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## ABSTRACT

In this paper we review a number of analytical methods and issues related to identifying and estimating the source of productivity growth. The two major methods used in measuring productivity growth -- index number and econometric estimation approach -- are briefly discussed. Substantive issues such as the contribution of R&D capital and R&D spillovers, infrastructure capital, allocative distortions, nature of the market structure and technological advancement on productivity growth at various levels of aggregation are examined. The attributes of the static and dynamic factor demand models used to estimate the contribution of different inputs to productivity growth are described and the evaluation of the production process changes in response to exogenous factors and their impact on productivity growth are discussed. Econometric issues and data considerations for proper estimation of the underlying structural models are noted briefly as well.

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## Contents

## 1 Introduction

Our paper will discuss the empirical and theoretical issues related to identifying and estimating the sources of productivity growth.[1] There is a voluminous literature on the subject and there exists a vast amount of empirical evidence based on aggregate, industry and firm data for the U. S., OECD, and developing countries. The pioneering work of Dale Jorgenson and his associates [2] and Zvi Griliches and his associates [3] and many others in U. S. universities and research institutions, the World Bank and research institutes in Europe and other countries are not discussed here. Our objectives are much narrower. We discuss only two approaches to productivity analysis: the index number approach and use of factor demand models. Both static and dynamic versions are used to specify the underlying technology and then estimate the factors that contribute positively or negatively to productivity growth. To illustrate the theoretical and empirical issues involved, we have presented a number of models and studies that we have been engaged in over the years. These studies are used as illustrations of the considerable progress achieved by the many researchers who have devoted their efforts to this general class of problems. The examples we have provided cannot represent or replicate all of other researchers' work but rather are intended to provide an illustration of the general class of studies on the subject.

Our paper examines how models of productivity can be modified to allow for regulatory distortions, endogenous industry structure, and certain specific collusive/monopolistic pricing games. Using these models we explore the contribution of innovative effort such as R&D expenditures and the spillover effects of R&D activity on productivity growth. Similarly we examine the role of public infrastructure capital in the productivity growth of U. S. industries and the aggregate economy. These models are presented to illustrate how the production structure of an industry or firm is related to its productivity performance, how market structure changes in the aggregate economy, and how government capital formation affects the dynamics of industry evolution and the growth rate of its productivity, output and factor input decisions. An important objective, in its own right and as a

[1] The authors would like to thank Anthony Postert and Paul Heidhues for their research and editorial contributions and Peter Schmidt and William Greene for their editorial oversight and criticism. The usual caveat applies.

[2] For a recent survey of Jorgenson's voluminous work on productivity, see Dale W. Jorgenson's *Productivity-Vol. I and II* (MIT Press, Cambridge, Mass., 1995).

[3] For Griliches' work on this subject the reader should consult the workings papers of the NBER Productivity Program over the past several years.

consequence of these modeling techniques, is to identify the magnitude of technical change and decompose the conventional total factor productivity measures into pure technical change, i.e. shifts in the production function controlling for scale, price and market effects and movements along the production function. We motivate and illustrate these issues empirically using real cost and demand data for firms and industries in the U.S. and other countries. Since the topic of technical efficiency, a best practice rather than an average practice concept, is covered elsewhere in this Handbook (Greene, 1996), we confine our discussion to the average production models.

As we have said, in this paper we discuss two broad approaches to measurement of productivity growth. The index number approach is designed to readily calculate a first order approximation of total factor productivity. The other approach, which we call the econometric approach is a flexible technique to identify the sources of productivity growth by explicitly specifying the underlying cost or production structure. The estimated parameters of the underlying cost/production model then are used to derive an index of total factor productivity growth.

The index number approach is discussed in section 2 of this paper. Here we define the analytics for calculating such indices and point out the basic assumptions that are used to derive a particular index. We note the desirable properties of both unilateral and multilateral productivity indices based on index number methodology and note their uses in economic analysis. Their basic shortcomings are also noted. The econometric approach has the flexibility to incorporate pertinent features of the market and industry structure as well as technological features that affect firms' or industries' productivities. This contrasts to the index number approach that by its very construction cannot distinguish between a shift and a movement along a production function. The econometric approach to calculating total and partial factor productivity is described in sections 3 to 6. Using this approach it is possible to identify the sources of productivity growth such as shifts in the production function, increases in the scale of operation, differential utilization of factor inputs, innovations by undertaking R&D, and changes in market and industry structure.

In section 3 a static model of factor demands based on a translog cost function is outlined. This approach allows one to identify the contributions to productivity of exogenous demand shifts, relative price changes that are for example often observed in inflationary periods, the direct and indirect effects of technical progress. An example of the approach that incorporates other features of production such as regulatory distortions is discussed in sub-section 3.2. In section 3.3 we present a modeling scenario in which total factor productivity growth is decomposed into neutral factor specific contributions via a long run static translog cost function.

In section 4 a general framework for dynamic factor demand models is developed. It is shown how these models can be used to estimate the sources of total factor productivity growth. The main feature of these dynamic models is the incorporation of adjustments costs associated with investment in plant and equipment and other types of investments. In the short run the stock of capital is fixed and to augment it by undertaking new investments requires re-direction of resources from current production to investment activities to produce future output. The magnitude of the adjustment costs affect the path of investment and thereby influence the course of total factor productivity.

We illustrate the workings and usefulness of these types of dynamic models in the next three subsections 4.2 to 4.4. In 4.2 we formulate a dynamic factor demand model and illustrate how R&D capital affects other factor demand decisions and contributes to total factor productivity. We illustrate how the adjustment costs associated with physical and R&D capital can influence output, productivity growth, and investment decisions. The issue of externalities that are often associated with R&D is analyzed in section 4.3. Again a dynamic factor demand model is formulated to take account of interindustry spillover effects of R&D. Clearly, the spillover effects of R&D on productivity growth of the recipient industries are quite important in calculating the net social rate of return on R&D investment. Similarly, this approach allows incorporation of the effect of public sector investment on private sector productivity growth. This issue is taken up in section 4.4 and the results indicate that TFP growth in the private sector is clearly influenced by public sector investment. These illustrations,among many others, point to the flexibility of the econometric modeling in accounting for diverse sources of total factor productivity growth.

In section 5, the issue of allocative distortions and specification of technical change are addressed. Again the dynamic factor demand model framework is used to assess the sensitivity of estimates of the structure of technology to potentially nonoptimizing factor allocations and to different treatments for exogenous/endogenous technical change. The basic features of this approach are illustrated using firm level data from the U. S. airline industry. The sources of total factor productivity are identified and the nature of technical progress is approximated by the characteristics of the capital stock. We then compare our results to the index number approach that was discussed in section 2. The results establish a ranking of index number constructions based on characteristics of the production structure and the index numbers which approximate technical change.

To account for characteristics of markets in which firms operate, the basic econometric cost model is extended to account for effects of collusive behaviors such as cartel agreements. The relevant issues are discussed in section 6. It is clear that the nature and extent of demand and market structure critically affect productivity growth in particular industries. Section 7 points to some of the measurement issues which pertain to both approaches: the index number and the econometric approach to measurement of total factor productivity. The data requirements are quite stringent and any practitioner in the field must approach this problem with extreme care and perception. The quality of data is the essential ingredient in accurately measuring TFP growth. Section 8 provides some concluding remarks.

## 2 Index Number Approaches to Productivity Measurement

Index number approaches to measuring productivity growth have the advantage of not requiring direct estimation of the underlying technology and therefore, of not requiring econometric specification and estimation of technology. Since they may embody less stringent assumptions than are required by econometric models, they may provide valuable checks on the results of those models. However, for the index number approach to provide meaningful estimates of productivity and productivity growth, fairly strong assumptions about the underlying technology and allocation decisions by the firm must be maintained. Notably, one must often assume an inflexible description of technology, that input and output price ratios form a meaningful description of marginal products ratios and marginal rates of transformation, and/or that all inputs and outputs are measured. Over the last few decades many of these assumptions have been relaxed while still maintaining the advantages of traditional index number approaches. In other instances, the relaxation requires that auxiliary information be incorporated often obtained through an econometric estimation of the underlying technology.

While the techniques described in this section may have different origins, all are tied by the common theme of describing productivity as a ratio of outputs over inputs. This ratio may be *ad hoc* in its origin, describe a ratio of aggregator indices, or be based on cost minimzing behavior.

## 2.1 Classical Residual based Partial and Total Factor Productivity Measurement

Typically, measurements of productivity rely on a ratio of some function of outputs ($Y_i$) to some function of inputs ($X_i$). In the case where there is a single output, factor specific productivity measures are often constructed (often called partial factor productivity indices). A partial factor productivity index ($PFP$)can be constructed for each input and essentially describes the average product of labor ($AP_L$), capital ($AP_K$), etc.

$$PFP_i = AP_i = Y/X_i \tag{1}$$

While commonly used even today, these measures are potentially misleading because what passes for a difference in productivity, may in fact merely represent a different mix of input use. For example, using a more capital intensive (less labor intensive) production technique would increase the labor partial factor productivity index. This would result even if the more capital intensive technique was more costly, and consequently, a method that should be avoided.

To account for changing input mixes, modern index number analyses use some measure of total factor productivity (TFP). In its simplest form, this is a ratio of output to a weighted sum of inputs:

$$\text{TFP} = \frac{Y}{\sum a_i X_i}. \tag{2}$$

Historically, two common ways of assigning weights for this index are to use either an arithmetic or geometric weighted average of inputs. The arithmetic weighted average, due to Kendrick (1961), uses input prices as the weights. The geometric weighted average of the inputs, attributable to Solow (1957), uses input expenditure shares as the weights. Kendrick's approach is based on the linearly homogeneous production function $Y = AX_L X_K (cX_L^\rho + dX_K^\rho)^{-1/\rho}$ for the two inputs, labor ($X_L$) and capital ($X_K$). $A$ is typically referred to as the efficiency parameter and incorporates within it the level of productivity. It is commonly assumed that parameters of the production technology across either firms or time are the same with the exception of this efficiency parameter $A$. Differing values of this efficiency parameter, holding all else constant, map linearly with different magnitudes of output. Consequently, $A$ may be considered to embody the concept of total factor productivity since it can be can be viewed as an aggregate output measure divided by an aggregate input measure. Because the weighted average of the inputs is generally not scale invariant, TFP numbers must be compared to some reference point to be useful. The productivity growth that occurs over two points in time or the efficiency difference between two firms or countries would be measured by the fractional change in $A$, $(\Delta A/A)$ or as the ratio of the TFP measures for the two observations minus 1. Using 0 as the subscript for the reference time period (or firm) and denoting the price of input i to be $w_i$,the productivity growth rate (percentage productivity difference) with Kendrick's approach is:

$$\frac{\Delta \text{TFP}}{\text{TFP}} = \frac{Y_1/Y_0}{(w_L X_{L1} + w_K X_{K1})/(w_L X_{L0} + w_K X_{K0})} - 1. \tag{3}$$

As a notational convention, we will generally use superscripts to denote the reference point and subscripts to denote the reference observation. Thus the left hand side of equation (3) may also be denoted as $TFP_1^0$ and referred to as the total factor productivity of observation 1 relative to observation 0. When firms select inputs so as to minimize costs at prevailing price levels, this can also be stated as:

$$\dot{\text{TFP}} = \frac{Y_1/Y_0}{\alpha_0(X_{L1}/X_{L0}) + (1-\alpha_0)(X_{K1}/X_{K0})} \tag{4}$$

where $\alpha_0$ describes the cost minimizing expenditure share for labor.

Solow's measure is based on the Cobb-Douglas production function with constant returns to scale[4], $Y = AX_L^{\alpha}X_K^{1-\alpha}$ and leads to the TFP measure:

$$\text{TFP} = \frac{Y}{X_L^{\alpha}X_K^{1-\alpha}}. \tag{5}$$

At cost minimizing levels of inputs, the $\alpha$ parameter describes the input expenditure share for labor. The TFP growth rate would be described by:

$$\dot{\text{TFP}} = \frac{dY}{Y} - \left[\alpha\frac{dX_L}{X_L} + (1-\alpha)\frac{dX_K}{X_K}\right]. \tag{6}$$

In applied work, both sets of weights are often inconsistent with the observed data. For example, using Solow's assumptions regarding the functional form of technology, the expenditure shares should be constant over time irrespective of price changes. As long as the changes in inputs and outputs is not too large, both Kendrick's and Solow's measures of TFP growth arrive at similar results (Nadiri, 1970, 1982).

Where multiple outputs exist, TFP can also be described as a ratio of an index number describing aggregate output levels($y_j$) divided by an

[4]Solow dismissed non constant returns to scale as an identification problem

index number describing aggregate input levels($x_i$). As such, they derive many of their properties based the assumptions of the underlying aggregator functions used. Fisher (1927) laid out a number of desirable properties for these index numbers:

1. commodity reversal: the index value does not change if the ordering of the commodities is changed;
2. the identity test: the comparison of a situation in which prices and quantities do not change implies that the index is 1;
3. commensurability test: implies that the index is not sensitive to the units of measurement for quantities or prices;
4. the determinateness test: the index number is not zero, unbounded or indeterminate when individual quantities become zero;
5. the proportionality test: if inputs are all scaled up by some constant, the value of the index is that scaling constant;
6. the point reversal test: $z_f^{f'} = 1/z_{f'}^{f}$; and
7. the circularity (or transitivity) test: $z_f^{f'} = z_f^{f''} z_{f''}^{f'}$.

where $z$ can refer to either input, output, or total factor productivity indices and $f$, $f'$, $f''$, refer to the observations for different firms, time periods, or combinations of the two in panel data applications. Many of these properties are easily achievable, while others are not. Diewert (1976) adds two more desirable properties to Fisher's list. If an index can be derived from some underlying utility, cost, production, revenue, profit or transformation functions, Diewert calls index numbers which satisfy this criteria "exact." If that underlying functional form is flexible (in the sense that it provides a second order local approximation to an arbitrary functional form), an exact index is termed "superlative."[5] One of the most popular index numbers, the Tornqvist-Theil quantity index is superlative in that it can be derived from a translog production function of its components. This input index is:

[5] Diewert's contribution to the theoretical and applied literature involving index number approaches to productivity measurement is remarkable in its breadth and depth. As with Jorgenson and Griliches, it is not possible to provide a comprehensive discussion of Diewert's substantial work in this area. We point the interested reader to Diewert and Nakamura (1993) and to Diewert (1996) for a detailed accounting of his and many others' work on the topic.

$$\ln x_j^k = \frac{1}{2}\sum_{i=1}^{n}(S_{ij} + S_{ik})(\ln X_{ij} - \ln X_{ik}). \quad (7)$$

where $S_{ij}$ and $X_{ij}$ are the expenditure share and quantity, respectively, of subcomponent (i.e. input) $i$ at observation $j$ and $n$ is the number of subcomponents. It is important to note that the input index provides an "exact" (in the sense above) aggregator when firms are cost minimizing. As can be seen from the above formula, it is necessary to establish a point of reference or binary comparison with some other observation (in this case observation $k$) for the construction of the index. This choice of reference point and subsequent normalization of the index is not trivial. By far the most popular Tornqvist-Theil index, the discrete Divisia, is used in time series applications. The index uses information from the previous time period as the reference:

$$\ln x_t^{t-1} = \frac{1}{2}\sum_{i=1}^{n}(S_{it} + S_{it-1})(\ln X_{it} - \ln X_{it-1}). \quad (8)$$

Values of the index are "chained" off of this first observation so that any subsequent observation can be compared to the first one with:

$$\ln x_t^1 = \sum_{s=2}^{t}\ln x_s^{s-1}. \quad (9)$$

The value of the input index is typically normalized to be one in the first time period. Price or output indices can be derived assuming that the underlying utility or revenue function has a translog form. Output indices are similarly defined, using revenue shares rather than expenditure shares for the weights. Further, following Jorgenson and Griliches (1972), a total factor productivity index can be constructed as the difference between log output and log input indices:

$$\ln TFP = \ln y_t^1 - \ln x_t^1. \quad (10)$$

The natural ordering of observations in time means that the same path will always be used regardless which two time periods are being compared. Using the Good-Sickles airline data set for the period 1970I-1993IV (Schmidt and Sickles, 1984; Sickles, 1985; Good, 1985; Sickles et al., 1986; Cornwell et al., 1990; Alam and Sickles, 1995; Wingrove, et al., 1995; Ahn, et al., 1996) we have calculated the Kendrick partial productivity index, the Solow and the Jorgenson and Griliches total factor productivity indexes. These are presented in Figure 1 and indicate a broad consensus among the measures in terms of upturns and trends.

