of the company. However, any use of a single partial factor productivity index alone could give misleading indications leading to erroneous interpretations and conclusions. This is because these indexes not only depend on changes in input levels, but also on differences between output elasticities and cost shares, as well as on technological change and some measurement biases.

The Iowa type survivor curve approach to evaluate the capital investment proved to be a refinement over Stevenson's method, due to the fact that Iowa type survivor curve represents the actual investment and retirement of capital more accurately than that of Stevenson's method.

Apparently, this refinement in capital investment estimation did help remove some of the measurement biases in productivity analysis.

From the results of the goal programming model in resource allocation, several conclusions can be made:

1. The goal programming model fully demonstrated its ability of reaching a solution through its priority ranking scheme in spite of competing multiple objectives facing the utility company.
2. It provides alternatives in resource allocation problems according to the decision-makers' priority levels of achieving their goals.
3. With the incorporation of the productivity objective having the top priority ranking in the model, various alternatives of resource combinations are generated with an assurance of a 5 % productivity growth if these combinations of resources are utilized accordingly.

C. Recommendations

With regard to this research, some areas for further study are:

1. The effects of intangible factors, such as research and development, the quality of labor force, the regulatory rules, etc., may have some influence on the productivity measurement. An investigation of these intangible factors will help find further sources for productivity improvement.

2. Use of the results of actual analyses of the life and age distribution of generation, distribution and transmission may improve the measurement of productivity. This should be compared with the use of general survivor curves for these properties.
3. Upon the availability of various components of labor force, the estimation of labor factor in the productivity measurement can be improved through weighing scheme or some other technique. This would be true for other factors as well.
4. Different classes of the ultimate customers and their effect or contribution in the output growth. In other words, the kilowatt hours supplied to these customers may not be identical, in a sense that the process of generation, transmission and distribution might be different, both in physical and dollar value. An investigation in this area could be helpful.
5. The actual budgeted investment data and the ranking of priorities according to the management of the company could provide more realistic results for the resource allocation using the goal programming model. Upon the availability of these data, it would be worthwhile to re-evaluate the ranking scheme to seek an optimal resource allocation.

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XI. APPENDIX A: TABLES OF OUTPUT AND INPUT STATISTICS

Table A.1. Output statistics(in MWh)

Year	Sales to Ultimate Customers	Sales for Resale	Total Sales	Quantity Index (1976 = 100)
1974	2868259	165515	3033774	88
1975	3080880	206391	3287271	95
1976	3220826	227023	3447849	100
1977	3368555	276250	3644805	106
1978	3567168	294291	3861459	112
1979	3625337	291926	3917263	114

Table A.2. Labor statistics

Year	Fulltime Employee	Parttime Employee	Total Employee	Labor Expenses ($1000)	Labor Quantity Index (1976 = 100)
1974	1139	41	1160	17770	103
1975	1107	38	1126	17249	100
1976	1105	33	1122	17188	100
1977	1145	34	1162	17801	104
1978	1166	39	1186	18169	106
1979	1221	39	1241	19011	111

Table A.3. Fuel Statistics

Year	Recorded Expenditure	Average Cost ($\$/10^6$ Btu)	Fuel Consumed (10^9 Btu)	Fuel Expenses ($1000)	Fuel Quantity Index (1976=100)
1974	18094602	0.50	36189	23885	82
1975	23672730	0.58	40815	26938	93
1976	29069841	0.66	44045	29070	100
1977	36164577	0.75	48219	31825	110
1978	43282237	1.15	37637	24840	86
1979	40965337	1.01[a]	40509	26736	92

[a] Estimated from the annual report of the company.

Table A.4. Purchased power statistics

Year	Purchased Power (1000 kWh)	Interchange Net (1000 kWh)	Transmission Net (1000 kWh)	Total Purchased Power (1000 kWh)	Expense in 76 $ (1000 kWh)	Quantity Index (1976=100)
1974	430260	105523	-2259	533524	14112	155
1975	9992	418915	7703	436610	11549	127
1976	4481	338491	795	343767	9093	100
1977	4452	189938	5413	199803	5285	58
1978	308599	1273844	3153	1585596	41940	461
1979	363914	582116	4185	950215	25134	276

Table A.5. Miscellaneous materials statistics[a]

Year	Recorded Expenses for Operation and Maintenance	Purchased Power Expenses	Labor Expenses	Fuel Expenses	Adjustment	Net Expenses for Miscellaneous Materials	Price Index 1976=100	Deflated Expense	Quantity Index (1976=100)
1974	42,483	7,069	12,901	18,095	0	4,419	90.2	4,899	124
1975	50,297	6,323	15,821	23,673	0	4,480	94.2	4,756	120
1976	60,273	6,093	19,162	29,070	-998	3,946	100.0	3,946	100
1977	74,014	8,782	18,411	36,165	0	10,657	106.8	9,978	253
1978	90,191	35,216	20,218	43,282	-18,942	10,417	114.2	9,121	231
1979	118,157	31,356	22,539	40,965	0	23,297	128.8	18,087	458

[a] All values in thousands of dollars.

Table A.6. Estimation of rate of return and investment life in year 1976

	Amount ($1000)
1. Net Profit	10,819
2. Income taxes	13,956
3. Interest payment	16,482
4. Depreciation expenses	16,926
5. Total return on capital	58,183
6. Total capitalization	345,539
7. Rate of return on capital	16.84%

Major Plants	Service Life	Weights[a]
1. Nuclear production plant	28	.285
2. Steam production plant	33	.259
3. Transmission plant	33	.185
4. Distribution plant	30	.288
Weighted average service life (investment life)	30.71	1.000

[a] Calculated according to their investment dollars in year 1976.

Table A.7. Reconstructed capital investment using Stevenson's method (Method I)[a]

Year	Electric Utility Plants in Service	Adjusted H. W. Index (1976=100)	Reconstructed Capital Service	Capital Expenditure	Quantity Index (1976=100)
1974	452366	67.6	669180	105857	95
1975	464451	94	682036	107891	97
1976	486039	100	703624	111306	100
1977	497976	106	714886	113087	102
1978	533952	114	746444	118079	106
1979	566173	121	778665	123176	111

[a] All values in thousands of dollars.

Table A.8. Actual book and simulated balances of the steam production transmission and distribution investments[a]

	Steam Production Investment			Transmission Investment			Distribution Investment		
Year	Actual Book Balance	Simulated Book Balance[a]	Deviation	Actual Book Balance	Simulated Book Balance	Deviation	Actual Book Balance	Simulated Book Balance	Deviation
1974	79,400	64,327	15,073	59,772	58,219	1,553	104,061	99,121	4,940
1975	81,518	65,659	15,859	62,348	60,429	1,919	111,630	106,560	5,070
1976	89,981	73,303	16,678	67,369	64,957	2,412	118,324	112,837	5,487
1977	90,679	74,437	16,242	70,507	67,574	2,973	125,486	119,288	6,198
1978	112,591	95,529	17,062	74,941	71,452	3,489	134,657	128,029	6,628
1979	113,825	95,354	18,471	83,150	79,167	3,983	143,092	135,750	7,342

[a] The simulated balances were calculated using R_2 curve, and all values are in thousands of current dollars.