## 2.2 Multilateral Productivity Indices

The Divisia "chaining" approach has severe limitations in some applications. With cross-sectional or panel data there is no obvious way to chain the index and get comparisons between firms since "adjacent" makes little sense in the cross section. Caves, Christensen and Diewert (1982) address this issue of making comparisons in cross sections. Their solution to the problem is to construct a hypothetical firm whose subcomponent expenditure shares are the arithmetic mean expenditure shares for all firms$\left(\overline{S_i}\right)$, and whose subcomponent quantities are the geometric means of the subcomponent quantities across all firms$\left(\overline{\ln X_i}\right)$.Comparisons of individual firm observations (subscripted by $f$ ) are made relative to this reference firm (denoted with the superscript *) using the following index:

$$\ln x_f^* = \frac{1}{2}\sum_{i=1}^{n}(S_{fi} + \overline{S_i})(\ln X_{fi} - \overline{\ln X_i}). \tag{11}$$

This index has clear advantages in cross sectional work. It is transitive in a similar sense that the Divisia index is transitive. The sequence of comparisons is not ambiguous as all comparisons are made indirectly through the hypothetical firm. One undesirable property of this index is that it is now sample dependent. If the sample is extended to include more time periods or more firms, the entire set of index calculations must be revised. This is quite different from "chained" indices such as the Divisia where historical observations remain fixed after the addition of new data. The first application of this approach was in Caves, Christensen and Tretheway (1983) for a set of U.S. airlines.

For a panel data set, both the chaining approach of the Divisia and the hypothetical firm approach of Caves, Christensen and Diewert have appealing features. Chaining allows the information in the cost minimizing shares to be as close as possible to that appropriate for current technology. This is especially important when the cost minimizing shares of subcomponents are changing quickly, or when the time series is long. The hypothetical firm approach provides an unambiguous basis for comparison for observations which have no natural ordering. Good (1985) shows that both of these features can be incorporated into a single index. The primary requirement to maintain transitivity is that the "path" of comparison must not be ambiguous. This can be accomplished by constructing a hypothetical firm for each cross section and then chaining the hypothetical firms together over time. The resulting input quantity index describing the aggregate input at time $t$ for firm $f$ relative to the hypothetical firm at the base time period is:

$$\begin{aligned}\ln x^{*1}_{ft} &= \frac{1}{2}\sum_{i=1}^{n}(S_{fit}+\overline{S_{it}})(\ln X_{fit}-\overline{\ln X_{it}}) \\ &+\sum_{s=2}^{t}\frac{1}{2}\sum_{i=1}^{n}(\overline{S_{is}}+\overline{S_{i,s-1}})(\overline{\ln X_{is}}-\overline{\ln X_{i,s-1}}) \qquad (12)\end{aligned}$$

where the bar indicates an average over the relevant quantity (e.g., $\overline{\ln X_{i,s}}$ indicates the natural log of the geometric average quantity for input $i$ across all firms at time $s$). The terms in the first sum describe the difference between the actual firm $f$ and the hypothetical firm at time $t$ while the terms in the second sum chain together the hypothetical firms back to the base time period. A measure of TFP relative to the hypothetical firm in the base time period can be constructed as in equation (12) above:

$$\begin{aligned}\ln \mathrm{TFP}_{ft} &= \left[\frac{1}{2}\sum_{j=1}^{m}(R_{fjt}+\overline{R_{jt}})(\ln Y_{fjt}-\overline{\ln Y_{jt}})\right. \\ &\left.+\sum_{s=2}^{t}\frac{1}{2}\sum_{j=1}^{m}(\overline{R_{js}}+\overline{R_{j,s-1}})(\overline{\ln Y_{js}}-\overline{\ln Y_{j,s-1}})\right] \\ &-\left[\frac{1}{2}\sum_{i=1}^{n}(S_{fit}+\overline{S_{it}})(\ln X_{fit}-\overline{\ln X_{it}})\right. \\ &\left.+\sum_{s=2}^{t}\frac{1}{2}\sum_{i=1}^{n}(\overline{S_{is}}+\overline{S_{i,s-1}})(\overline{\ln X_{is}}-\overline{\ln X_{i,s-1}})\right], \qquad (13)\end{aligned}$$

where $R_{fjt}$ is the revenue share of output $j$ at firm $f$ in period $t$ and $m$ is the number of outputs. This index has been constructed for the Good-Sickles airline data. Average industry TFP as well as the max and min levels within the industry are presented in Figure 2.

This chained multilateral total factor productivity index also provides a decomposition of TFP change into two components that exploit between and within variations available in panel data for firms. When describing the change in TFP between firm $f$ at time $t$ and $t'$, the first set of terms:

$$\frac{1}{2}\sum_{j=1}^{m}\Big[(R_{fjt'}+\overline{R_{jt'}})(\ln Y_{fjt'}-\overline{\ln Y_{jt'}})$$
$$-(R_{fjt}+\overline{R_{jt}})(\ln Y_{fjt}-\overline{\ln Y_{jt}})\Big]$$
$$-\frac{1}{2}\sum_{i=1}^{n}\Big[(S_{fit'}+\overline{S_{it'}})(\ln X_{fit'}-\overline{\ln X_{it'}})$$
$$-(S_{fit}+\overline{S_{it}})(\ln X_{fit}-\overline{\ln X_{it}})\Big] \tag{14}$$

describes the change in TFP relative to that of the hypothetical or representative firm (catching up or falling behind or productive efficiency) while the remainder

$$\sum_{s=t}^{t'}\frac{1}{2}\sum_{j=1}^{m}(\overline{R_{js}}+\overline{R_{j,s-1}})(\overline{\ln Y_{js}}-\overline{\ln Y_{j,s-1}})$$
$$-\sum_{s=t}^{t'}\frac{1}{2}\sum_{i=1}^{n}(\overline{S_{is}}+\overline{S_{i,s-1}})(\overline{\ln X_{is}}-\overline{\ln X_{i,s-1}}) \tag{15}$$

describes the change in productivity for the typical firm (technological innovation or technological change).

Similar TFP indices based on different functional form assumptions are also possible for panel data situations using Diewert's results. These generalized indexes are based on aggregator functions which map a set of values, say inputs $X_{fi}$, into an index, here $x_f$. For example, a more general form of this index is provided by the quadratic mean of order $r$ aggregator function:

$$f(x_f, r)=\left[\sum_{i=1}^{n}\sum_{k=1}^{n}b_{ik}X_i^{r/2}X_k^{r/2}\right]^{1/r}. \tag{16}$$

This form nests several popular functional forms: the generalized Leontief or Diewert ($r=1$), the quadratic ($r=2$) and the translog ($r\rightarrow 0$). When the $b_{ik}=0$ for all $i\neq k$, this form becomes the CES. If both $b_{ik}=0$, *for all* $i\neq k$, and $r\rightarrow 0$ it becomes the Cobb-Douglas. When the local technology is best represented by a quadratic mean of order $r$, the chained multilateral total factor productivity index is given by:

$$\mathrm{TFP}_{ft} = \left[\frac{\sum_{j=1}^{m}R_{fjt}(Y_{fjt}/\overline{Y_{jt}})^{r/2}}{\sum_{j=1}^{m}\overline{R_{jt}}(\overline{Y_{jt}}/Y_{fjt})^{r/2}}\right]^{1/r}\left[\frac{\sum_{i=1}^{n}S_{fit}(X_{fit}/\overline{X_{it}})^{r/2}}{\sum_{i=1}^{n}\overline{S_{it}}(\overline{X_{it}}/X_{fit})^{r/2}}\right]^{-1/r}$$

$$\cdot \prod_{s=2}^{t} \left\{ \left[ \frac{\sum_{j=1}^{m} R_{js}(Y_{js}/\overline{Y_{j,s-1}})^{r/2}}{\sum_{j=1}^{m} \overline{R_{j,s-1}}(\overline{Y_{j,s-1}}/\overline{Y_{js}})^{r/2}} \right]^{1/r} \cdot \left[ \frac{\sum_{i=1}^{n} \overline{S_{is}}(\overline{X_{is}}/\overline{X_{i,s-1}})^{r/2}}{\sum_{i=1}^{n} \overline{S_{i,s-1}}(\overline{X_{i,s-1}}/\overline{X_{is}})^{r/2}} \right]^{-1/r} \right\} \tag{17}$$

The major advantage of these index number procedures is that they do not require any estimation of the parameters in the production technology. By assuming cost minimization and/or profit maximizing behavior on the part of the firm, these parameters become embedded in the observed expenditure and revenue share information. An important application of the index number approach has been in the growth accounting literature (Solow, 1957; Denison, 1967, 1979; Kendrick, 1973, Jorgensen and Griliches, 1967; and surveyed in Nadiri, 1970). This approach begins with an aggregate production function and attempts to allocate the growth rate of national income to different sources: growth rates in individual factors of production and a residual interpreted as technological change. In particular, if equation (6) is readjusted so that the growth in aggregate output (income) is placed on the left hand side, it can be allocated to the growth rates of labor and capital, weighted by shares, and the TFP growth residual. These early works varied greatly in their assumptions regarding returns to scale, the level of capital utilization, measurement of capital as a stock or flow, the extent of input adjustments for quality differences, explicit treatments of government sponsored research and development, the embodiment of technological change, and both short and long run optimzation on the part of firms. Not surprisingly, the magnitude of the total factor productivity residual tended to be quite sensitive to these assumptions. For example, if returns to scale were not constant, then equation (6) would either over or understate the level of total factor productivity growth.[6] Recent work has attempted to relax the assumptions in these early studies on several fronts. First, it tends to focus on firm level rather than aggregate production. In addition, several of the other assumptions have been relaxed by estimating their influence directly, or by allowing for less restrictive functional forms. This problem is addressed in the next section within the context of econometric models. Second, these indices assume long run optimization, or that the capital stock is at right level. A problem that is considered in section 4. Third, if firms are constrained cost minimizers, perhaps due to regulatory constraints, quantity and expenditure share information may no longer be

[6]See Solow (1957) on this subject.

optimal in the traditional sense, particularly if the regulatory constraint is changing. This problem is addressed, within the econometric approach, in section 3.2. Fourth, existence of nonmeasured, nonmarket factors of production, e.g. pollution, can make these indexes uninformative, a problem that could be handled more adequately using the econometric approach as noted in of section 5.

# 3 Static Factor Demands

## 3.1 TFP Growth Decompositions

Static factor demand models can be used to measure the effect of economies of scale on total factor productivity growth. As was noted, TFP is basically a measure of output per unit of total factor input. Total factor input is a weighted average of inputs where the weights depend on the underlying production function. If there are increasing returns to scale, part of the growth in TFP will reflect changes in the scale of operations while the remainder can be ascribed to a shift in the production frontier itself. If there were constant returns to scale, the change in TFP would be identical to the technological shift (assuming other factors are exhaustively and accurately measured). To illustrate the role of economies of scale and technical change in the decomposition of TFP growth consider the translog cost function

$$\begin{aligned} \ln C &= \alpha_0 + \alpha_Y \ln Y + \sum_i \alpha_i \ln w_i + \frac{1}{2}\alpha_{YY}(\ln Y)^2 \\ &+ \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln w_i \ln w_j + \sum_i \gamma_{iY} \ln w_i \ln Y \\ &+ \sum_i \theta_i \ln w_i t + \theta_Y \ln Y t + \beta_t t + \frac{1}{2}\beta_{tt} t^2 \end{aligned} \tag{18}$$

where $i, j = 1, ..., N$ index the $N$ different inputs; $Y$ is the level of output used; $t$ is an index of time. All variables are defined around some expansion point. A set of cost share equations associated with the translog cost function (18) is implied by duality theory. Also, there are several parametric restrictions such as linear homogeneity in factor prices and symmetry conditions which must be met in estimating (18).[7] An important economic measure is the output cost elasticity, $\eta_c$,which measures the response of cost

[7]See Berndt (1991) and Greene (1993) for a more detailed discussion of translog systems and their empirical implementation.

to an increase in output. $\eta_c$can be obtained by differentiating (18) with respect to output, $Y$. That is,

$$\eta_c = (\alpha_Y + \alpha_{YY} \ln Y + \sum_i \gamma_{iY} \ln w_i + \theta_Y t)^{-1}$$

which will vary with relative price and the levels of output and technology. The inverse of the cost elasticity, $\eta_c$, measures the scale elasticity, SE.

Define the rate of growth of TFP as

$$\dot{\text{TFP}} = \dot{Y} - \dot{F}$$

where $\dot{F}$ is the cost share weighted average of growth rate of inputs: $\dot{F}= \sum_i (w_i X_i / C)\ \dot{X}_i$; $\sum_i w_i X_i = C$. To take account of shifts in technology on equilibrium output we can derive the expression

$$\dot{p} = -\dot{T} + (\eta_c - 1)\dot{Y}$$

where $\eta_c$ is the output cost elasticity, $\dot{p}$ is the change in output price and $\dot{T}$ is the rate of autonomous technical change (Nadiri and Schankerman, 1981, pp. 236-241). This expression captures the effect of technology on equilibrium output which comes about due to the output expansion effects of technology and the indirect effect due to the inward shift of isoquants from technical changes. The growth of output demand can be stated as $\dot{Y} = -\eta_r \dot{p}$, where $\eta_r$ is the output price elasticity. Therefore the relation between equilibrium output and technical change, $\dot{T}$, can be stated as $\dot{Y}= \psi\dot{T}$ where $\psi = \eta_r / [1 - \eta_r(1 - \eta_c)]$. The final decomposition of $\dot{\text{TFP}}$ can be formalized as:

$$\dot{\text{TFP}} = \eta_c^{-1}(1 - \eta_c)\ \dot{F}_d - (1 - \eta_c)\psi \sum_i S_i\ \dot{w}_i + (1 - \eta_c)(\psi - 1)\dot{T} - \dot{T}. \quad (19)$$

where $\dot{F}_d$ is the exogenous shift in demand. $\dot{F}_d$ is calculated from the identity

$$\dot{F} \equiv \dot{F}_T + \dot{F}_f + \dot{F}\ d$$

where total factor input growth ($\dot{F}$ ) consists of parts induced by technical changes ($\dot{F}_T$), factor price changes ($\dot{F}_f$), and exogenous shifts in demand ($\dot{F}_d$). The first term on the right of (19) is the effect of exogenous demand; the second term depicts the effect of changes in real factor prices; the third term captures the indirect effect of technical change and the direct effect of technical change is captured by the last term. The net scale effect is the sum of the first two effects while the total effect of technical change in the sum of the last two terms in (19).

Variations of this approach have been used in a number of empirical studies (see, Nadiri, 1970, and Morrison, 1992 for references) to delineate the contribution of economies of scale and shifts in the production function due to technical change. Sickles (1985) utilized a structural model in which technical change was further decomposed into factor specific contributions of capital, labor, energy, and materials in his study of the technology of airline service, based in part on the model of Nadiri and Schankerman (1981). The Sickles study also explored the implications of multivariate random effects in systems of translog cost, share, and TFP growth equations. As an illustration consider the application of the Nadiri and Schankerman model to the predivestiture Bell System. Table 1 provides the results of their decomposition.

These results suggest that the direct effect of technical change ($\dot{T}$ which is independent of $\eta_d$, the elasticity of demand) accounts for about a third (30.6%) of TFP growth over the sample period. There is a distinct trend over the sub periods, however, with contributions rising from about 14% during 1947–1957 to 44% during 1968–1976. The indirect effect of technology is positive and about 10% as large as the direct effect over the whole period. However, the size and even the direction of the indirect contributions of technology are sensitive to the magnitude of the elasticity of demand. The rationale for this is that where the magnitude of $\eta_d$ is small, the output expansion effect of technical change will be highly restricted so the reduction in input use due to the inward shift of the isoquants dominates.

As expected, the rise in real factor prices over time has been a drag on TFP growth. The magnitude of the effect is sensitive to the demand elasticity; for the whole period the real price effect (with $\eta_d = -0.8$) is almost 18%, that is the rate of growth of TFP during the period 1947–1976 would have been increased by nearly a percentage point if the contractionary effect of factor prices had been absent.

Shifts in the demand curve appear to be the major source of TFP growth. The measured contribution of demand shifts does not depend on the assumption about the elasticity of demand. During the first period the negative effect of factor prices swamps the contribution of technical change, so that the measured contribution of shifts in demand exceeds 100%. Although this seems implausible at first glance, this finding simply says that had demand remained stationary, TFP would have declined. The contribution of demand to TFP growth declines steadily overtime, however, to about 65% during the last sub-period.

The results indicate that the net scale effect, which is the sum of price and exogenous demand effects, is substantial. Empirically the net contribution of economies of scale varies inversely with the elasticity of demand. Over the entire period, scale economies account for 67% of the growth of TFP, but it is not constant over time. The relative contribution of scale economies to growth in TFP declines steadily. Note that the average TFP growth rate steadily increases during this period in this industry. Scale economies still remain an important source of TFP growth, accounting for 50% of total TFP during 1968–1976 but their relative importance has eroded over time.

These results illustrate the potentials for exploiting duality theory to explore the production structure and the sources of growth of total factor productivity. The evolution of output demand and the structure of costs identifies the different effects of demand shifts, scale of operations, and technology on TFP growth. Thus, econometric models of the kind described above are a natural complement to the index number approach described in Section 2.

A similar decomposition based on data for the U.S. total manufacturing sector and its two component industries, total durables and nondurables, over the period 1958–1978 confirm the same conclusion (Nadiri and Schankerman, 1981). The growth in TFP declined sharply throughout the entire period. In percentage terms, $\dot{TFP}$ declined by about 45 percent in manufacturing, 60 percent in durables, and 30 percent in nondurables between each pair of subperiods. The relative contributions of the different factors vary among industry groups and between subperiods. Real factor prices contribute only modestly to the deceleration in $\dot{TFP}$ from 1958–65 to 1965–73, except in nondurables. Factor prices contribute more to the decline in $\dot{TFP}$ from 1965–73 to 1973–78. These differences may be partly spurious, and simply reflect the inclusion of the petroleum industry in nondurables. If durables are a good guide, the factor-price effect has been modest.

The slowdown in demand growth is an important factor in the retardation of $\dot{TFP}$ in all industry groups. About 10–20 percent of the decline in $\dot{TFP}$ from 1958–65 to 1965–73 is accounted for by the demand effect, but this rises dramatically to more than 50 percent from 1965–73 to 1973–78. Factor prices and demand together (total scale effect) account for most, and in total manufacturing more than all, of the deceleration in $\dot{TFP}$. The evidence points to the scale effect, and mainly demand deceleration, as a major factor behind the decline in $\dot{TFP}$ from 1965–73 to 1973–78.

The decline in the growth of the R&D stock contributes modestly to the slowdown in $\dot{TFP}$ from 1958–65 to 1965–73, less than 10 percent. The same is true for nondurables from 1965–73 to 1973–78, but in durables and total manufacturing R&D plays a very significant role, accounting for nearly a quarter of the retardation in $\dot{TFP}$.[8]

The technical change effect is computed residually and therefore captures all contributory factors not accounted for by the model (including measurement error). This residual accounts for the bulk of the decline in $\dot{TFP}$ from 1958–65 to 1965–73 (about 75 percent in manufacturing and durables and 45 percent in nondurables), but very little from 1965–73 to 1973–78. In fact, the negative contribution in manufacturing and nondurables suggests that residual technical change accelerated at the same time that $\dot{TFP}$ declined.

The conclusion of these studies and recent ones suggest that deceleration of demand has been the major cause of the slowdown in TFP growth. Relative input prices and to some extend R&D investment have also contributed to the productivity slowdown but the policies that were responsible for the slowdown of aggregate demand may have played a significant role in the slowdown of $\dot{TFP}$ in the U.S. economy in the period 1973 to 1985. Thus understanding the forces behind the slowdown in demand becomes critically important in order to formulate policies to stimulate total factor productivity growth.

## 3.2 Factor Demands and Regulatory Distortions

When an industry is regulated, the regulatory body effectively takes the place of the market. This generates two distinct results. First, since efficiency is only one of several goals of regulation, the equilibrium allocation of resources will not be Pareto optimal. One would then expect deregulation to remove the disincentives for technical inefficiency. To investigate this hypothesis, one can model firm specific temporal misapplication of technology using the cost function. A measure of relative technical efficiency can then be constructed from the cost function. The behavior of this measure can then be examined to see if it supports expectations. Second, regulation effectively introduces a new goal for firms in the industry: conforming to guidelines. Thus, firms are geared to respond to the regulators' signals in addition to those of the markets. Put another way, regulation reduces the

[8]For a sample of the extensive literature on the relationship between output and productivity growth on R&D investment and on determinants of R&D expenditure see Baumol and Wolff (1983), Bernstein and Nadiri (1989a), Cuneo and Mairesse (1984), Englander et al. (1988), Griliches (1979,1986), Grilliches and Lichtenberg (1984), Griliches and Mairesse (1990), Mansfield (1988), Mohnen (1990a,c), Mohnen, et al. (1986), Nadiri (1980), Nadiri and Bitros (1980), Nadiri and Prucha (1990), Nadiri and Schankerman (1981), Patel and Soete (1988), Scherer (1984), Terleckyj (1974).

industry's ability to adjust to changes in the price of inputs, demand for output and so on. An inflexible industry structure would be reflected by inelastic factor demand curves relative to an unregulated industry. We focus below on the own price elasticity of labor demand and examine its elasticity before and after a regulatory epoch.

The form of regulation imposed on our empirical archetype—the airline industry whose formal deregulation began in 1978—makes a cost approach more revealing than that of profit maximization. Since efficient carriers could not expand or cut fares, inefficient carriers were often protected. In many cases, new routes were awarded to unprofitable airlines to strengthen their finances. Restrictions on entry ensured existing firms protection from competition from more efficient new carriers. Also, the protective policies of the regulatory body essentially eliminated the risk of financial ruin for inefficient airlines. Consequently, profits are not a very informative indicator of firms' decisions. Regulation clearly limited the incentives for carriers to reduce costs. It is this distortionary influence on the allocative process that will be investigated.

Given the nature of the regulations that governed the airline industry, it would be expected that workers in the industry were receiving economic rents. Subsequently, it would be anticipated that deregulation would reduce airline employees earnings. Empirical studies provide only limited support for the hypothesis that regulation increases earnings above competitive levels.

Hendricks, *et al.* (1980) found that a slight majority of regulated airline occupations had significantly higher earnings than comparable occupations in non-regulated industries. However, after controlling for industry and personal characteristics, no significant difference in earnings was found. Card (1986) found little change in airline mechanics wage rates for the first five years of deregulation. He did note a significant employment shift from the large to the small carriers. Other transportation regulation studies have shown some positive effects of regulation on earnings (Hendricks, 1977; Hirsch, 1988; Long and Link, 1983; Rose, 1987). Thus the results of empirical tests of regulatory effects on earnings have been ambiguous.

These ambiguous results may reflect institutional arrangements that evolved over forty years of regulation and did not greatly change in the first few years of deregulation (Hendricks *et al.*, 1980). Industry unionization levels, for example, have not changed dramatically. This is because the non-union low wage carriers that have entered the industry represent less that 10% of the market. So the effects of these non-union entrants on industry unionization levels has been small (Capelli, 1985). Also, industry concentration levels have remained high.

The concentration ratio of the top five firms in terms of revenue share (Eastern, United, Delta, TWA, and American) for the airline industry for the period 1970Q1 - 1985Q4 is presented in Figure 3. It is worth noting that the same firms comprise the top five for the whole period. At the beginning of 1970, the top five firms accounted for about 80% of the total revenue of the airline industry. While the importance of these firms declined through the 1970's, this trend was reversed in 1982 (with two carriers dropping out in that year). The concentration ratio of the top five firms stayed around 0.74 until 1985 when it fell to about 0.72. These figures are likely to overstate the degree of market concentration in the post deregulation period. This is due to the fact that new entrants were not included in the sample because they consistently misreported data. However, most of the new entrants were interstate carriers, and did not account for more than 10% of the market.

Estimates from a long run static translog cost and share system for the period 1970I-1985IV reveal some interesting results as they relate to factor demand, TFP growth (normalized about unity) and the effects of regulation. In Figure 4 we have decomposed the estimated TFP growth using a variant of (19) into the pure technical change component and a residual component which captures changes in TFP due to such factors as regulatory and market structure effects. We have also overlaid a plot of total employment in the airline industry (normalized at unity in the median period) which reveals its business cycle behavior. The economic downturns in 1972 and 1982 are apparent. The recession in the early eighties was exacerbated by the air traffic controllers strike and its aftermath. Recovery of employment in this industry did not take place till 1984, helped in part by the deregulation of fares in January 1983 and the resulting growth in demand for passenger service due to reduced fares.

# 4 Dynamic Models of Factor Demand

Many different models of firms' choice of factors of production have been examined in the literature. One category is static models which attempt to consistently account for substitution among the factors, while at the same time trying to avoid imposing strong restrictions on the production structure. Models like these often assume a very general functional form for the underlying production technology (an example of such a model is Berndt and Wood, 1975; Christensen and Greene, 1976). A second category would consist of dynamic models that incorporate the costs of adjusting the factors of production that are fixed in the short-run, the so-called "quasi-fixed" factors. Although these models have often be estimated with data aggregated over firms (one good example which also contains an assumption of rational expectations is Pindyck and Rotemberg, 1983b), it is often the case that the substantial micro structure utilzed in such models requires that firm level time series, or panel data, be available to estimate the structural parameters (for an example, see Wolfson, 1993).

In this section we first discuss the generic dynamic factor demand model, implement it using a particular specification due to Pindyck and Rotemberg (1983b) and discuss its empirical implications using U. S. airline panel data. We next discuss how the dynamic spillover effects of R & D capital investment can impact productivity growth. We pursue the issue of spillovers further in terms of public capital expenditures. The section on dynamic models of factor demand ends with a discussion of productivity growth and endogenous capital depreciation.

## 4.1 General Framework of Dynamic Factor Demand Models

Assume that the firm at time $t$ chooses $J$ variable factors of production. Input quantities and prices are given by the two vectors $X_t = (X_{it})$ and $w_t = (w_{it})$, respectively, where $N - J$ inputs are assumed to be quasi-fixed factors whose quantities are given by the vector $X_{N-J,t} = (X_{ft})$. These inputs are used by the firm to produce a single output, $Y_t$.[9]

The firm's technology can be represented by a short-run or restricted cost function $C_t$. A restricted cost function specifies the minimum expenditure on variable (flexible) factors necessary to produce $Y_t$, given the levels of the quasi-fixed factors $X_{N-J,t}$, and the variable factor prices $w_{vt}$. The restricted cost function is given by

$$C_t(Y_t, w_{vt}, X_{N-J,t}, t), \tag{20}$$

where $C$ is increasing and concave[10] in $w_v$, i.e. $C_{w_v} > 0$ and $C_{w_v w_v} < 0$, but decreasing and convex in $X_{N-J}$, $C_{X_{N-J}} < 0$ and $C_{X_{N-J}X_{N-J}} > 0$ . The inclusion of $t$ captures independent technological progress.

The firm is assumed to incur (nonlinear) costs when it adjusts the quasi-fixed factors of production, and these adjustment costs are assumed to be convex and external to the firm. Adjustment costs will be represented in nominal terms by

$$p_t h(\Delta X_{N-J,t}) \tag{21}$$

[9] This section is based on Pindyck and Rotemberg (1983a).

[10] Only quasi-concavity is required (Berndt, 1991).

where $p_t$ is the price of output at time $t$ and $\Delta X_{N-J,t} = X_{N-J,t} - X_{N-J,t-1}$ , the change in levels of quasi-fixed factors. The firm faces direct expenditures for its use of quasi-fixed inputs, and because of tax and financing considerations these expenditures are allowed to be spread over time. Outlays (net of adjustment costs) at time $t$, $H_t$, are then assumed to be a function of current and past values of the quasi-fixed factors

$$H_t = H(X_{N-J,t}, X_{N-J,t-1}, ...., X_{N-J,t-(t-1)}). \tag{22}$$

Assume that the firm maximizes expected present discounted value of profits, which implies that the firm minimizes expected present discounted value of costs. Thus at time t the firm chooses a path for the vector of quasi-fixed factors, $X_{N-J,t}$, in order to minimize

$$\min_{\mathbf{X}_{N-J}} \mathcal{E}_\tau \sum_{t=\tau}^{\infty} D_{\tau,t}[C_t + p_t h(\Delta X_{N-J,t}) + H_t] \tag{23}$$

where $\mathcal{E}_\tau$ is the expectation conditional on all available information at time $\tau$, and $D_{\tau,t} = \frac{1}{1+r_{\tau,t}}$ is the discount factor applied at time $\tau$ for costs incurred at time $t$, and $r_{\tau,t}$ is the real interest rate between times $\tau$ and $t$. Setting the first-order conditions of the minimization problem equal to zero then yields Euler equations for $i = 1, 2, ..., m$. If we let $D_{t,t} = 1$, then the Euler equations are

$$\begin{aligned} 0 \quad = \quad & \mathcal{E}_\tau\{\frac{\partial C_t}{\partial X_{ft}} + p_t \frac{\partial h(\Delta X_{N-J,t})}{\partial X_{ft}} \\ & -p_{t+1} D_{t,t+1} \frac{\partial h(\Delta X_{N-J,t})}{\partial X_{ft}} + \sum_{j=1}^{T} D_{t,t+j} \frac{\partial H_{t+j}}{\partial X_{ft}}\} \end{aligned} \tag{24}$$

These $m$ Euler equations state that the net change in expected discounted costs from "hiring" one more unit of $X_f$ at time $t$ is zero. The net change is the sum of increases in variable costs, the extra cost of adjustment at t, and the expected discounted value of the extra expenditures associated with holding one more unit of $X_i$ , minus the expected discounted savings from future costs of adjustment (i.e. since an adjustment is done today the expected future adjustment cost will be lower). One can also obtain additional first-order conditions from Shepherd's lemma. These take the form of static demand equations for the flexible factors of production

$$X_{it} = \frac{\partial C_t}{\partial w_{vt}}, \qquad i = 1, 2, ..., J. \tag{25}$$

To conclude, our estimation problem has now been reduced to simultaneously estimating the $m+n+1$ equations given by (23), (24), and (25).

We next lay out a specific model that can be used for estimating the factor demands dynamically for the airline industry.[11] To begin with we need some simplifying assumptions. Assume that the industry is competitive in its factor markets, i.e. the firms in the industry take input prices as given. Consider a representative firm facing a certain technology, which is represented by a restricted cost function. Alternatively we could think of many firms whose *aggregate* technology is represented by the restricted cost function.[12] Assume a stochastic environment in which firms have rational expectations. The firms, represented by the representative firm, then maximize the expected sum of discounted profits, which is equivalent to minimizing the expected sum of discounted costs. Firms minimize costs by choosing optimal levels of four factors of production: labor $X_L$, capital $X_K$, energy $X_E$, and materials $X_M$. Denote the real prices of the factors as $w_L$,$w_K$ ,$w_E$ , and $w_M$, respectively. The factor prices are allowed to evolve stochastically over time. In this illustration energy and materials are treated as flexible factors, and labor and capital as quasi-fixed factors.[13] The production technology (i.e. the restricted cost function) is specified conditional at time $t$ on $X_{Kt}$, $X_{Lt}$, and output $Y_t$. The minimum level of real expenditures on the two flexible inputs, energy and materials, is then given by

$$C(Y_t, w_{Et}, w_{Mt}, X_{Kt}, X_{Lt}, t) \tag{26}$$

where C satisfy the curvature requirements given above. Changing the quasi-fixed factors of production is assumed to result in costs of adjustment, which are represented by the convex symmetric functions $C_1(I_t)$ , and $C_2(H_t)$ , where $I$ is the part of investment subject to adjustment costs, and $L$ is the net labor hirings

$$I_t = X_{Kt} - (1-\delta)X_{Kt-1} \tag{27}$$

[11]The model is based on Pindyck and Rotemberg's (1983a) study of the U.S. Manufacturing between 1947 and 1974 and was recently applied to the airline industry by Hultberg (1994).