Table A.9. Reconstructed capital investment using Iowa type survivor curve approach[a]

Year	Nuclear Production Plant	Steam Production Plant	Transmission Plant	Distribution Plant	Total Reconstructed Investment	Expenditure on Capital	Quantity Index (1976=100)
1974	237,872	214,696	135,058	230,520	818,146	129,422	98.1
1975	237,273	213,278	136,501	235,727	822,779	130,155	98.6
1976	238,050	215,786	140,238	240,069	834,143	131,952	100.0
1977	238,419	210,842	141,933	244,466	836,660	132,350	100.3
1978	238,564	221,152	144,519	249,974	854,209	135,126	102.4
1979	249,443	219,214	149,974	254,262	872,893	138,082	104.6

[a] All values are in thousands of constant (1976) dollars.

XII. APPENDIX B: A PART OF COMPUTER PRINTOUTS FOR THE CENSUS II DECOMPOSITION METHOD

```
          *** SIBYL/RUNNER INTERACTIVE FORECASTING ***
                     VAX/VMS VERSION 1.0
             THESE PROGRAMS ARE OWNED AND SUPPORTED BY
          APPLIED DECISION SYSTEMS, LEXINGTON, MA. 02173

************ CENSUS II ************

DO YOU WANT A DESCRIPTION OF THIS METHOD?
(Y OR N)? N

DATA FILENAME? TOTAL
HOW MANY OBSERVATIONS DO YOU WANT TO USE? 72

WHAT IS THE LENGTH OF SEASONALITY (0=NONE,H=HELP)? 12

DO YOU WANT ALL POSSIBLE OUTPUT?
(Y OR N)? Y


ORIGINAL DATA
2750. 2549. 2406. 2326. 2186. 2360. 2823. 2803. 2480. 2344. 2530. 2782.
2843. 2816. 2693. 2495. 2382. 2599. 3046. 3112. 2794. 2535. 2683. 2874.
3111. 3013. 2807. 2530. 2485. 2700. 2970. 3054. 2881. 2713. 2989. 3223.
3501. 3313. 2873. 2656. 2639. 2974. 3325. 3165. 2922. 2785. 2937. 3357.
3635. 3511. 3100. 2888. 2740. 2941. 3366. 3285. 3536. 3043. 3110. 3451.
3764. 3628. 3209. 3055. 2802. 2999. 3207. 3433. 3306. 2993. 3310. 3467.


CENTERED 12-MONTHS RATIOS (ORIG./MOV. AVER.)
  0.0   0.0   0.0   0.0   0.0   0.0 111.5 110.1  96.5  90.5  97.2 106.1
107.6 105.7 100.1  92.0  87.4  95.0 110.7 112.4 100.4  90.9  96.0 102.5
110.9 107.7 100.3  90.0  87.8  94.5 102.8 104.7  98.2  92.2 101.2 108.5
116.8 109.8  95.0  87.7  87.2  98.1 109.3 103.5  95.1  90.0  94.5 107.9
116.9 112.6  98.5  90.7  85.6  91.5 104.5 101.6 109.1  93.5  95.3 105.6
115.3 111.2  98.4  94.0  86.1  91.9   0.0   0.0   0.0   0.0   0.0   0.0
```

```
DO YOU WANT A TABLE OF ACTUAL AND PREDICTED?
(Y OR N)? Y

PERIOD          ACTUAL          FORECAST          ERROR   PCT ERROR
   1           2749.54          2890.95         -141.41      -5.14%
   2           2548.79          2783.79         -235.00      -9.22%
   3           2406.32          2465.78          -59.46      -2.47%
   4           2325.99          2315.12           10.87       0.47%
   5           2185.63          2212.24          -26.61      -1.22%
   6           2359.93          2414.80          -54.87      -2.33%
   7           2823.01          2686.17          136.84       4.85%
   8           2803.16          2700.29          102.87       3.67%
   9           2479.81          2666.53         -186.72      -7.53%
  10           2343.59          2405.45          -61.86      -2.64%
  11           2530.38          2557.75          -27.37      -1.08%
  12           2781.58          2798.65          -17.07      -0.61%
  13           2842.53          3060.38         -217.84      -7.66%
  14           2816.07          2946.14         -130.07      -4.62%
  15           2693.11          2608.89           84.22       3.13%
  16           2495.41          2448.84           46.57       1.87%
  17           2382.35          2339.41           42.94       1.80%
  18           2599.08          2552.95           46.13       1.77%
  19           3045.97          2839.11          206.86       6.79%
  20           3112.10          2853.31          258.79       8.32%
  21           2794.07          2816.93          -22.86      -0.82%
  22           2535.31          2540.48           -5.17      -0.20%
  23           2682.85          2700.67          -17.82      -0.66%
  24           2873.87          2954.31          -80.44      -2.80%
  25           3111.10          3229.80         -118.70      -3.82%
  26           3013.48          3108.49          -95.01      -3.15%
  27           2807.42          2752.00           55.42       1.97%
  28           2530.08          2582.56          -52.48      -2.07%
  29           2485.36          2466.57           18.79       0.76%
  30           2700.22          2691.09            9.13       0.34%
  31           2970.19          2992.05          -21.86      -0.74%
  32           3054.48          3006.33           48.15       1.58%
  33           2880.71          2967.32          -86.61      -3.01%
  34           2713.27          2675.52           37.75       1.39%
  35           2989.03          2843.59          145.44       4.87%
  36           3223.15          3109.96          113.19       3.51%
  37           3500.73          3399.22          101.51       2.90%
  38           3312.91          3270.84           42.07       1.27%
  39           2873.09          2895.10          -22.01      -0.77%
  40           2655.91          2716.28          -60.37      -2.27%
  41           2639.38          2593.74           45.64       1.73%
  42           2974.27          2829.24          145.03       4.88%
  43           3325.01          3144.99          180.02       5.41%
  44           3165.21          3159.35            5.86       0.19%
  45           2922.43          3117.72         -195.29      -6.68%
```

```
  46         2784.72      2810.56      -25.84     -0.93%
  47         2937.09      2986.50      -49.41     -1.68%
  48         3357.29      3265.61       91.68      2.73%
  49         3635.26      3568.65       66.61      1.83%
  50         3510.56      3433.19       77.37      2.20%
  51         3099.88      3038.21       61.67      1.99%
  52         2888.33      2850.00       38.33      1.33%
  53         2740.26      2720.90       19.36      0.71%
  54         2940.79      2967.39      -26.60     -0.90%
  55         3366.31      3297.93       68.38      2.03%
  56         3284.52      3312.37      -27.85     -0.85%
  57         3535.61      3268.12      267.49      7.57%
  58         3043.09      2945.59       97.50      3.20%
  59         3110.38      3129.42      -19.04     -0.61%
  60         3450.62      3421.27       29.35      0.85%
  61         3763.55      3738.07       25.48      0.68%
  62         3628.26      3595.54       32.72      0.90%
  63         3209.29      3181.32       27.97      0.87%
  64         3054.84      2983.72       71.12      2.33%
  65         2802.01      2848.07      -46.06     -1.64%
  66         2999.00      3105.53     -106.53     -3.55%
  67         3207.48      3450.87     -243.39     -7.59%
  68         3432.83      3465.39      -32.56     -0.95%
  69         3306.00      3418.51     -112.51     -3.40%
  70         2993.17      3080.63      -87.46     -2.92%
  71         3309.96      3272.34       37.62      1.14%
  72         3467.26      3576.92     -109.66     -3.16%

MEAN SQUARED ERROR (MSE)           =10589.1
MEAN ABSOLUTE PC ERROR   (MAPE)    =    2.7%
MEAN PC ERROR (MPE) OR BIAS        =  -0.08%

FORECAST FOR HOW MANY PERIODS AHEAD (0 = NONE, 24 = MAX)? 12

PER       FORECAST

 73          3847.27
 74          3712.32
 75          3295.72
 76          3101.06
 77          2969.68
 78          3248.50
 79          3621.16
 80          3647.78
 81          3609.58
 82          3262.77
 83          3476.31
 84          3811.27
```