[12]Here we ignore all the problems associated with consistent aggregation, in particular the aggregation would *not* be equivalent to the summing up of many firms each of which has the given technology. Strictly speaking such aggregation would only be applicable when each technology takes the Gorman polar form. However, Lucas and Prescott (as quoted in Pindyck and Rotemberg, 1983a) showed that if all firms are competitive, then the approach would be justified since when competitive firms maximize profits (or equivalently, minimize costs) they act as if a central planner maximized welfare.

[13]Pindyck and Rotemberg (1983a) found that labor might be more appropriately viewed as a flexible factor. We will test this for the airline industry.

$$L_t = X_{Lt} - X_{Lt-1} \tag{28}$$

where $\delta$ measures the extent of investments which incur adjustment costs.[14]

The factor demands are then given by the solution to

$$\min_{X_K, X_L} \mathcal{E}_t \sum_{\tau=t}^{\infty} D_{t,\tau} [C(Y_\tau, w_{E\tau}, w_{M\tau}, X_{K\tau}, X_{L\tau}) \tag{29}$$

$$+ w_{K\tau} X_{K\tau} + w_{L\tau} X_{L\tau} + C_1(I_\tau) + C_2(L_\tau)] \tag{30}$$

subject to (27) and (28).

The expectation is taken over all future values of $w_{E\tau}$, $w_{M\tau}$, $w_{K\tau}$, $w_{L\tau}$, and $Y$, all of which are treated as being stochastic. $Y$ is not considered to be predetermined, but the path of $Y$ depends on the realization of $w_E$, $w_M$, $w_K$ and $w_L$ as firms minimize costs. First-order conditions for the minimization problem then are

$$X_{Et} = \frac{\partial C}{\partial w_{Et}} \tag{31}$$

$$X_{Mt} = \frac{\partial C}{\partial w_{Mt}} \tag{32}$$

$$\frac{\partial C}{\partial X_{Kt}} + w_{Kt} + \frac{\partial C_1(I_t)}{\partial X_{Kt}} + \mathcal{E}_t \left[ D_{t,t+1} \frac{\partial C_1(I_{t+1})}{\partial X_{Kt}} \right] = 0 \tag{33}$$

$$\frac{\partial C}{\partial X_{Lt}} + w_{Lt} + \frac{\partial C_2(H_t)}{\partial X_{Lt}} + \mathcal{E}_t \left[ D_{t,t+1} \frac{\partial C_2(H_{t+1})}{\partial X_{Lt}} \right] = 0 \tag{34}$$

Using the equations for the adjustment costs given by (27) and (28) the last two first-order equations can be rewritten as

$$\begin{aligned} 0 &= \frac{\partial C}{\partial X_{Kt}} + w_{Kt} + \frac{\partial C_1(X_{Kt} - (1-\delta)X_{Kt-1})}{\partial X_{Kt}} \\ &\quad + \mathcal{E}_t \left[ D_{t,t+1} \frac{\partial C_1(X_{Kt+1} - (1-\delta)X_{Kt})}{\partial X_{Kt}} \right] \end{aligned} \tag{35}$$

[14] Pindyck and Rotemberg (1983a) point out that if $\delta$ is equal to the depreciation rate the capital adjustment costs depend on gross investment, while if $\delta$ is zero cost is a function of net investment.

$$0 = \frac{\partial C}{\partial X_{Lt}} + w_{Lt} + \frac{\partial C_2(X_{Lt} - X_{Lt-1})}{\partial X_{Lt}} + \mathcal{E}_t \left[ D_{t,t+1} \frac{\partial C_2(X_{Lt+1} - X_{Lt})}{\partial X_{Lt}} \right] \quad (36)$$

where equations (31) and (32) are obtained from Shepherd's lemma and from the fact that $C$ gives the minimum variable cost $w_{Et}X_{Et} + w_{Mt}X_{Mt}$. Equations (35) and (36) are the Euler equations, which show the expected evolution of the quasi-fixed factors. (35) states that the net effect on expected profits from the last unit of capital is zero. The net effect is made up of variable cost savings $\frac{\partial C}{\partial X_{Kt}}$, a rental cost on the unit of capital $w_{Kt}$, a current adjustment cost $\frac{\partial C_1}{\partial X_{Kt}}$, and an expected discounted saving in future adjustment costs equal to $D_{t,t+1}\frac{\partial C_1(I_{t+1})}{\partial X_{Kt}}$. Similarly, equation (36) says that the net effect on expected profits from the marginal unit of labor is equal to zero, and is made up of a variable cost saving, a real wage rate cost, a current adjustment cost, and savings of future expected adjustment costs.

To close the model, transversality conditions are needed. These express the notion that when the representative firm looks to the future the quantities of quasi-fixed factors that it expects to hold should not differ from the quantities it would want to hold in the absence of adjustment costs. The transversality conditions then are

$$\lim_{\tau \to \infty} \mathcal{E}_t D_{t,\tau} \left[ \frac{\partial C}{\partial X_{K\tau}} + w_{K\tau} + \frac{\partial C_1(X_{K\tau} - (1-\delta)X_{K\tau-1})}{\partial X_{K\tau}} \right] = 0 \quad (37)$$

$$\lim_{\tau \to \infty} \mathcal{E}_t D_{t,\tau} \left[ \frac{\partial C}{\partial X_{L\tau}} + w_{L\tau} + \frac{\partial C_2(X_{L\tau} - X_{L\tau-1})}{\partial X_{L\tau}} \right] = 0 \quad (38)$$

Finding the full solution to equations (29), (31), (32), (35), (36), (37) and (38) would give a path for the firm's factors of production which depend on the current state variables $(Y_t, w_{Et}, w_{Mt}, X_{Kt}, X_{Lt})$ as well as expected future values of prices and output. However, closed-form solutions are not in general available. One typically simplifies the problem by assuming that the cost function, $C$, and the adjustment cost functions, $C_1$ and $C_2$, are quadratic.[15] The simplification stems from the fact that with a quadratic system the Euler equations become linear in the state variables. The adjustment cost functions become[16]

$$C_1(I_t) = \frac{\beta_1 I_t^2}{2} \quad (39)$$

[15]Pindyck and Rotemberg (1983b) point out that assuming quadratic adjustment costs imposes an implicit assumption about the firm's expectations, namely that they are static with regards to the evolution of input and output prices.

[16]We neglect the possibility of cross-effects where changes in one factor of production affect the costs of adjusting the other (quasi-fixed) factor.

$$C_2(L_t) = \frac{\beta_2 L_t^2}{2}. \quad (40)$$

The restricted cost function can be specified as translog of the form

$$\begin{aligned}
\ln C_{it} \;=\;& \alpha_0 + \alpha_1 \ln w_{Mit} + \alpha_2 \ln(\frac{w_{Eit}}{w_{Mit}}) + \alpha_3 \ln X_{Kit} + \alpha_4 \ln X_{Lit} \\
&+\alpha_5 \ln Y_{it} + \lambda t + \frac{1}{2}\gamma_{11}(\ln(\frac{w_{Eit}}{w_{Mit}}))^2 + \gamma_{13} \ln(\frac{w_{Eit}}{w_{Mit}}) \ln X_{Kit} \\
&+\gamma_{14} \ln(\frac{w_{Eit}}{w_{Mit}}) \ln X_{Lit} + \gamma_{15} \ln(\frac{w_{Eit}}{w_{Mit}}) \ln Y_{it} + \frac{1}{2}\gamma_{33}(\ln X_{Kit})^2 \\
&+\gamma_{34} \ln X_{Kit} \ln X_{Lit} + \gamma_{35} \ln X_{Kit} \ln Y_{it} + \frac{1}{2}\gamma_{44}\ (\ln X_{Lit})^2 \\
&+\gamma_{45} \ln X_{Lit} \ln Y_{it} + \frac{1}{2}\gamma_{55}(\ln Y_{it})^2 \qquad (41)
\end{aligned}$$

where $\lambda$ represents the rate of neutral technological progress.[17]

The first-order conditions become

$$\begin{aligned}
\frac{\partial \ln C}{\partial \ln \left(\frac{e_t}{m_t}\right)} \;=\;& \frac{w_{Et} X_{Et}}{w_{Et} X_{Et} + w_{Mt} X_{Mt}} = S_{Et} \\
=\;& \alpha_2 + \gamma_{11} \ln \left(\frac{w_{Eit}}{w_{Mit}}\right) + \gamma_{13} \ln X_{Kit} \\
&+\gamma_{14} \ln X_{Lit} + \gamma_{15} \ln Y_{it} \qquad (42)
\end{aligned}$$

$$\frac{w_{Mt} X_{Mt}}{w_{Et} X_{Et} + w_{Mt} X_{Mt}} = S_{Mt} = 1 - S_{Et} \quad (43)$$

and

$$\begin{aligned}
0 \;=\;& \left(\frac{C_t}{X_{Kt}}\right) \frac{\partial \ln C}{\partial \ln X_{Kt}} + w_{Rt} + \beta_1[X_{Kt} - (1-\delta) X_{Kt-1}] \\
&+\mathcal{E}_t\{-D_{t,t+1}(1-\delta)\beta_1[X_{Kt+1} - (1-\delta) X_{Kt}]\} \qquad (44)
\end{aligned}$$

where

$$\frac{\partial \ln C}{\partial \ln X_{Kt}} = \alpha_3 + \gamma_{13} \ln \left(\frac{w_{Et}}{w_{Mt}}\right) + \gamma_{33} \ln X_{Kt} + \gamma_{34} \ln X_{Lt} + \gamma_{35} \ln Y_t \quad (45)$$

[17] Our specification of the restricted cost function implies that capital and labor investments become productive the same period. Thus we don't allow for a 'time-to-build' as suggested by Kydland and Prescott (1982).

and finally

$$0 = \left(\frac{C_t}{X_{Lt}}\right)\frac{\partial \ln C}{\partial \ln X_{Lt}} + w_{Lt} + \beta_2[X_{Lt} - X_{Lt-1}] + \mathcal{E}_t\{ -D_{t,t+1}\beta_2[X_{Lt+1} - X_{Lt}] \} \tag{46}$$

where

$$\frac{\partial \ln C}{\partial \ln X_{Lt}} = \alpha_4 + \gamma_{14} \ln(\frac{w_{Et}}{w_{Mt}}) + \gamma_{34} \ln X_{Kt} + \gamma_{44} \ln X_{Lt} + \gamma_{45} \ln Y_t. \tag{47}$$

Here equations (42) and (43) are derived from Shephard's lemma and represent static demand equations, while (44) and (46) are the new Euler equations. These are the equations (after dropping one of the static demand equations), together with the restricted cost function which are to be estimated. The simultaneous equation system consists of four equations; one restricted variable cost function, two Euler equations, and a static demand equation. The Euler equations tell us that the expected values, conditional on all available information at time t, of one marginal unit of a quasi-fixed factor of production (capital or labor) is zero.

A natural choice for an estimator of the system is an instrumental variables estimator which minimizes the squared correlation between any variable known at time t and the residuals of the Euler equations.[18] The residuals are computed by using the actual values of $X_{Kt+1}$ and $X_{Lt+1}$ on the left-hand side of the Euler equations. In this way the residuals can be thought of as being expectational errors. When estimating the equations any variable known at time t could be used in the instrument set provided the cost function and static demand (or share) equation hold without error as they theoretically should. However, in practice at least three sources of error will make this a zero probability event. The three sources of contamination are measurement errors, optimization errors, and various technological shocks. All these errors are likely to be correlated with variables present in all our equations, which of course is undesirable. However, it is plausible that the equations will hold in expectation with respect to some conditioning set, and this set ought to be a proper subset of the conditioning set that applies to the Euler equations when the cost and demand equations fit exactly (Pindyck and Rotemberg, 1983b). The solution to this problem is to lag the

[18] Hansen's (1982) generalized method of moments reduces to three-stage least squares if errors are conditionally homoscedastic (Pindyck and Rotemberg, 1983a), something we will assume in this exercise.

instrument set one or more periods to take account of effects of measurement error on the variables of the model.

Panel data such as that used in the airline studies can be used to deal with unobserved heterogeneity appearing in the in the restricted cost function by adding fixed effect dummy variables. The four equations that are estimated are then given by the cost equation, one of the static factor demand equations, and the two Euler equations for capital and labor:

$$X_{Kit+1} = \alpha_3 A^{-1}\left(\frac{C_{it}}{X_{Kit}}\right) + \gamma_{13} A^{-1}\left(\frac{C_{it}}{X_{Kit}}\right) \ln\left(\frac{w_{Eit}}{w_{Mit}}\right)$$
$$+\gamma_{33} A^{-1}\left(\frac{C_{it}}{X_{Kit}}\right) \ln X_{Kit} + \gamma_{34} A^{-1}\left(\frac{C_{it}}{X_{Kit}}\right) \ln X_{Lit}$$
$$+\gamma_{35} A^{-1}\left(\frac{C_{it}}{X_{Kit}}\right) \ln Y_{it} + A^{-1} w_{Kit} \tag{48}$$
$$+A^{-1}(\beta_1 + (1-\delta))X_{Kit} - A^{-1}\beta_1(1-\delta)X_{Kit-1}, \tag{49}$$

where

$$A = D_{t,t+1}(1-\delta)\beta_1, \tag{50}$$

$$X_{Lit+1} = \alpha_4 B^{-1}\left(\frac{C_{it}}{X_{Lit}}\right) + \gamma_{13} B^{-1}\left(\frac{C_{it}}{X_{Lit}}\right) \ln\left(\frac{w_{Eit}}{w_{Mit}}\right)$$
$$+\gamma_{33} B^{-1}\left(\frac{C_{it}}{X_{Lit}}\right) \ln X_{Kit} + \gamma_{34} B^{-1}\left(\frac{C_{it}}{X_{Lit}}\right) \ln X_{Lit}$$
$$+\gamma_{45} B^{-1}\left(\frac{C_{it}}{X_{Lit}}\right) \ln Y_{it} + B^{-1} w_{Lit}$$
$$+(1 + \beta_2 B^{-1})X_{Lit} + \beta_2 B^{-1} X_{Lit-1}, \tag{51}$$

$$B = D_{t,t+1}\beta_2, \tag{52}$$

This system was estimated using the Good-Sickles airline data for the period 1970I-1985IV. Results indicate rather small short-run Allen-Uzawa and price elasticities for energy and materials of about -0.13 and -0.14 while long-run price elasticities for capital and labor are about -0.8 and -1.2 respectively. TFP growth averaged about 2.2% during the period, of which about 40% of the 2.2% was due to pure technical change.[19]

[19] Although long-run elasticities can serve a useful purpose, one has to be careful when interpreting them. Since the long-run expected equilibrium is a solution to a stochastic control problem, and since such solutions are often difficult to find, one often resorts to the deterministic control problem instead. In the deterministic approach it is assumed that the firm ignores the variance of future prices when responding to input price changes.