XIII. APPENDIX C: THE INPUT DATA AND THE OUTPUT VALUES OF THE ACTUAL AND PREDICTED FOR THE MULTIPLE REGRESSION ANALYSIS

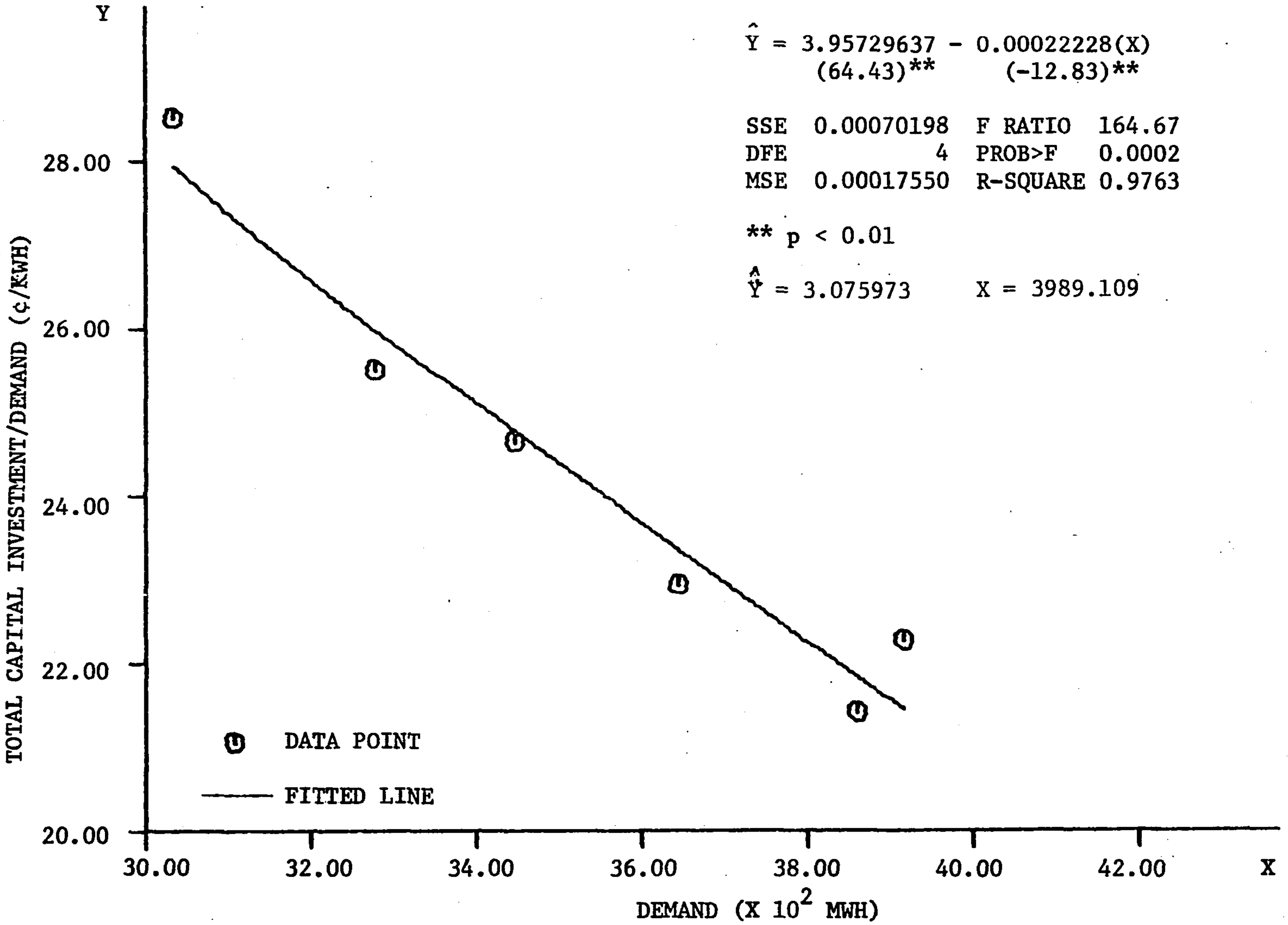
```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                        C
C  ** INPUT DATA FOR THE FORECASTING MODEL ANALYSIS **   C
C                                                        C
C     VARIABLES ARE DEFINED AS FOLLOWS:                  C
C       YR = YEAR (I.E. 1974, 1975, ..., 1979)           C
C       MO = MONTH (I.E. 1, 2, ..., 12)                  C
C       T  = NUMBER OF OBSERVATIONS (72 TOTAL OBS.)      C
C       S  = SEASONAL FACTORS FROM THE CENSUS II PROG.   C
C       HDD = HEATING DEGREE DAYS BASED ON 65 DEGREE F   C
C       CDD = COOLING DEGREE DAYS BASED ON 65 DEGREE F   C
C       DEMAND = MONTHLY DEMANDS (LOADS) IN 1000 KWH     C
C       M1-M12 = DUMMY VARIABLES FOR THE MONTH (0 OR 1)  C
C       T1 = DUMMY VARIABLE FOR THE FIRST SLOPE EST.     C
C            FOR THE YEARS 1974 TO 1978, INCLUSIVELY     C
C       T2 = DUMMY VARIBALE FOR THE SECOND SLOPE EST.    C
C            FOR THE YEARS 1978 AND 1979                 C
C                                                        C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

DATA FINAL;
INPUT YR MO T S HDD CDD DEMAND M1-M12 T1 T2;
  S=S/10.0;
  M1=M1-M12; M2=M2-M12; M3=M3-M12; M4=M4-M12;
  M5=M5-M12; M6=M6-M12; M7=M7-M12; M8=M8-M12;
  M9=M9-M12; M10=M10-M12; M11=M11-M12;
  LND=LOG(DEMAND);
CARDS;
74  1  1 1111 1427    0 274954 1 0 0 0 0 0 0 0 0 0 0 0 1 0
74  2  2 1063 1092    0 254879 0 1 0 0 0 0 0 0 0 0 0 0 1 0
74  3  3  990  848    0 240632 0 0 1 0 0 0 0 0 0 0 0 0 1 0
74  4  4  917  405   10 232599 0 0 0 1 0 0 0 0 0 0 0 0 1 0
74  5  5  874  228   37 218563 0 0 0 0 1 0 0 0 0 0 0 0 1 0
74  6  6  945   45  118 235993 0 0 0 0 0 1 0 0 0 0 0 0 1 0
74  7  7 1084    0  401 282301 0 0 0 0 0 0 1 0 0 0 0 0 1 0
74  8  8 1086   19  166 280316 0 0 0 0 0 0 0 1 0 0 0 0 1 0
74  9  9  984  200   38 247981 0 0 0 0 0 0 0 0 1 0 0 0 1 0
74 10 10  912  361    1 234359 0 0 0 0 0 0 0 0 0 1 0 0 1 0
74 11 11  976  802    0 253038 0 0 0 0 0 0 0 0 0 0 1 0 1 0
74 12 12 1058 1188    0 278158 0 0 0 0 0 0 0 0 0 0 0 1 1 0
75  1 13 1116 1351    0 284253 1 0 0 0 0 0 0 0 0 0 0 0 2 0
75  2 14 1069 1222    0 281607 0 1 0 0 0 0 0 0 0 0 0 0 2 0
75  3 15  988 1137    0 269311 0 0 1 0 0 0 0 0 0 0 0 0 2 0
75  4 16  913  601    1 249541 0 0 0 1 0 0 0 0 0 0 0 0 2 0
75  5 17  873  110   88 238235 0 0 0 0 1 0 0 0 0 0 0 0 2 0
75  6 18  946   24  202 259908 0 0 0 0 0 1 0 0 0 0 0 0 2 0
75  7 19 1080   10  331 304597 0 0 0 0 0 0 1 0 0 0 0 0 2 0
75  8 20 1079    0  293 311210 0 0 0 0 0 0 0 1 0 0 0 0 2 0
75  9 21  987  202   43 279407 0 0 0 0 0 0 0 0 1 0 0 0 2 0
75 10 22  913  338   23 253531 0 0 0 0 0 0 0 0 0 1 0 0 2 0
```

75	11	23	975	714	0	268285	0	0	0	0	0	0	0	0	0	0	1	0	2	0
75	12	24	1059	1160	0	287387	0	0	0	0	0	0	0	0	0	0	0	1	2	0
76	1	25	1126	1401	0	311110	1	0	0	0	0	0	0	0	0	0	0	0	3	0
76	2	26	1079	923	0	301348	0	1	0	0	0	0	0	0	0	0	0	0	3	0
76	3	27	985	826	0	280742	0	0	1	0	0	0	0	0	0	0	0	0	3	0
76	4	28	909	385	14	253008	0	0	0	1	0	0	0	0	0	0	0	0	3	0
76	5	29	872	229	18	248536	0	0	0	0	1	0	0	0	0	0	0	0	3	0
76	6	30	947	12	157	270022	0	0	0	0	0	1	0	0	0	0	0	0	3	0
76	7	31	1071	1	328	297019	0	0	0	0	0	0	1	0	0	0	0	0	3	0
76	8	32	1067	9	217	305448	0	0	0	0	0	0	0	1	0	0	0	0	3	0
76	9	33	995	129	68	288071	0	0	0	0	0	0	0	0	1	0	0	0	3	0
76	10	34	914	596	10	271327	0	0	0	0	0	0	0	0	0	1	0	0	3	0
76	11	35	973	1049	0	298903	0	0	0	0	0	0	0	0	0	0	1	0	3	0
76	12	36	1061	1449	0	322315	0	0	0	0	0	0	0	0	0	0	0	1	3	0
77	1	37	1138	1818	0	350073	1	0	0	0	0	0	0	0	0	0	0	0	4	0
77	2	38	1091	1067	0	331291	0	1	0	0	0	0	0	0	0	0	0	0	4	0
77	3	39	980	695	0	287309	0	0	1	0	0	0	0	0	0	0	0	0	4	0
77	4	40	906	307	31	265591	0	0	0	1	0	0	0	0	0	0	0	0	4	0
77	5	41	869	56	130	263938	0	0	0	0	1	0	0	0	0	0	0	0	4	0
77	6	42	946	16	188	297427	0	0	0	0	0	1	0	0	0	0	0	0	4	0
77	7	43	1059	1	380	332501	0	0	0	0	0	0	1	0	0	0	0	0	4	0
77	8	44	1054	24	152	316521	0	0	0	0	0	0	0	1	0	0	0	0	4	0
77	9	45	1006	80	57	292243	0	0	0	0	0	0	0	0	1	0	0	0	4	0
77	10	46	916	456	0	278472	0	0	0	0	0	0	0	0	0	1	0	0	4	0
77	11	47	972	846	0	293709	0	0	0	0	0	0	0	0	0	0	1	0	4	0
77	12	48	1061	1369	0	335729	0	0	0	0	0	0	0	0	0	0	0	1	4	0
78	1	49	1147	1750	0	363526	1	0	0	0	0	0	0	0	0	0	0	0	5	0
78	2	50	1099	1488	0	351056	0	1	0	0	0	0	0	0	0	0	0	0	5	0
78	3	51	976	1047	2	309988	0	0	1	0	0	0	0	0	0	0	0	0	5	0
78	4	52	907	473	0	288833	0	0	0	1	0	0	0	0	0	0	0	0	5	0
78	5	53	867	213	69	274026	0	0	0	0	1	0	0	0	0	0	0	0	5	0
78	6	54	943	25	192	294079	0	0	0	0	0	1	0	0	0	0	0	0	5	0
78	7	55	1049	1	269	336631	0	0	0	0	0	0	1	0	0	0	0	0	5	0
78	8	56	1045	7	242	328452	0	0	0	0	0	0	0	1	0	0	0	0	5	0
78	9	57	1016	66	170	353561	0	0	0	0	0	0	0	0	1	0	0	0	5	0
78	10	58	918	439	1	304309	0	0	0	0	0	0	0	0	0	1	0	0	5	0
78	11	59	972	848	0	311938	0	0	0	0	0	0	0	0	0	0	1	0	5	0
78	12	60	1060	1370	0	345062	0	0	0	0	0	0	0	0	0	0	0	1	5	0
79	1	61	1151	1829	0	376255	1	0	0	0	0	0	0	0	0	0	0	0	5	1
79	2	62	1103	1486	0	362826	0	1	0	0	0	0	0	0	0	0	0	0	5	1
79	3	63	974	976	0	320929	0	0	1	0	0	0	0	0	0	0	0	0	5	1
79	4	64	909	568	1	305484	0	0	0	1	0	0	0	0	0	0	0	0	5	1
79	5	65	866	213	43	280201	0	0	0	0	1	0	0	0	0	0	0	0	5	1
79	6	66	941	19	170	299900	0	0	0	0	0	1	0	0	0	0	0	0	5	1
79	7	67	1043	2	264	320748	0	0	0	0	0	0	1	0	0	0	0	0	5	1
79	8	68	1042	16	245	343283	0	0	0	0	0	0	0	1	0	0	0	0	5	1
79	9	69	1021	74	97	330600	0	0	0	0	0	0	0	0	1	0	0	0	5	1
79	10	70	918	407	10	299317	0	0	0	0	0	0	0	0	0	1	0	0	5	1
79	11	71	972	847	0	330996	0	0	0	0	0	0	0	0	0	0	1	0	5	1
79	12	72	1059	1066	0	346726	0	0	0	0	0	0	0	0	0	0	0	1	5	1

```
---------------------------- YR=74 -----------------------------

OBS      HDD        CDD       DEMAND       PRED        ERRPERCT

  1     1427          0       274954      278006       -1.1101
  2     1092          0       254879      268808       -5.4649
  3      848          0       240632      246387       -2.3916
  4      405         10       232599      230846        0.7536
  5      228         37       218563      220467       -0.8712
  6       45        118       235993      235199        0.3366
  7        0        401       282301      285186       -1.0220
  8       19        166       280316      267423        4.5993
  9      200         38       247981      257313       -3.7633
 10      361          1       234359      235935       -0.6726
 11      802          0       253038      254343       -0.5157
 12     1188          0       278158      276167        0.7159

---------------------------- YR=75 -----------------------------

OBS      HDD        CDD       DEMAND       PRED        ERRPERCT

 13     1351          0       284253      290350       -2.1451
 14     1222          0       281607      289215       -2.7016
 15     1137          0       269311      271245       -0.7181
 16      601          1       249541      249461        0.0322