## 4.2 Productivity Growth and R&D Investment

The generic dynamic model just presented can be modified to handle a variety of particular institutional settings and types of investment (human as well as machine) in assessing productivity growth. As an illustration of modeling the effect of R&D investment on growth of output and labor productivity, consider the case of electrical machinery of the U.S. and Japan. These industries experienced a very high rate of output growth, are technologically very progressive (measured by the rate of expenditure on R&D), and are highly competitive in the domestic U.S. and world markets. Given the presence of large firms in the electrical machinery industries of both the United States and Japan, constant returns to scale is not imposed a priori. A normalized restricted cost function of the following general form is assumed:

$$C(Y_t, w_{vt}, X_{N-J,t-1}, \Delta X_{N-J,t}, T_t) = \\ C(w_{vt}, X_{N-J,t-1}/Y_t^{1/p}, \Delta X_{N-J,t}/Y_t^{1/p}, T_t)Y_t^{1/p}. \tag{53}$$

In the empirical analysis we take materials, $X_M$, and labor (hours worked), $X_L$, as the variable factors and the stocks of capital, $X_K$, and research and development, $X_R$, as the quasi-fixed factors $X_{N-J}$. Let $w_L$ be the real wage rate and let the price of materials be the numeraire. Technical change, other than that reflected by the stock of R&D, is represented by a simple time trend, $T_t = t$. We specify the following functional form for the normalized restricted cost function:

$$\begin{aligned} C(Y_t, w_{vt}, X_{N-J,t-1}, \Delta X_{N-J,t}, T_t) &= \alpha_0 + \alpha_W w_{Lt} + \alpha_{WT} w_{Lt} T_t \\ &+ \alpha_{WW} w_{Lt}^2 / 2Y_t^{1/p} + a' X_{N-J,t-1} + b' X_{N-J,t-1} w_{Lt} \\ &+ c' X_{N-J,t-1} T_t + X'_{N-J,t-1} A X_{N-J,t-1} / (2Y_t^{1/p}) \\ &+ \Delta X'_{N-J,t} B \Delta X_{N-J,t} / (2Y_t^{1/p}) \end{aligned} \tag{54}$$

where

$$a = \begin{bmatrix} \alpha_K \\ \alpha_R \end{bmatrix}, b = \begin{bmatrix} \alpha_{KW} \\ \alpha_{RW} \end{bmatrix}, c = \begin{bmatrix} \alpha_{KT} \\ \alpha_{RT} \end{bmatrix},$$

$$A = \begin{bmatrix} \alpha_{KK} & \alpha_{KR} \\ \alpha_{KR} & \alpha_{RR} \end{bmatrix}, B = \begin{bmatrix} \alpha_{\dot{K}\dot{K}} & 0 \\ 0 & \alpha_{\dot{R}\dot{R}} \end{bmatrix}.$$

In light of the above discussion, we can view (54) as a second-order approximation to a general normalized restricted cost function that corresponds to a homogeneous technology of degree $\rho$. Expression (54) is a generalization of the normalized restricted cost function introduced by Denny, Fuss, and Waverman (1981) and Morrison and Berndt (1981) for linear homogeneous technologies. As in these references parameter restrictions are imposed such that the marginal adjustment costs at $\Delta X_{N-J,t} = 0$ are zero. The convexity of $C(\cdot)$ in $X_{N-J,t-1}$ and $\Delta X_{N-J,t}$ and concavity in $w_{vt}$ implies the following inequality parameter restrictions: $\alpha_{KK} > 0$, $\alpha_{RR} > 0$, $\alpha_{KK}\alpha_{RR} - \alpha_{KR}^2 > 0$, $\alpha_{\dot{K}\dot{K}} > 0$, $\alpha_{\dot{R}\dot{R}} > 0$, $\alpha_{WW} < 0$.

This model was estimated using data for the US and Japanese electrical industries for the periods 1968–1979.[20] The general results of estimation suggest that the structure of the electrical machinery industry in the two countries characterized by the patterns of factor input substitution and complementarity as well as the degree of scale, is qualitatively similar. Quantitatively, there are some differences in scale and in responses of inputs to changes in prices and output in the two industries. Both industries are characterized by increasing returns to scale. However, the Japanese industry has a higher scale, which substantially influences its productivity growth and is the major source of divergence between the productivity growth rate in this industry in the two countries.

Using the estimates of the production structure, we can quantitatively examine the sources of output and productivity growth. The contributions of the factor inputs, technical change, and adjustment costs to output growth are shown in Table 2. This decomposition is based on the approximation:

$$\begin{aligned}\Delta \ln Y_t &= \frac{1}{2}\sum_{t=1}^{6}[\epsilon_{YZ_i}(t) + \epsilon_{YZ_i}(t-1)]\Delta \ln Z_{it} \\ &\quad + \frac{1}{2}[\lambda_Y(t) + \lambda_Y(t-1)], \qquad (55)\end{aligned}$$

with $Z_1 = X_L$, $Z_2 = X_M$, $Z_3 = X_{K,-1}$, $Z_4 = X_{R,-1}$, $Z_5 = \Delta X_K$, and $Z_6 = \Delta X_R$. The $\epsilon_{YZ_i}$'s denote respective output elasticities and $\lambda_Y(t) = (1/Y_t)(\partial Y_t/\partial t)$ denotes the technical change.

The average growth of gross output was very rapid in Japan in the period 1968–1973, but growth decelerated substantially in the period 1974–79. For the United States, output growth rates were similar in the two periods. The contributions of various inputs to the growth of output differ considerably between the two periods and the two industries. The most significant source of gross output growth is materials growth, particularly in Japan. The contribution of capital is larger in Japan that in the United States, but falls

[20]For detailed parameter estimates, see Nadiri and Prucha (1990)

in both countries over the post-OPEC period. The R&D stock contributes significantly to the growth of output in both industries. In the post-OPEC period its contribution falls in the United States but remains the same for Japan. The large contribution of R&D to the output growth may come as a surprise but can be explained by two factors. First, the share of R&D investment in gross output is very high in the electrical machinery industries of both countries; second, the marginal product of R&D, because of the relatively large adjustment costs and the considerable degree of scale, is fairly large in the two industries. The direct contributions of the adjustment costs are fairly small, as one would expect. The contribution of technical change is clearly important in explaining the growth of output in both industries. Its contribution is twice as large in Japan as in the United States.

The decomposition of labor-productivity growth is based on the approximation:

$$\Delta \ln(Y_t/X_{Lt}) = \frac{1}{2}\sum_{i=1}^{6}[\epsilon_{YZ_i}(t) + \epsilon_{YZ_i}(t-1)]\Delta(\ln Z_{it}/X_{Lt}) + \frac{1}{2}[\lambda_Y(t) + \lambda_Y(t-1)] + (\rho - 1)\Delta \ln X_{Lt}, \qquad (56)$$

where $\rho$ is the scale elasticity. In Table 3 the sources of labor productivity growth for the two industries are presented. The most significant contribution again stems from the growth of materials, particularly in Japan, although the contribution of physical capital is also important. In comparison to the results reported by Norsworthy and Malmquist (1983) for the total manufacturing sector, the contribution of physical capital is somewhat larger for the United States but smaller for Japan. The contribution of R&D is somewhat smaller and rising for Japan. For the United States, the contribution of R&D is very substantial in the pre-OPEC period but only marginal in the post-OPEC period. The direct contribution of adjustment costs is again small. The contribution of technical change is very substantial (particularly in Japan) and rising in both countries.

The labor effect, given by the last term on the right-hand side of (56), follows from the fact that scale is not equal to one. Its effect is positive in Japan in the pre-OPEC period and negative in the post-OPEC period. The opposite is the case for the United States. This reflects the growth pattern of the labor input in the two industries over the two periods.

Denny, Fuss, and Waverman (1981) have shown that if all factors are variable, then the traditional measure of total factor productivity (using cost shares) can be decomposed into two components, one attributable to scale and one to technical change. Nadiri and Prucha (1986, 1990) extend this decomposition to technologies with adjustment costs. More specifically, consider the Törnqvist approximation of the growth rate of total factor productivity, $\Delta TFP_t$, defined implicitly by:

$$\Delta \ln Y_t = \frac{1}{2}\sum_{i=1}^{4}[S_{z_i,t} + S_{z_i,t-1}]\Delta \ln Z_{it} + \Delta TFP_t \qquad (57)$$

with $Z_1 = X_L$, $Z_2 = X_M$, $Z_3 = X_{K,-1}$, $Z_4 = X_{R,-1}$ and where the $S_{z_i}$'s *denote* respective long-run cost shares. Given increasing returns to scale and adjustment costs we find that the output elasticities $\epsilon_{YZ_i}$ exceed the cost shares $S_{z_i}$. As a consequence, as is evident from a comparison of equations (56) and (57), total factor productivity will not equal technical change. Prucha and Nadiri (1986, 1990) show that total factor productivity growth can be decomposed as follows:

$$\Delta TFP = (1-\rho^{-1})\Delta \log Y_t + \phi_{1t} + \phi_{2t} + \frac{1}{2}[\lambda_X(t) + \lambda_X(t-1)], \qquad (58)$$

where $\lambda_X = (1/\rho)\lambda_Y$. The first term on the right-hand side of (58) represents the scale effect and the last term the pure effect of technical change on the growth of total factor productivity. The term $\phi_1$ is attributable to the fact that, in short-run temporary equilibrium, the rate of technical substitution between the quasi-fixed and variable factors differs from the long-run price ratios. We will refer to $\phi_1$ as the temporary equilibrium effect. The term $\phi_2$ reflects the direct adjustment-cost effect in terms of foregone output due to the presence of $\Delta X_K$ and $\Delta X_R$ in the production function. We will refer to $\phi_2$ as the direct adjustment cost effect.[21] The decomposition of total factor productivity for the two industries is based on (58). The scale effect is, by far, the most important contributor to total factor productivity growth. This is particularly the case in the Japanese industry where the output growth was very rapid and the estimated degree of scale larger than in the U.S. industry. It is possible to decompose the scale contribution into effects of shifts in demand and that of relative input prices as shown in section 3. The growth of demand is probably a major source of growth of TFP in these two industries. The temporary equilibrium effect, $\phi_1$, is fairly large in the United States and about twice as big as in the Japanese electrical machinery industry. The direct effect of the adjustment costs, $\phi_2$, is negligible. The

[21] Explicit expressions for the terms $\phi_1$ and $\phi_2$(and a further discussion of those terms) are given in Appendix C of Nadiri and Prucha (1990).

combined effect of $\phi_1$ and $\phi_2$ due to the adjustment costs is 15% and 4% of the measured total factor productivity growth for the United States and Japan, respectively, and hence not negligible, particularly for the United States. Consequently, if zero adjustment costs would have been imposed, a nonnegligible portion of measured total factor productivity growth would have been misclassified. In addition, inconsistency of the estimates of the underlying technology parameters would have distorted the decomposition of total factor productivity growth. The contribution of technical change to the growth of total factor productivity is second only to the scale effect. For each of the sample periods, the unexplained residual is small.

### 4.3 Productivity Growth, Spillovers and Externalities of R&D Capital

In many industries firms undertake research and development (R&D) investment in order to develop new products or new processes. A feature of R&D investment that distinguishes it from other forms of investment is that firms which do the investing are often not able to exclude others from freely obtaining the benefits from the R&D projects. If this is the case the benefits from R&D investment spill over to other firms in the economy, although the recipient firms have not paid for the use of the knowledge generated by the R&D activity.

The significance of spillovers in modeling and estimating the effects of R&D investment has been emphasized by Griliches (1979, 1993) and Nadiri (1994). Theoretical treatments (e.g., Reinganum, 1981; Spence, 1984) have analyzed the implications of R&D spillovers in terms of a dynamic model of industry conduct and performance. In particular, Spence assumed that through spillovers a firm's R&D investment reduces production costs of rival firms. Thus the industry-wide cost-reduction effect of R&D investment is enhanced. Simultaneously, however, because spillovers generate free-rider problems, a firm's incentive to undertake R&D activity is diminished.

In recent years there has been a considerable effort to model and estimate the role of R&D spillover. There are a number of different approaches that have been taken to specify and measure technical spillover effects.[22] The interested reader may consult the survey papers by Griliches (1993) and

[22] For some of the specifics studies on the R&D spillover effects, the interested reader may consult the following studies: Bernstein (1988, 1989), Bernstein and Nadiri (1988, 1989b), Cohen and Levinthal (1986), Evenson and Kislev (1973), Fecher (1989), Goto and Suzuki (1989), Griliches (1991), Jaffe (1984, 1986, 1989), Levin and Reiss (1984), Mohnen (1990a,c), Spence (1984), Terleckyj (1980),Vickery (1986), Wolff and Nadiri (1987).

Nadiri (1994).

An approach developed by Bernstein and Nadiri (1989b) analyzes the cost-reducing and incentive effects of technological spillover for several U. S. industries. R&D spillovers are embodied in the technology of a firm which can be represented by

$$Y(t) = F(X_{K_{Ph}}(t), X_V(t), X_{K_{RD}}(t), \theta X_R(t), I_{Ph}(t), I_{RD}(t)), \tag{59}$$

where $Y(t)$ is the output flow, $F$ is the production function, $X_{K_{Ph}}(t)$ is the physical capital service flow, $X_V(t)$ is the variable factor service flow, and $X_{K_{RD}}(t)$ is the R&D capital service flow. The R&D spillover is given by the variable $X_R(t)$, which is the R&D capital service flow of other firms in the economy. Indeed, $X_R(t) = \sum_f X_{fK_{RD}}(t)$, where the summation is taken over all firms other than the one whose technology is represented by equation (59). The parameter $\theta$ captures the extent to which R&D capital is appropriable. If $\theta = 1$, then R&D capital is completely appropriable and all knowledge is common; and if $0 < \theta < 1$, then there is incomplete appropriability.

The presence of investment, which is given by $I_i(t), i = Ph$ (physical) and $i = RD$ (R&D), in the specification of the technology implies that there are internal adjustment costs associated with changes in the level of the capital inputs (i.e., the quasi-fixed factors). These adjustment costs are measured in terms of foregone output (see Treadway, 1971, 1974; Mortensen, 1973; and Epstein, 1981). Increases in investment decrease output at a decreasing rate. However, increases in the variable, physical and R&D capital inputs increase output at a decreasing rate.

There are three effects associated with the R&D spillover. First, from the production function given the inputs and investment, changes in the spillover generate changes in the quantity of output. This is the productivity effect. Second, given input levels and the investment rates, changes in the R&D spillover cause factor substitution. Indeed, the variable factor, physical capital and R&D capital may be complements or substitutes to the spillover. It is important to note that not only R&D capital responds to the spillover, but in principle each factor of production can be affected by knowledge obtained from other firms in the economy. In the language of the technological change literature, changes in the R&D spillover cause factor biases, which may be either factor using or factor reducing.

Because the technology incorporates adjustment costs, there is a third effect. Given output and factor quantities in the production function, changes in the R&D spillover cause quasi-fixed factor-adjustment as the rates of investment change. Thus the dynamic nature of the model implies that the incentive effect associated with the R&D spillover can be attributed to two sources: changes in factor demands and changes in quasi-fixed factor accumulation.

The accumulation of physical and R&D capital stocks is governed by

$$\dot{X}_{K_i} = I_i - \delta_i X_{K_i}, i = Ph, RD \tag{60}$$

where $0 \leq \delta_i \leq 1, i = Ph, RD$ are the fixed rates of depreciation of the two types of capital stocks.

The costs of the variable factor, of purchasing physical capital and of developing knowledge capital are

$$C^v = G(Y, X_{K_{Ph}}, X_{K_{RD}}, \theta X_R, I_{Ph}, I_{RD}) + p_{PH} I_{Ph} + p_{RD} I_{RD} \tag{61}$$

where $C^v$is normalized cost, normalised with respect to the variable factor price, $p_i$ $(i = Ph, RD)$ is the normalized (or relative) investment price and $G$ is the variable factor requirements function, which is derived by inverting the production function (denoted by $F$ in equation (59)). Using a value function whose form is assumed to be is generalized quadratic in the factor prices and linear in output, the capital stocks and R&D spillover, the estimating equations for this dynamic model are:[23]

$$\begin{aligned} X_V^e(t)/Y(t) &= .5b_0^* - .5b_{11} w_{Ph}^2(t) - .5b_{22} w_{RD}^2(t) - b_{12} w_{Ph}(t) w_{RD}(t) + \\ &\quad h_0^*/Y(t) + a_1(1+\rho) X_{K_{PH}}(t-1)/Y(t) + \\ &\quad a_2(1+\rho) X_{K_{RD}}(t-1)/Y(t) - a_1 X_{K_{Ph}}^e(t)/Y(t) - \\ &\quad a_2 X_{K_{RD}}^e(t)/Y(t) + a_0 X_R(t-1)/Y(t) + u_\ell(t) \end{aligned} \tag{62}$$

$$\begin{aligned} X_{K_k}^e(t)/Y(t) &= (a_{ii} b_{ii} + a_{ij} b_{ij}) w_k(t) + (a_{ii} b_{ij} + a_{ij} b_{jj}) w_\ell(t) + \\ &\quad h_i^*/Y(t) + b_i^* + (1 + \rho - a_{ii}) X_{K_k}(t-1)/Y(t) - \\ &\quad a_{ij} X_{K_l}(t-1)/Y(t) + c_i X_R(t-1)/Y(t) + u_k(t), \end{aligned} \tag{63}$$

$i, j = 1, 2, i \neq j; k, \ell = Ph, RD, k \neq \ell.$

Equation (62) represents variable factor demand while equation (63) represents the investment demand functions for physical and R&D capital. The

[23]See Bernstein and Nadiri (1989b) for details.

R&D spillover variable, the magnitudes of capital stocks, and the adjustment costs of physical and R&D capital affect both sets of equations. Thus the effect of R&D spillovers on both the level of factors of production and also on the path of investment can be estimated.

The equations are non-linear in the parameters, with parameter restrictions within and across equations. The error terms reflect optimizing errors and are assumed to be jointly normally distributed, with zero expected value, $\mathcal{E}(u) = 0$, and with positive definite symmetric covariance matrix, $\mathcal{E}(uu^T) = \Omega$.

Equations (62–63) are estimated for each of the four industries (Chemicals, Petroleum, Machinery, Instruments) with cross section and time series data pooled together. In order to account for interfirm differences within an industry the parameters $b_0^*, b_1^*, b_2^*, h_0^*, h_1^*, h_2^*$ are allowed to vary across firms. Since factor prices are not firm specific, the parameter matrices $A_{wk}$ and $B_{ww}$ are assumed to be invariant across firms.

R&D spillovers cause average cost to decline and factor demand to change for the spillover-receiving firms. These cost-reducing and factor-biasing effects of R&D spillovers can be determined from equations (62–63). By differentiating equations (62–63) with respect to $x_r(t-1)$ we can obtain the short run R&D spillover elasticities of factor demands (physical capital, R&D capital and the variable factor). Similarly, the productivity effect of R&D spillover can be derived from equations (62–63). This can be done by formulating the effects of R&D spillovers on short-run and long run cost functions.

The estimation results suggest that for each industry, the short-run demand for R&D and physical capital decreased in response to an increase in the intraindustry spillover. Thus the spillover was R&D and physical capital-reducing (or saving). No complementarity effects between the intraindustry spillover and a firm's own R&D capital were evident. It appeared that the spillover was a substitute for own R&D capital. In the short run, both the variable and average costs for each industry and every firm declined in response to the intraindustry spillover. These productivity effects suggest that a one percent increase in the spillover on average decreased variable cost by around 0.1 percent for machinery and instruments and by 0.2 percent for chemicals and petroleum. The effects on average cost were about 50 percent to 70 percent of the elasticities on variable cost. Spillover-receiving firms gained a 0.05 percent, 0.08 percent, 0.11 percent, and 0.13 percent average cost reduction, respectively, in the instruments, machinery, petroleum, and chemical industries as a results of a 1 percent increase in the intraindustry spillover.

Not surprisingly, the spillover elasticities of the quasi-fixed factors were more elastic in the long run than in the short run. In addition, the signs did not change between the short and long run. In the long run the spillover was physical and R&D capital reducing. Moreover, on average, in the long, the elasticities for physical and R&D capital were still highly inelastic. Once again these results occurred for each firm in each industry and were very stable over time. Variable and average costs also decreased in the long run as the R&D spillover increased. The long-run effects on variable and average costs were generally more elastic than the effects on physical and R&D capital. In the long run a one percent increase in the intraindustry spillover caused average cost to decline by around 0.1 percent for instruments and machinery and by approximately 0.2 percent for chemicals and petroleum. These long-run cost-reductions were twice those estimated for the short run.

Using these model estimates, it is possible to calculate the social rate of return to R&D capital. The results indicate that for all four industries the net social rate of return greatly exceeded the net private return. The machinery industry exhibited a difference of 30 percent between the returns. This was the smallest differential. The differences in returns for chemicals and instruments were 67 percent and 90 percent, respectively. The petroleum industry showed the greatest difference in returns, as the net social rate was more than twice the net private rate of return.

There have not been many empirical studies which have investigated the extent to which intraindustry R&D spillovers create a divergence between the social and private rates of return on R&D capital. Jaffe (1986) has looked at spillovers for a cross section of manufacturing firms. Jaffe estimated that the social returns on R&D capital was 40 percent higher than would be the case in the absence of spillovers. Mansfield et al. (1977) conducted an analysis of a small group of major R&D projects and concluded that the social rate of return was 77 to 150 percent greater than the private return. The results reported here on the deviation between the social and private rates of return were consistent with the previous findings.

Empirical work relating to R&D spillovers has surged in the last few years (see Griliches, 1993, and Nadiri, 1994, for partial references). These studies attempt to estimate the magnitude of the inter- and intra-industry R&D spillover and the spillover effects of R&D performed in Universities and scientific laboratories on industry or firm productivity. Also, effort is underway to examine the cross-border effect of investment in R&D in one country to another. The studies differ in their methodologies and applications. Though as yet there is no consensus, most of these studies point in the direction that there is some effect of R&D spillover on the productivity growth of the receiving industry or economies. Also, these spillover effects do change to some extent the investment behavior of the recipients. Using rigorous methodologies and appropriate econometrics to estimate models similar to those surveyed here will contribute substantially to our understanding of the process by which technology diffusion and spillovers affect TFP growth among firms, industries, and countries.

## 4.4 Infrastructure Capital and TFP Growth

A substantial number of studies have utilized cost function specifications to measure productivity effects of total or specific infrastructure capital on regional, industry, and metropolitan output growth and TFP performance.[24] The earlier studies based on simple production function specifications attributed substantial impact on growth of output and TFP to public infrastructure. Estimated output elasticities ranged between 0.33 and 0.66 which implied rates of return to infrastructure capital of close to 100% .[25] Recent studies employing flexible cost functions have led to substantial refinement and reassessment of the earlier results (Nadiri and Mamuneas, 1994). As an example, consider the recent study by Nadiri and Mamuneas (1996).

Let the output demand for an industry, $f$, be

$$\dot{Y}_f = \lambda_f + \alpha_f(\dot{p}_{yf} - \dot{P}_g) + B_f\,\dot{Z} + (1-\beta_f)\,\dot{N} \qquad (64)$$

where $\dot{Y}_f$and $\dot{p}_{yf}$are the growth rates of output and prices in industry $f$; $\dot{Z}$, $\dot{N}$,and $\dot{P}_g$are the growth rates of aggregate real income, population, and GNP deflator, respectively.[26] The industry's technology is represented by the cost function

$$\ln C_f \;=\; \left\{ \frac{\sum_i \sum_j a_{ij} w_{if} w_{jf}}{[\sum_i \theta_i w_{if}]} + \sum_i b_{1i} w_{if} + [\sum_i c_{it} w_{if}]t \right.$$

[24]As a representative of the diverse approaches to the analysis of public infrastructure capital and productivity the interested reader may consider Aschauer (1989a,b), Berndt and Hansson (1991), Conrad and Seitz (1992), Deno (1988), Duffy-Deno and Eberts (1991), Eberts (1986), Eisner (1991), Fernald (1992), Gramlich (1994), Holtz-Eakin (1992), Hulten and Schwab (1984), Keeler and Ying (1988), Lynde and Richmond (1992), McGuire (1992), Morrison and Schwartz (1991), Munnell (1990a,b), Nadiri and Mamuneas (1993), Nienhaus (1991), Shah (1992), Tatom (1991).

[25]For a review of the literature, see Aschauer (1993), Aaron (1990), and Nadiri and Mamuneas (1993).

[26]Equation (64) is estimated in first difference form in order to account for potential nonstationarity. The variables are cointegrated in the first-difference form.

$$+b_{yy}[\sum_i \gamma_i w_{if}]Y_f + [\sum_i c_{is} w_{if}]X_{PCS} + d_{ss}[\sum_i \phi_i w_{if}]X^2_{PCS} \Big\} Y_f$$

$$+\sum_i b_i w_{if} + C_{PCS}[\sum_i \psi_i w_{if}]X_{PCS} \quad (65)$$

where $a_{ij} = a_{ji}$, $w_{if}$ are relative input prices, $Y_f$ is industry output, $t$ is a time trend and $X_{PCS}$ is an m-dimensional vector of public capital services. This functional form is the symmetric generalized McFadden cost function introduced by Diewert and Wales (1987) augmented to include infrastructure capital services. The cost function is dual to a well-behaved production function if it is non negative, monotonically increasing, homogeneous of degree one, and concave in input prices. If in addition, for some reference point $w^* \gg 0$, $Y^* > 0$, $X^*_{PCS} > 0$, the following restrictions are satisfied

$$\begin{aligned} \sum_i a_{ij} w_i^* &= 0, \\ \sum_i \theta_i w_i^* &\neq 0, \ \sum_i \gamma_i w_i^* \neq 0, \ \sum_i \phi_i w_i^* \neq 0 \text{ and } \sum_i \psi_i w_i^* \neq 0 \end{aligned}$$

then $C(\cdot)$ is a flexible, linearly homogeneous in input prices, cost function. The advantage of this functional form over the translog cost function is that if the estimated matrix $A = [a_{ij}]$ is negative semidefinite, then the cost function will be concave in input prices. However, if $A$ is not negative semidefinite, we can impose concavity in input prices globally by a Cholesky factorization, without destroying the flexibility property of the cost function (See Diewert and Wales, 1987, for a further discussion).

The system of estimating equations can be derived by applying Shephard's Lemma ($X_i = \partial C / \partial w_i$)

$$\begin{aligned} X_{if}/Y_f = & \frac{\sum_j a_{ij} w_{if}}{[\sum_i \theta_i w_{if}]} - \frac{\frac{1}{2}\sum_i \sum_j a_{ij} w_{if} w_{jf} \theta_i}{[\sum_i \theta_i w_{if}]^2} \\ & + c_{it} t + c_{iu} u_f + b_{ii} + b_{yy} \gamma_i y_f \\ & + c_{is} X_{PCS} + d_{ss} \phi_i X^2_{PCS} + b_i / Y_f + c_s \psi_i X_{PCS} / Y_f + \epsilon_{if} \end{aligned} \quad (66)$$

where i, $j = 1, ..., N$; $f = 1, ..., F$; $\epsilon_f = (\epsilon_{1f}, ..., \epsilon_{nf})$ has zero mean and constant covariance matrix $\Omega$. We require the system of equations to satisfy the usual regularity conditions. In particular, for the cost function to be concave in input prices, its Hessian matrix $(\partial^2 C / \partial w_i \partial w_j)_{ij}$ of second-order derivatives with respect to variable input prices should be negative semidefinite. Also, the cost function should be nondecreasing in output and linearly homogeneous in input prices. Finally, in order for public capital input to have a cost reducing effect, the cost function should be nonincreasing in $X_{PCS}$.

The marginal benefit of highway capital services can be calculated by taking the derivative of the cost function with respect to infrastructure service $X_{PCS}$.

$$-\partial C_f/\partial X_{PCS} = -\{\sum_i c_{is}w_{if} + 2d_{ss}[\sum_i \phi_i w_i]X_{PCS}\}Y_f - [\sum_i \psi_i w_{if}]c_s \quad (67)$$

Note that if the estimated parameter $d_{ss}$ is positive, then this condition can be interpreted as the demand for highway capital. Also, if the user fee of infrastructure is known, say equal to $Q_f$, then this condition can be imposed in estimation. Condition (67) is the shadow value or marginal benefit of highway capital services. By knowing the marginal cost of public capital (ignoring consumption), we can also directly estimate the optimal amount of different public capital that will equate the sum of marginal benefits to its marginal cost. That is,

$$-\sum_f \partial C_f/\partial X_{PCS} = Q_{PCS}$$

where $Q_{PCS}$is the marginal cost of highway capital.

Finally, the indirect effects of highway capital on private inputs like capital and employment are given by

$$\partial X_{if}/\partial X_{PCS} = \{c_{is} + 2d_{ss}\phi_i X_{PCS}\}Y_f + \psi_i c_s. \quad (68)$$

Thus, we can estimate whether public capital is biased toward labor, materials, and private capital.

The productivity effects of the infrastructure capital (highways) is analyzed in the context of a general framework based on equations (65) and (66). Define $\dot{\text{TFP}}$ as

$$\dot{\text{TFP}} = \dot{Y} - \sum_i \pi_i \dot{X}_i$$

where $\dot{X}_i$ denotes the rate of growth and $\pi_i = w_i X_i/p_y Y$ is the output share of the $i$th private input.[27] It can be shown that $\dot{\text{TFP}}$ can be written as[28]

[27]For simplicity we have droped the firm index f.

[28]See Nadiri and Schankerman (1981) for the derivation.

$$\dot{\text{TFP}} = \left(\frac{\kappa - \eta^*}{\kappa}\right)\dot{Y} - \frac{1}{\kappa B}\sum_k \eta_{ck}\dot{X}_{PCS_k} - \frac{1}{\kappa B}\dot{T} \tag{69}$$

where $\kappa$ is the ratio of output price to average total cost; $\eta^*$ is the cost elasticity of output when both private and public inputs are included; $\eta$ is the cost elasticity of output when private inputs are considered. $\eta^* = \eta/B$ where $B = 1 - \sum_k \eta_{ck}$; $\eta_{ck}$ is the private cost elasticity with respect to public inputs. According to equation (69), TFP growth can be decomposed into three components: a gross total scale effect given by the first term; a public capital stock effect given by the second term; and the technological change effect given by the last term. To further decompose the scale effect, we assume that the price of output is related to private marginal cost according to:

$$p_y = (1+\theta)\partial C/\partial Y$$

where $\theta$ is a markup over the marginal cost. The markup will depend on the elasticity of demand as well as on the conjectural variations held by the firms within an industry. Using the definition of the output elasticity, $\eta$, along the private cost function, we obtain

$$p_y = (1+\theta)\eta C/Y. \tag{70}$$

Time differentiating (70), the pricing rule implies

$$\dot{p}_y = (1+\dot{\theta}) + \dot{\eta} + \dot{C} - \dot{Y} \tag{71}$$

where $(\cdot)$ denotes growth rate. Differentiating the private cost function with respect to time and using Shephard's lemma,and by substituting for $\dot{Y}$ from the demand function, we obtain the reduced form function for the growth rate of total factor productivity

$$\begin{aligned} \dot{\text{TFP}} &= A[\alpha\dot{\eta} + \alpha(1+\dot{\theta})] + A\alpha\left(\sum_i \zeta_i \dot{w}_i - \dot{P}_g\right) \\ &\quad + A[\lambda + B\dot{Z}(1-B)\dot{N}] + A\alpha\sum_k \eta_{ck}\dot{X}_{PCS_k} \\ &\quad - \frac{1}{\kappa B}\sum_k \eta_{ck}\dot{X}_{PCS_k} + A\alpha\dot{T} - \frac{1}{\kappa B}\dot{T} \end{aligned} \tag{72}$$

where $A = [(\kappa - \eta^*)/\kappa]/[1 - \alpha(\eta - 1)]$ and $\zeta_i$ is the share of the ith input in private cost C.

Equation (72) decomposes $\dot{\text{TFP}}$ into the following components:

1. a factor price effect $A\alpha[\sum_i \zeta_i \dot{w}_i - \dot{P}_g]$;

2. an exogenous demand effect $A[\lambda + B\ \dot{Z}\ (1-B)\ \dot{N}]$;

3. a public capital effect $\left(A\alpha - \frac{1}{\kappa B}\right) \sum_k \eta_{ck} \dot{X}_{PCS_k}$ and

4. disembodied technical change $[A\alpha\frac{1}{\kappa B}]\dot{T}$.

The public capital and disembodied technical change effects can be further decomposed into direct and indirect effects. The direct effect of infrastructure capital, for instance, is given by $(\eta_{ck}/\kappa B)\dot{X}_{PCS_k}$ while the indirect effect is given by $A\alpha\eta_{ck}\dot{X}_{PCS_k}$. Thus an increase of public infrastructure initially increases total factor productivity by reducing the private cost of production, which in turn leads to lower output price and higher output growth. Change in output growth in turn leads to changes in TFP growth.

The important parameters in (72) are the price and income elasticities of demand and the cost elasticities of the private cost function. Note that if the demand function is completely inelastic ($\alpha = 0$) then shifts in the cost function due to real factor price changes, public capital, or disembodied technical change have no effect on output and hence no indirect effect of TFP. Second, if there are constant returns to scale including the public inputs, $\eta^* = \kappa = 1$,then (72) collapses to $\dot{\text{TFP}} = \frac{1}{B}\sum_k \eta_{ck}\dot{X}_{PCS_k} - \frac{1}{B}\dot{T}$.

The model is estimated using the disaggregated industry data developed by Jorgenson, Gallop, and Fraumeni (1987). The data cover 35 U. S. sectors and two digit industries for the period 1947 to 1989 and include gross output, materials input, labor and capital and their prices for all industries. The aggregate time series data for the highway capital was constructed by the Bureau of Economic Analysis. The model consisting of demand, cost and share equations is estimated using the panel data for the 35 industries over the period 1950–1989 using Three Stage Least Squares with lagged values of the independent variables as instruments.