 17      110         88       238235      235639        1.0896
 18       24        202       259908      259786        0.0471
 19       10        331       304597      289734        4.8797
 20        0        293       311210      302821        2.6957
 21      202         43       279407      272559        2.4508
 22      338         23       253531      251447        0.8218
 23      714          0       268285      265177        1.1586
 24     1160          0       287387      290434       -1.0603

---------------------------- YR=76 -----------------------------

OBS      HDD        CDD       DEMAND       PRED        ERRPERCT

 25     1401          0       311110      308807        0.7402
 26      923          0       301348      292491        2.9392
 27      826          0       280742      273843        2.4576
 28      385         14       253008      257232       -1.6695
 29      229         18       248536      243192        2.1502
 30       12        157       270022      266880        1.1636
 31        1        328       297019      305015       -2.6920
 32        9        217       305448      306551       -0.3611
 33      129         68       288071      288886       -0.2829
 34      596         10       271327      273539       -0.8152
 35     1049          0       298903      293875        1.6822
 36     1449          0       322315      319736        0.8002
```

```
--------------------------- YR=77 ---------------------------

      OBS      HDD      CDD     DEMAND      PRED     ERRPERCT

      37      1818        0     350073    346301       1.0775
      38      1067        0     331291    315332       4.8171
      39       695        0     287309    283741       1.2420
      40       307       31     265591    271200      -2.1120
      41        56      130     263938    267029      -1.1710
      42        16      188     297427    287011       3.5021
      43         1      380     332501    331794       0.2127
      44        24      152     316521    312556       1.2525
      45        80       57     292243    300992      -2.9936
      46       456        0     278472    281444      -1.0672
      47       846        0     293709    301350      -2.6014
      48      1369        0     335729    333740       0.5924

--------------------------- YR=78 ---------------------------

      OBS      HDD      CDD     DEMAND      PRED     ERRPERCT

      49      1750        0     363526    362095       0.3936
      50      1488        0     351056    353823      -0.7881
      51      1047        2     309988    315581      -1.8043
      52       473        0     288833    288154       0.2350
      53       213       69     274026    278533      -1.6448
      54        25      192     294079    304149      -3.4244
      55         1      269     336631    328797       2.3272
      56         7      242     328452    346617      -5.5304
      57        66      170     353561    338358       4.3000
      58       439        1     304309    296624       2.5255
      59       848        0     311938    318293      -2.0373
      60      1370        0     345062    352454      -2.1422

--------------------------- YR=79 ---------------------------

      OBS      HDD      CDD     DEMAND      PRED     ERRPERCT

      61      1829        0     376255    372490       1.0006
      62      1486        0     362826    359750       0.8477
      63       976        0     320929    317326       1.1228
      64       568        1     305484    297282       2.6850
      65       213       43     280201    279100       0.3930
      66        19      170     299900    305202      -1.7679
      67         2      264     320748    333495      -3.9741
      68        16      245     343283    353590      -3.0024
      69        74       97     330600    330435       0.0499
      70       407       10     299317    301840      -0.8429
      71       847        0     330996    323672       2.2127
      72      1066        0     346726    343076       1.0527
```