The specific quantitative results can be summarized briefly. Highway capital does contribute to output and productivity growth at both industry and aggregate economy levels. Its contribution varies across industries. The elasticity of output with respect to highway capital at the aggregate level is approximately 0.05 which is much smaller than the comparable estimates reported in the literature. All industries indicate some degree of economies of scale but the degree of returns to scale are fairly modest, in the range of 1.05 to 1.2. The marginal products of labor, capital and intermediate inputs were all positive and the output elasticities of material inputs were the largest, followed by those of labor and capital at both industry and aggregate economy levels. The elasticities of output with respect to highway capital were much smaller, by almost four times, than those for private capital in all industries. Clearly, private capital input dominates, in terms of contribution to output, the public capital , i.e. highway capital.

The effects of public capital on demand for private inputs in different industries are significant. The degree of "bias" varies across industries but it mainly reduces demand for private capital while it increases the demand for labor in some industries. The marginal benefits of highway capital in most industries range from 0.004 to 0.028: they are a measure of the willingness to pay for highway services. The marginal benefits in some industries is negative suggesting that in those industries the existing stock of highway capital may be over supplied. The patterns of marginal benefits imply corresponding taxation and subsidies to fully utilize the existing highway capital services.

Using the industry marginal benefits calculations and the user cost of highway capital, taking into account the distorting effects of taxation to finance this infrastructure capital, it is possible to estimate the net social rate of return to highway capital. This rate was high, about 0.35 in the 1950's and 1960's, then declined considerably in the 1970's and was about 0.10 in 1989. This pattern reflects the phenomenon of inadequate highway capital in the 1950–1965 period when the National Highway System was being constructed. As this system was completed the rate of return declined and in the late 1980's the rates of return on private and public capital have converged. The model allows calculation of the "optimum" level of highway capital. The ratio of the "optimum" to actual highway capital was very high immediately after World War II and after 1960 this ratio steadily declined. By the end of the 1980's there seems to be no evidence of under-or over-investment in highway capital.

The decomposition of $T\dot{F}P$ was carried out according to equation (72). The main contribution to $T\dot{F}P$ was the shift in exogenous demand reflecting the growth of real income and population growth. The contribution of exogenous demand varied across industries but it contributed, on the average, about 60%. The relative input prices contributed negatively in almost all of the industries but the magnitude of the dampening effect of relative input price increases on $T\dot{F}P$ ranged between -0.10 to -0.40. At the aggregate economy level the contribution of relative price to $T\dot{F}P$ was about -0.07 while that of the exogenous demand stood at about 0.67.

The contribution of highway capital to $T\dot{F}P$ in all industries, except a few, was positive but varied considerably. In the manufacturing industries the contribution of highway capital was much higher than in other industries.

At the aggregate level, highway capital contributed to about 0.17% of TFP growth. Another feature of the results was that while highway capital did contribute to the long term growth of TFP, it contributed very little to the acceleration or deceleration of TFP growth at the industry level.

# 5 Structural Approaches to Productivity Measurement in Models with Fixed Factor Dynamics and Allocative Distortions

In this section we outline an integrated model that nests a wide range of features of the production process.[29] Particularly, we will assess the sensitivity of the structure of technology to three common assumptions: (1) cost-minimizing behavior, (2) the endogeneity of the production technique, and (3) the specification of technical change. We employ the concept of virtual prices to allow estimation of a technology that corresponds to efficient resource allocation despite potentially noncost-minimizing behavior by the firms.[30] We formulate a multiple output technology in which the choice of production technique is an endogenous decision. Finally, rather than using time trends as proxies for disembodied technological change, we employ a variable cost function which explicitly incorporates characteristics of the embodied production technique. The U.S. airline data are used for empirical illustrations.

Distorted cost-minimizing behavior is introduced into the standard model in the following way.[31] Consider the transformation function $F(Y, X) \leq 0$

[29] These innovations have included flexible functional forms (see Nadiri, 1982), models allowing multiple outputs (Brown, Caves and Christensen, 1979), the incorporation of characteristics of those outputs (*e.g.*, Spady and Friedlaender, 1978), models of interrelated demand functions and temporary equilibria (*e.g.*, Nadiri and Rosen, 1969; Pindyck and Rotemberg, 1983a,b; Berndt and Morrison, 1981), and models allowing noncost-minimizing behavior (*e.g.*, Lovell and Sickles, 1983; Atkinson and Halvorsen, 1984).

[30] An alternative interpretation of a divergence between virtual and observed prices is that there exist binding constraints on firm decision making and that the firm is in fact optimizing relative to those constraints. In the U.S. airline industry, specification of these constraints is problematic, and empirical vehicles for modeling them have not been developed. However, to the extent that we can identify and estimate parameters that explain the divergence between virtual and observed prices, their role in explaining distortions in optimizing behavior is consistent with either of these interpretations.

[31] The following model is based on the work of Toda (1976), Lovell and Sickles (1979), Atkinson and Halvorsen (1984), Sickles, Good, and Johnson (1986), Eakin and Kniesner (1988), Kumbhakar (1993) and Atkinson and Cornwell (1994a,b), It can also be viewed as a dual approach to other parametric inefficiency models in which inefficiency is time

characterized by a technology set endowed with the standard properties as set forth in Diewert (1982). Firms are assumed to employ inputs $X = \{X_J, X_{N-J}\} > 0$ to produce outputs $Y = \{Y_K, Y_{M-K}\}$, where the last $N - J$ inputs are assumed to be quasi-fixed (*e.g.*, aircraft fleets) and where the last $M - K$ elements of $Y$ are output characteristics (*e.g.*, service quality, network configurations, etc.). Consider the technology of airline service and the input and output decisions consistent with the standard assumptions of duality theory, in particular with the assumption that the firm is an unconstrained cost minimizer. Label these functions and variables with a '*' and refer to them as "virtual" or "shadow" functions and variables. Next let virtual prices diverge from observed prices by an amount given by the parameter vector $\theta = \{\theta_1, ..., \theta_N\}$. The cost-minimizing conditions in terms of the virtual (shadow) prices $w^*$ of input pair $i, j$ are thus modified to be

$$w_i^*/w_j^* = \frac{\partial F/\partial X_i}{\partial F/\partial X_j}, \qquad \text{where } w_i^* = w_i + \theta_i. \tag{73}$$

Based on Shephard's lemma, factor demands derived from the firm's minimum virtual cost function are

$$X_J^*(Y, w_J^*; X_{N-J}) = \frac{\partial C^*(Y, w_J^*; X_{N-J})}{\partial w_j^*}. \tag{74}$$

The observed variable cost function and associated short-run factor shares are

$$C(Y, w_J^*, w_J; X_{N-J}) = \sum_j w_j X_j^*(Y, w_J^*; X_{N-J}) \tag{75}$$

and

$$S_i = \frac{w_i X_i}{C(Y, w_J^*, w_J; X_{N-J})}, \qquad i = 1, ..., J. \tag{76}$$

Since virtual shadow cost shares are $S_i^* = \partial \ln C^*/\partial \ln w_i^* = w_i^* X_i/C^*$, observed input use can be related to virtual prices and quantities by $X_i = S_i^* C^*/w_i^*$. Observed costs can then be re-expressed as

$$C = C^* \left[\sum_i (S_i^* w_i/w_i^*)\right] \tag{77}$$

varying.

and observed factor *cost* shares can be re-expressed as

$$S_i = \frac{S_i^* w_i / w_i^*}{\sum_j \left( S_j^* w_j / w_j^* \right)}. \tag{78}$$

Equations (77) and (78) provide the key linkages between an observable cost function and the virtual technology when the application of that technology is systematically distorted.

The empirical vehicle for examining distortions in input allocations described by (77) and (78) is a second order translog approximation to the variable cost function amended parsimoniously to incorporate input and output characteristics. Included among these are characteristics of technology which may react to changes in market conditions and/or short-run and long-run changes in input substitution and output transformation possibilities. The virtual variable translog cost function $\ln C^*$ is given by

$$\begin{aligned}
\ln C^* \;=\;& \alpha + \sum_i \alpha_i \ln Y_i + \frac{1}{2} \sum_i \sum_j \alpha_{ij} \ln Y_i \ln Y_j \\
&+ \frac{1}{2} \sum_l \sum_m \gamma_{lm} \ln Y_l \ln(w_m + \theta_m) + \frac{1}{2} \sum_n \sum_o v_{no} \ln Y_n \ln X_{J+o-1} \\
&+ \sum_i \beta_i \ln(w_i + \theta_i) + \frac{1}{2} \sum_p \sum_q \beta_{pq} \ln(w_p + \theta_p) \ln(w_q + \theta_q) \\
&+ \frac{1}{2} \sum_r \sum_s \lambda_{rs} \ln(w_r + \theta_r) \ln X_{J+S-1} + \sum_i \rho_i \ln X_{J+i-1} \\
&+ \frac{1}{2} \sum_t \sum_u \rho_{tu} \ln X_{J+t-1} \ln X_{J+u-1}.
\end{aligned} \tag{79}$$

Virtual cost shares are given by

$$S_i^* = \beta_i + \sum_j \beta_{ij} \ln(w_j + \theta_j) + \sum_j \gamma_{ji} \ln Y_j + \sum_j \lambda_{ij} \ln X_{J+j-1}. \tag{80}$$

The relationship between the observed cost and cost share system and those of the virtual technology are given by

$$\begin{aligned}
\ln C \;=\;& \ln C^* \\
&+ \ln \left\{ \sum_i \left[ \beta_i + \sum_j \beta_{ij} \ln(w_j + \theta_j) + \sum_j \gamma_{ji} \ln Y_j \right.\right. \\
&\left.\left. + \sum_j \lambda_{ij} \ln X_{J+j-1} \right] \frac{w_i}{(w_i + \theta_i)} \right\}
\end{aligned} \tag{81}$$

$$
\begin{aligned}
S_i^* &= [S_i w_i/(w_i+\theta_i)]\,/ \\
&\left\{\sum_j \left[\beta_i + \sum_k \beta_{jk}\ln(w_k+\theta_k) + \sum_k \gamma_{kj}\ln Y_k \right.\right. \\
&\left.\left. + \sum_k \lambda_{jk}\ln X_{J+k-1}\right]\cdot \frac{w_j}{(w_j+\theta_j)}\right\}. \qquad (82)
\end{aligned}
$$

Symmetry and linear homogeneity in input prices are imposed on the virtual cost function by the restrictions $\alpha_{ij}=\alpha_{ji}$, $\forall i,j$; $\beta_{ij}=\beta_{ji}$, $\forall i,j$; $\sum_i \beta_i = 1, \sum_j \beta_{ij}=0$, $\sum_j \lambda_{ij}=0$, $\forall i$, and $\sum_j \gamma_{ij}=0, \forall i$.

Summary statistics based on the virtual translog and its associated share equations are provided by the Morishima and Allen-Uzawa[32] substitution elasticities, and several measures of returns to scale which extend from the short-run to the long-run. A measure of excess costs due to the divergence of virtual and measured prices is given by the difference between the estimated observed $\ln C$ and estimated $\ln C$ for which $\theta=0$. Any divergence between observed and virtual price for any input will cause this difference to be positive when the virtual cost function is concave.

The endogeneity of technology in this series of illustrative examples arises from the notion that an air carrier optimizes not only to obtain the appropriate multiple input mix but also to select the correct configuration of the fleet and the type of service its fleet is being chosen to serve. The choice of these characteristics will depend on the market prices and trade-offs between the benefits and costs of different technological features of the fleet and various dimensions of its routes.

This menu of production techniques is modeled with a set of attributes of the aircraft fleet, and the effects of changes in these attributes over time are examined (see Baltagi and Griffin, 1988 for an alternative panel data treatment of technological change). We consider four attributes of the capital stock: vintage, size, diversity in size, and percentage of the fleet that is jet-powered.[33] Also included in the cost function are two measured outputs—scheduled and nonscheduled service; three variable inputs—labor, fuel and materials (an aggregation of supplies and outside services); one quasi-fixed input—flight and ground equipment; and four attributes of airline networks—the stage length, the number of cities serviced, the extent of

[32]See Blackorby and Russell (1989) for a discussion of the relative merits of the Morishima and Allen-Uzawa elasticities.

[33]The rationale for using these attributes are discussed in Good, Nadiri, and Sickles (1991).

network connectivity, and the load factor. The technology has three variable inputs, one quasi-fixed factor, four technology characteristics, two measured output quantities, and four output service characteristics. Fixed firm effects are controlled for by including firm dummy variables in the cost equation. These firm effects can be given the reduced form interpretation of omitted variables that are specific to the firm and display little variability over the sample period of seven years, or can be given a more structural interpretation as time-invariant technical inefficiencies from a stochastic frontier cost function (Schmidt and Sickles, 1984). However, it is not clear that the latter structural interpretation does justice to the data given the results of Cornwell, Schmidt and Sickles (1990). We thus view the time invariant fixed effects as unobserved/unmeasured firm specific heterogeneity.

The econometric analysis focuses on three related modeling issues. The first is whether or not the assumption that virtual and observed prices are the same is supported in the airline industry during the deregulatory transition. The competing hypotheses are represented by comparing restricted models (where $\theta = 0$) with their unrestricted counterparts. The second issue deals with how technological progress should be specified. We consider two approaches: the commonly used time trend specification and our capital attribute specification. In our capital attribute model, a menu of different production technologies is explicitly described. Technological change is captured by how the adopted production technique changes over time. The third deals with endogeneity of output, its characteristics and the production technique. Two estimators are considered: the commonly used iterated seemingly unrelated regression method, ITSUR (Zellner, 1962), and iterated three stage least squares, IT3SLS. We allow the outputs, output characteristics, capital stock and the production technique to be endogenous.[34]

Results from estimating the eight separate models based on the two treatments of allocative inefficiency, the two treatments of technical changes, and the two treatments of endogeneous technology can be found in Good et al. (1991). The assumption that firms were unconstrained cost-minimizers is rejected at standard nominal significance levels. The specification of disembodied technical change proxied by a time trend leads to a breakdown of the model in that regularity conditions fail at almost all of the sample observations. Results based on the most general model which allows for allocative distortions and endogenous embodied technical change suggest that

[34]The instruments are constructed from nine input prices, the time trend, interactions among the input prices and time, as well as seasonal and airline dummies. We construct the instruments so that they are homogeneous of degree zero in prices in order to preserve the linear homogeneity of the estimated virtual cost function.

the airlines in our sample are over utilizing both labor and capital. Moreover, there is evidence of an underutilization of energy and overutilization of materials relative to levels consistent with unconstrained cost-minimization; labor and materials are overused by 12 and 9 percent respectively, and fuels are underused by approximately 14 percent. Even though labor and materials are overused, these inputs are still productive and are substituted for using less energy. Consequently, the 2.6% increase in cost due to the incorrect input mix is substantially less than the expenditures on the overused inputs. The distortion estimates indicate that in order for firms to be unconstrained cost-minimizers, labor's share in total cost should have fallen during the sample period by 7.3 percent. The share of energy should have increased by 10.1 percent. The share of materials should have fallen by 7.2 percent. The share of capital should have fallen by about 4.5 percent. These figures are comparable to the 1977–83 sample changes of 5.3, 10.2, 0.3, and 3.2 percent.

Short-run factor demands for all variable factors are inelastic, with energy (−0.088) the least elastic, followed by labor (−0.305) and materials (−0.466). The Morishima substitution elasticities for the labor/materials pair are [0.552, 0.941] while the Allen-Uzawa elasticity is 1.006. Comparable estimates for the materials/energy and labor/energy pairs are [0.081, 0.458] and −0.036, and [0.362, 0.184] and 0.203 respectively. These substitution possibilities are due, in part, to the ability of firms to substitute labor within the firm with outside labor services (predominantly contract maintenance and travel agent commissions) and to contract out for maintenance and spare parts. The substitution elasticities for the labor/energy pair are small and appear to be best characterized by fixed coefficients.