XIV. APPENDIX D: SUMMARIES OF CAPITAL INVESTMENTS FOR VARIOUS PLANTS AND ESTIMATION OF MISCELLANEOUS MATERIALS USING REGRESSION ANALYSIS



$\hat{Y} = 3.95729637 - 0.00022228(X)$

$(64.43)^{**} \quad (-12.83)^{**}$

SSE	0.00070198	F RATIO	164.67
DFE	4	PROB>F	0.0002
MSE	0.00017550	R-SQUARE	0.9763

** $p < 0.01$

$\hat{Y} = 3.075973 \qquad X = 3989.109$

Figure D.1. Summary of total capital investment per kWh demand

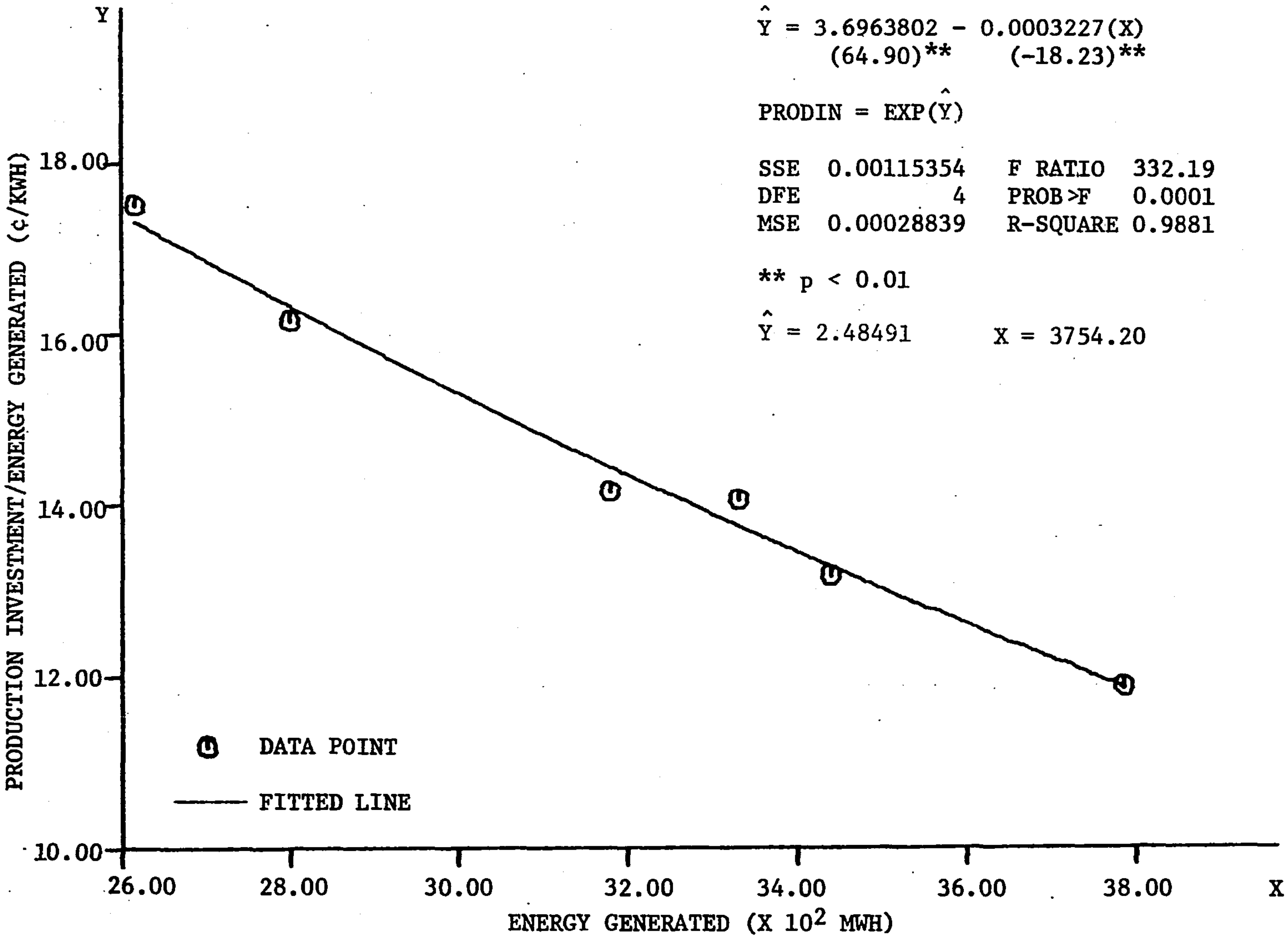
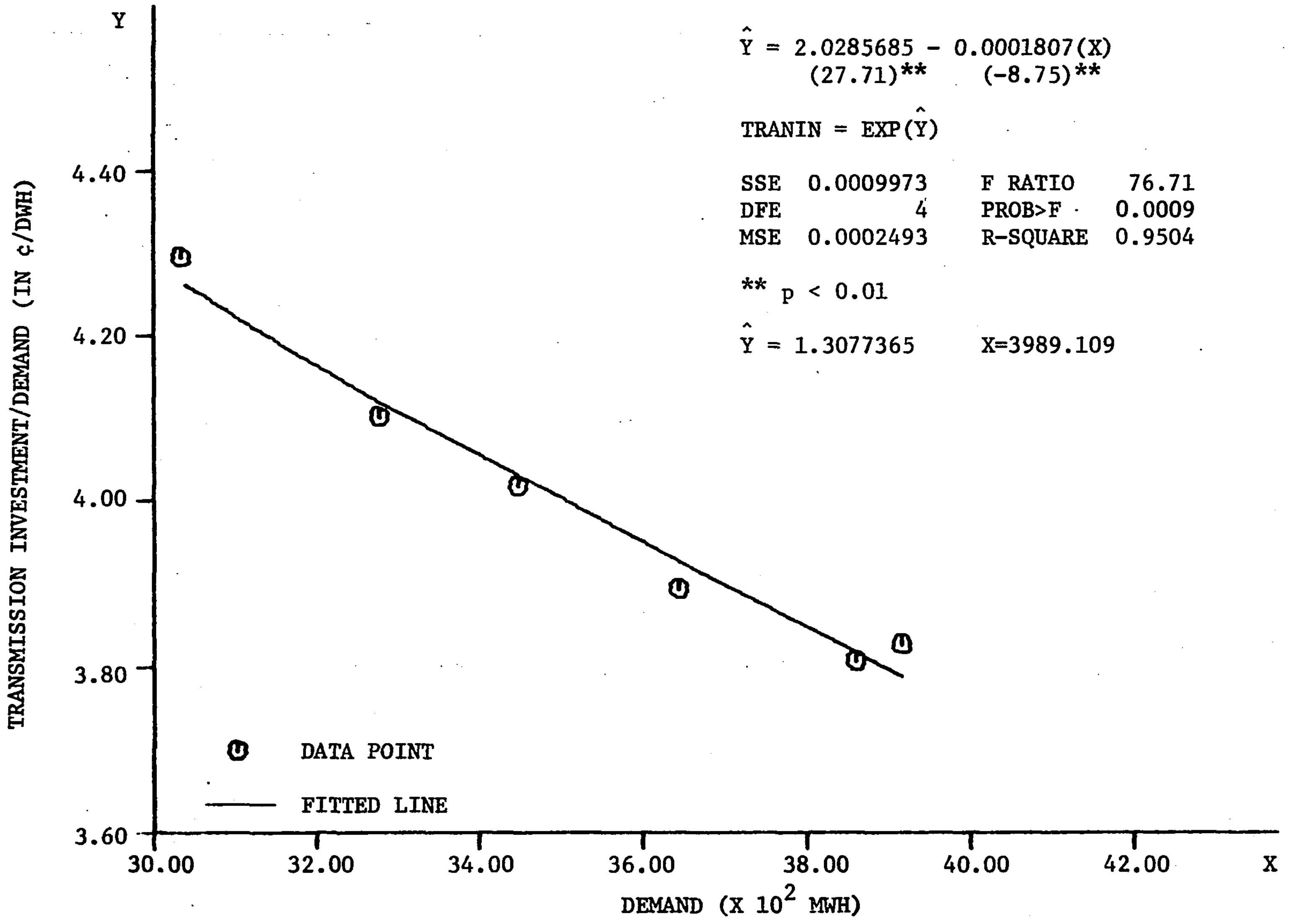


Figure D.2. Summary of production investment per kWh generated



$\hat{Y} = 2.0285685 - 0.0001807(X)$
(27.71)** (-8.75)**

TRANIN = EXP($\hat{Y}$)

SSE	0.0009973	F RATIO	76.71
DFE	4	PROB>F	0.0009
MSE	0.0002493	R-SQUARE	0.9504

** $p < 0.01$

$\hat{Y} = 1.3077365$ X=3989.109

Figure D.3. Summary of transmission investment per kWh demand

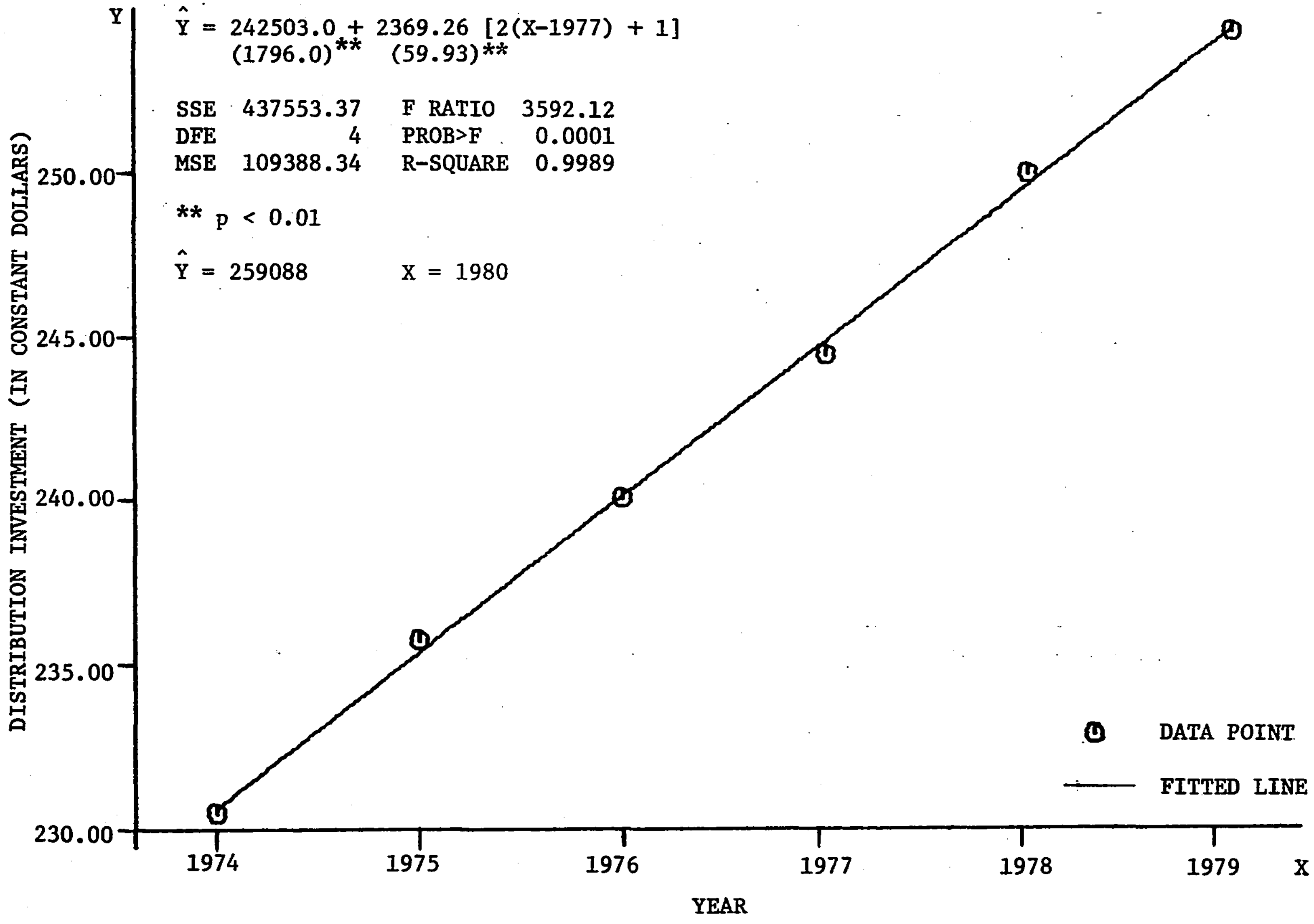
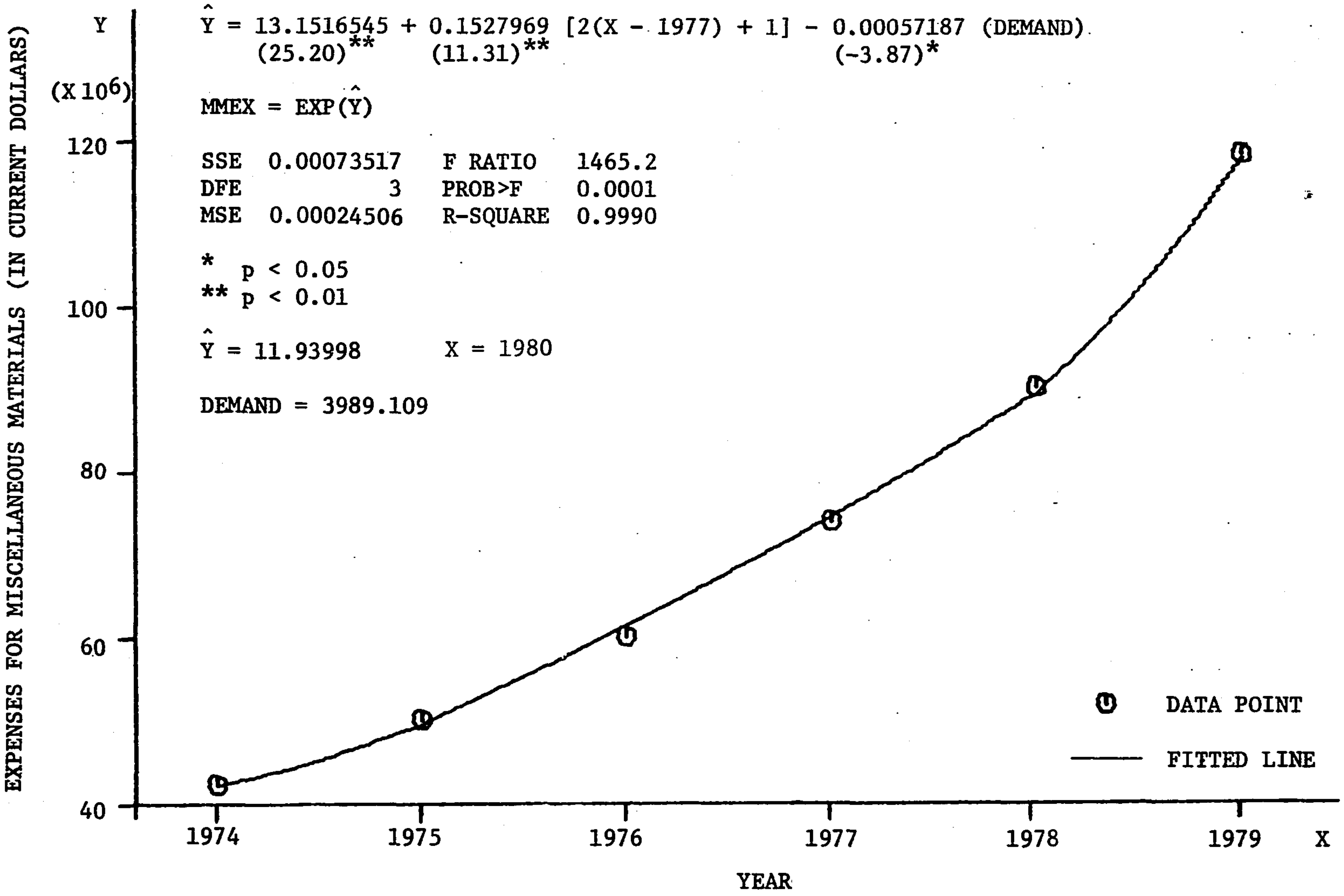


Figure D.4. Summary of distribution investment estimation statistics



$$\hat{Y} = 13.1516545 + 0.1527969\,[2(X - 1977) + 1] - 0.00057187\,(\text{DEMAND})$$
$$(25.20)^{**} \qquad (11.31)^{**} \qquad (-3.87)^{*}$$

$\text{MMEX} = \text{EXP}(\hat{Y})$

SSE	0.00073517	F RATIO	1465.2
DFE	3	PROB>F	0.0001
MSE	0.00024506	R-SQUARE	0.9990

* $p < 0.05$
** $p < 0.01$

$\hat{Y} = 11.93998$ $X = 1980$

DEMAND = 3989.109

Figure D.5. Summary of miscellaneous materials expense estimation

XV. APPENDIX E: THE INPUT DATA FOR THE GOAL PROGRAMMING MODEL (CASE I)

```
PROB 28 26   9
LGGGGLLGLGLGLLLLLLLLLLLLLGLG
OBJ
NEG      1     7  1.
POS      2     7  2.
POS      3     7  3.
POS      4     7  4.
POS      5     7  5.
NEG      6     2  1.
NEG      7     6  2.
POS      8     6  5.
NEG      9     6 10.
POS     10     4  4.
NEG     11     4  1.
POS     12     4  2.
NEG     13     9  2.
NEG     14     9  1.
NEG     15     8 86.
NEG     16     8 62.
NEG     17     8 76.
NEG     18     8 94.
NEG     19     8 49.
NEG     20     8 68.
NEG     21     8 95.
NEG     22     3  3.
NEG     23     3  2.
NEG     24     3  1.
NEG     25     3  4.
POS     26     6  1.
NEG     27     1  1.
POS     28     5  1.
DATA
         1     1 1.
         1     2 1.
         1     3 1.
         2     3 1.
         3     2 1.
         4     1 1.
         4     5 -0.12
         5     4 1.
         5     6 -0.12
         5     7 -0.12
         6     5 1.
         6     6 1.
         6     7 1.
         7     6 1.
         8     7 1.
         9     6 1.
         9     7 1.
        10     8 1.
```

```
11     8 1.
11     9 0.5
12     9 1.
13     6 0.043142
13     7 0.032285
13     8 19.659
13     9  9.8295
13    10 1.
13    11 0.001665
13    12 0.002324
13    13 0.001726
13    14 0.001541
13    15 0.002399
13    16 0.002126
13    17 0.003405
13    18 0.002209
13    19 0.002057
13    20 0.003278
13    21 0.002269
13    22 0.002032
13    23 0.002598
13    24 0.002389
13    25 0.003340
13    26 0.000377
14     1 0.15820
14     2 0.15820
14     3 0.15820
14     6 0.02645
14     7 0.02645
14     8 15.319
14     9  7.6595
14    10 0.6744
14    11 0.001059
14    12 0.000855
14    13 0.001189
14    14 0.001952
14    15 0.000950
14    16 0.001097
14    17 0.002218
14    18 0.001026
14    19 0.001089
14    20 0.002261
14    21 0.001105
14    22 0.001110
14    23 0.001753
14    24 0.001142
14    25 0.002261
14    26 0.000264
15    11 0.08604
15    12 0.08604
```

```
16    13 0.06197
16    14 0.06197
16    15 0.06197
17    16 0.07660
17    17 0.07660
17    18 0.07660
18    19 0.09399
18    20 0.09399
18    21 0.09399
19    22 0.04985
19    23 0.04985
19    24 0.04985
20    25 0.06849
21    26 0.09494
22    11 1.
22    13 1.
22    16 1.
22    19 1.
22    22 1.
23    12 1.
23    15 1.
23    18 1.
23    21 1.
23    24 1.
24    14 1.
24    17 1.
24    20 1.
24    23 1.
24    25 1.
25    26 1.
26     5 -1.
26    11 0.08604
26    12 0.08604
26    13 0.06197
26    14 0.06197
26    15 0.06197
26    16 0.07660
26    17 0.07660
26    18 0.07660
26    19 0.09399
26    20 0.09399
26    21 0.09399
26    22 0.04985
26    23 0.04985
26    24 0.04985
26    25 0.06849
26    26 0.09494
27     1 6.96534
27     2 6.96534
27     3 6.96534
```

```
       27     6 1.16815
       27     7 1.16815
       27     8 676.87349
       27     9 338.43674
       27    10 44.230663
       27    11 0.029129
       27    12 0.029129
       27    13 0.029129
       27    14 0.029129
       27    15 0.029129
       27    16 0.029129
       27    17 0.029129
       27    18 0.029129
       27    19 0.029129
       27    20 0.029129
       27    21 0.029129
       27    22 0.029129
       27    23 0.029129
       27    24 0.029129
       27    25 0.029129
       27    26 0.029129
       28    10 1.
RGHT
888960.   259088.   152719.   0         0         4388020.  370574.   350000.
967604.   1243.     1284.     41.       159567.   227050.   693373.   38339.
258052.   517898.   144687.   28031.    2224685.  16767245. 2152190.  400690.
22343435. 0         9698484.  18418.
```