Short-run returns to scale are estimated to be 1.77. While on the surface this may seem high, it is due mainly to large fluctuations in demand exhibited in our quarterly data. Its primary effect is to capture increasing utilization rates of capital and labor over these seasonal fluctuations. The value of what Caves, Christensen and Tretheway (1984) term "returns to density" is estimated at 1.67. This measure assesses the change in cost as outputs are proportionately increased while holding the network, its characteristics, and the characteristics of the aircraft fleet fixed.[35] Long-run returns to scale, or

[35]While higher than the Caves, Christensen and Tretheway value of 1.24, it can again partially be explained by the use of quarterly data and a somewhat different study period. An alternative measure of scale economies examines the returns to additional cities added to the network with no new route segments. This type of output change can be accomplished only if additional use is made of sparser networks (such as by using hub-and-spoke or loop type networks). We term this returns to hubbing and estimated it at 1.44.

returns to size, allows output, capital, the number of cities and the number of routes to increase proportionately and is estimated to be 1.07.[36] The estimate of cost complementarity indicates that scheduled passenger output and cargo/nonscheduled output are slight substitutes. While the belly of aircraft scheduled for passenger services can also hold cargo, the decline in popularity of combination aircraft since deregulation has meant that most cargo is carried by air freighters.

It is well known that when there are increasing returns to scale, when a regulatory constraint is binding, or when the other conditions just mentioned are present, standard total factor productivity estimates misrepresent the rate of technological change. Here we outline the appropriate decomposition of technical change in which the choice of technique is endogenous and observed input levels may be suboptimal.

Using the Divisia index number method, total factor productivity growth is computed to be

$$\dot{\mathrm{TFP}} = \sum R_i \dot{Y}_i - \sum_{i \neq k} S_i \dot{X}_i - S_k \dot{X}_K \tag{83}$$

where $R_i$ is the observed revenue share of output $i$ and $S_j$ is the observed *cost* share for input $j$. Here $X_K$ is the quasi-fixed level of an arbitrary input, e.g. capital. Adapting an approach by Denny, Fuss, and Waverman (1981) to allow for the quasi-fixed input, nonoptimality in the level of input utilization, a set of output characteristics, $z$, and a set of capital characteristics, $c$, the observed variable cost function is

$$C^v(Y, w, X_K, z, c) \tag{84}$$

The growth rate of observed variable cost is

$$\dot{C^v} = \sum \varepsilon_i \dot{Y}_i + \varepsilon_k \dot{X}_K + \sum \eta_i \dot{z}_i + \sum \left[\frac{\partial \ln C^v}{\partial \ln w_i}\right] \dot{w}_i + \dot{T} \tag{85}$$

where $T$ describes the rate of cost diminution due to changing technology (changes in the growth rate of capital characteristics or time). In addition to the appearance of terms for capital and output characteristics, this differs from other decompositions since the cost elasticity with respect to input

[36]The way that airline networks have changed falls somewhere between the returns to hubbing and returns to size estimates, but their magnitudes suggest that the intensity of merger activity since deregulation may have resulted, in part, from some modest scale economies. It may also represent benefits from increases in feed traffic and the desire of consumers to complete their entire flight with the same carrier.

prices is not necessarily the expenditure share due to potential allocative distortions. Since $C^v = \sum w_i X_i$ , the growth rate of observed variable cost can also be described by $\dot{C}^v = \sum S_i^v \dot{w}_i + \sum S_i^v \dot{X}_i$. A bit of algebra reveals that

$$\sum S_i^v \dot{X}_i = \sum \varepsilon_i \dot{Y}_i + \varepsilon_k \dot{X}_K + \sum \eta_i \dot{z}_i + \sum \left[ \frac{\partial \ln C^v}{\partial \ln w_i} - S_i^v \right] \dot{w}_i + \dot{T} \quad (86)$$

The discrepancy between total cost expenditure shares in equation (83) and the variable cost expenditure shares in equation (86) can be remedied by recognizing that $S_i = (1 - S_k) S_i^v$ . Combining equation (85) with equation (86) yields the following decomposition

$$\begin{aligned} \dot{\text{TFP}} &= \sum [R_i - (1 - S_k)\varepsilon_i] \, \dot{Y}_i \\ &\quad - [S_k + \varepsilon_k (1 - S_k)] \, \dot{X}_K - \sum (1 - S_k) \eta_i \dot{z}_i \\ &\quad - (1 - S_k) \sum \left[ \frac{\partial \ln C^v}{\partial \ln w_i} - S_i^v \right] \dot{w}_i - (1 - S_k) \dot{T} \end{aligned} \quad (87)$$

The first term on the right can be further decomposed into a scale effect and a nonmarginal cost pricing effect:

$$\begin{aligned} \dot{\text{TFP}} &= \left[ \sum R_j - \frac{\varepsilon_j}{\sum \varepsilon_k} \right] \dot{Y}_j + \left[ 1 - (1 - S_k) \sum \varepsilon_i \right] \frac{\sum (\varepsilon_j \dot{Y}_j)}{\sum \varepsilon_i} \\ &\quad - [(1 - S_k)\varepsilon_k + S_k] \, \dot{X}_K - (1 - S_k) \sum \left[ \frac{\partial \ln C^v}{\partial \ln w_i} - S_i^v \right] \dot{w}_i \\ &\quad - (1 - S_k) \sum \eta_i \dot{z}_i - (1 - S_k) \dot{T} \end{aligned} \quad (88)$$

The first term describes the component of TFP growth which can be attributed to nonmarginal cost pricing (output mix). Given the plethora of prices charged in the industry the resemblence of airline pricing decisions to marginal cost pricing may be questionable. The second term presents a multiple output component of TFP growth which is attributable to scale economies. The third term depicts productivity growth due to changing the quantity of the quasi-fixed factor, e.g. capital. The fourth term describes TFP growth which can be attributed to non-cost minimizing behavior. Note that when Shephard's lemma is applied, cost elasticities and input shares are identical and the term disappears. The fifth component describes TFP growth which is attributable to changing output and network characteristics.

Finally, the last term describes the amount of technical change, that is, the rate of cost diminution attributable to shifts in the production technology.

Figure 5 demonstrates the close correspondence of TFP growth estimates and TFP growth based on index number calculations. Figures 6 and 7 display the temporal decomposition of TFP growth. It provides additional insights into the process of growth. Seasonal fluctuations have been smoothed in Figure 6 using a 4-period moving average process. The decomposition based on equation (88) demonstrates that an important contribution to total factor productivity growth has been a reduction in output mix departures from those consistent with marginal cost pricing, but that by 1984 the reduction in these distortions was largely played out. This is consistent with other work (Sickles, Good and Johnson, 1986). Economies of scale played an important role in TFP growth prior to deregulation and the period from 1982–1983, but provided significant negative contributions in the period from 1979 through 1981. Both output scale and output characteristics contributions to TFP growth seem to have been significantly affected for the worse by the 1979–1980 oil price shock. Input distortions were a significant drain on TFP growth prior to 1982. In fact, during the early deregulatory period, they slowed TFP growth by a full percentage per quarter. Changing the attributes of the capital stock led to a sizable productivity growth of approximately 0.15% per quarter with the exception of the recession period beginning in 1982 where little equipment replacement occurred.

# 6 Alternative Structural Models of Productivity in Collusive Markets

## 6.1 Econometric Model of European Cartel Behavior

The previous sections have pointed to the need to properly specify both demand conditions and dynamics of production when investigating the sources of TFP growth. In this section we broaden the scope for endogenous demand and market structure in TFP calculations by considering a model of collusion in an oligopoly structure with product differentiation. European airline industry data for the period 1976–1990 are used to examine endogenous production decisions and market structures. A more detailed discussion of these and other modeling approaches as well as the data sources can be found in Good et al. (1993a,b, 1994), Captain (1993), Roeller and Sickles (1994), Captain and Sickles (1996), Captain, Good, and Sickles (1996).

Consider an industry in which $N$ firms produce a differentiated output,

$Y$, using $n$ inputs $X = (X_1, \ldots, X_n)$. The market demand function facing firm $f$ at time $t$ is of the form:[37]

$$Y_{ft} = Y_f(p_t, p_{mt}, Z_t, \delta), \tag{89}$$

where $p_{mt}$ is an index of all the other firms prices, $Z_t$ are the other variables (measured on the country level) shifting demand and $\delta$ are unknown parameters of the demand function. "Perceived" Marginal Revenue is:

$$PMR = p_t + D_1 Y_{ft}, \tag{90}$$

where $D_1 = \partial p_{ft}/\partial Y_{ft}$. The cost function facing firm $f$ is:

$$C_{ft} = C^f(Y_{ft}, w_{lt}, Q_t, \gamma), \tag{91}$$

where $w_{lt}$ is the vector of factor prices paid by firm $f$ at time $t$, $Q_t$ are the other industry variables shifting cost and $\gamma$ are unknown parameters of the cost function. Marginal cost is written as:

$$MC = C_1(Y_{ft}, w_t, Q_t, \gamma) \tag{92}$$

The firm chooses optimal output where $MC$ equals "perceived" Marginal Revenue in an oligopolistic industry ( $PMR = p$ in a perfectly competitive setting). Thus the quantity-setting condition is:

$$C_1(Y_{ft}, w_t, Q_t, \gamma) = p_t + D_1(p_{ft}, p_{mt}, Z_t, \gamma)Y_{ft}\theta \tag{93}$$

The parameter $\theta$ is an index of the competitive nature of the firm. If $\theta = 0$, price equals marginal cost and the industry is perfectly competitive, while a $\theta = 1$ is consistent with Nash behavior. In a price-setting game (Bertrand, 1883), the first order conditions for profit maximization imply:

$$\frac{\partial Y_{ft}}{\partial p_{ft}} p_t + Y_{ft} - \frac{\partial C_{ft}}{\partial Y_{ft}} \frac{\partial Y_{ft}}{\partial p_{ft}} = 0.$$

Summing over the $N$ firms we have $y_t = \sum_f Y_{ft}$ and thus

$$\frac{\partial y_t}{\partial p_t} p_t + y_t - \sum_f \frac{\partial C_{ft}}{\partial Y_{ft}} \frac{\partial Y_{ft}}{\partial p_{ft}} = 0.$$

Assuming symmetry in costs, the behavioral equation reduces to the form:

$$p_t = \frac{\partial C_{ft}}{\partial Y_{ft}} - \frac{y_t}{\frac{\partial y_t}{\partial p_t}} \theta \tag{94}$$

[37] For different forms of this model, see Bresnahan(1990)

The cost function is specified as translog:

$$\ln C(Y, w) = \ln a_0 + \sum_i a_i \ln(w_i) + \frac{1}{2}\sum_i \sum_j b_{ij} \ln(w_i)\ln(w_j)$$

$$+b_Y \ln(Y) + \frac{1}{2} b_{YY} \ln(Y)^2 + \frac{1}{2}\sum_i b_{Yi} \ln(Y)\ln(w_i) + Q. \qquad (95)$$

Here, the inputs are capital ($X_K$), labor ($X_L$) and materials ($X_M$). The prices of the inputs are $w_K$, $w_L$ and $w_M$ respectively. $Q$ contains heterogeneity controls for service and capital characteristics which are added linearly and include log(average stage length), log(network size), log(load factor), percentage of planes that are wide bodied, and percentage of planes that are turbo prop. Returns to scale, computed as the inverse of the elasticity of costs with respect to output, are $\mu = 1/\varepsilon_{cY}$ where $\varepsilon_{cY} = [b_Y + b_{YY}(\ln Y) + b_{YL}(\ln w_L) + b_{YM}(\ln w_M) + b_{YK}(\ln w_K)]$. The market demand function is specified as semi-logarithmic:

$$\begin{aligned} \ln Y &= d_0 + d_1 p + d_2 P_{INDEX} + d_3 GDP \\ &\quad + d_4 GASP + d_5 GCONS + d_6 PRAIL \end{aligned} \qquad (96)$$

where $Y$ is the output of firm $f$, $p$ is the price of firm $f$, $P_{INDEX}$ is an index of the other $N-1$ firms' prices, $GDP$ is Gross Domestic Product, $GASP$ is the retail price of gasoline (inclusive of taxes) and $PRAIL$ is the price of rail travel.

The behavioral equation[38] which identifies the degree of competition is $P = MC - \Theta/d_1$. Additive disturbances are appended to the system of five equations – translog cost, labor share, capital share, demand and behavior – are estimated by iterative nonlinear three stage least squares, treating $p$, $Y$, $C$, $S_L$ (labor share), $S_K$ (capital share), and $w_L$ as endogenous and all others as exogenous (the standard panel data firm fixed effects is specified in the cost equation). Endogeneity of the labor's price is due to the strong national carrier status of the European carriers over the sample period and the use of the national carriers to pursue macroeconomic employment stabilization policies. This method ensures that all parameter estimates, log-likelihood values and estimated standard errors are invariant to the choice of which share equation is deleted (Berndt, 1991).

[38]The behavioral equation is: $p_t = \frac{\partial C_{kt}}{\partial Y_{kt}} - \frac{y_t}{\frac{\partial y_t}{\partial p_t}}\theta$. Given the semi-log demand specification, $\frac{\partial \ln y_t}{\partial p_t} = d_1 \Rightarrow \frac{\partial y_t}{\partial p_t} = y_t d_1 \Rightarrow p_t = M - \frac{\theta}{d_1}$

The results below are based on a panel of the eight largest European carriers-Air France, Alitalia, British Airways, Iberia, KLM, Lufthansa, Sabena, and SAS-with annual data from 1976 through 1990. The data come from several sources. The primary sources for the production, cost, network, and fleet data are the *Digest of Statistics* from the International Civil Aviation Organization (ICAO) and *World Air Transport Statistics* from the International Air Transport Association (IATA). Demand data was obtained from the OECD and from *Jane's World Railways.*

To identify the underlying market structure, one can test the null hypothesis that $\Theta = 1$ for a non-cooperative Nash equilibrium, with the alternate hypothesis that $\Theta < 1$. The null hypothesis was rejected at the 95% confidence level. The demand elasticities show that the demand for air travel is elastic (-1.308) implying that consumers are sensitive to price changes by the local airline (a 1% increase in price results in a 1.29% drop in quantity demanded at sample averages). Further, while there may be some variation in individual markets, on the aggregate industry level, the cross-price elasticity indicates that all airlines are close substitutes (3.27). This number would indicate that the level of product differentiation in the industry is minimal. The parameter of the price of rail travel is positive and highly significant. The cross price elasticity is positive (0.224) implying that rail travel is also a substitute to air travel in the market. All the output elasticities were highly significant. Further, countries with higher GDP's have a higher demand for air travel. The variables in the demand equation are all significant and have the expected signs with the exception of the retail price for gasoline. This may be an artifact of the trend in the prices for aviation fuel. Another possible explanation is that air travel and car travel may be complementary goods in Europe, with a large percentage of cars rented at airports.

The estimated cost equation is monotonically increasing with fitted shares positive for all observations. It is strictly quasi-concave in input prices—the $3 \times 3$ matrix of substitution elasticities is negative semi-definite evaluated at the mean of the panel. Returns to scale variable averaged over all observations is 1.28 ($s.e. = 0.0025$). The five airline specific variables all have the expected signs and are significant with the exception of $\ln(load\ factor)$. The sign on $\ln(stage\ length)$ implies that the larger the stage length, the lower the cost of the flight. Airlines that have a higher percentage of wide-body aircraft in their fleet and fewer turbo-props have lower cost structures. Further, increasing the size of the network lowers the total cost of the airline.

The Allen partial elasticities of substitution indicate that capital, labor and materials are substitutable inputs, but are insignificant. Average markups ($p - MC$) can also be calculated by year and airline. The results are striking. The average mark-up from 1976–1986 was 2.72 % which implies that the prices set in the bilateral agreements were close to the competitive levels (*i.e.*, the governments did a good job regulating the industry). However, as the European markets slowly opened to more competition after 1986 (and less regulation), the markups increased significantly. To analyze these results even further, one can evaluate the yearly profits of these eight airlines. The data indicate that all the airlines with the exception of Lufthansa experienced losses in the early period from 1976–1986. However, after 1986 most of the airlines significantly improved their profitability or reduced their losses. British Airways, which was privatized in 1987, experienced a huge turnaround and averaged a profit margin of over $150 million for the period 1987–1990 (after consistently being in the red from 1976 through 1986).

There is strong evidence from the parameter estimates to support the claim that the high prices in Europe were not entirely due to monopoly power. The markups over price were minimal over the 1976–1986 period, but did rise dramatically from 1987–1990, when we added a single year at a time to the model. The demand for air travel in the home market was highly elastic and the cross-price elasticities showed that all airlines and the local railways on the industry level were close substitutes over the entire sample. This suggests that the high prices especially in the earlier years was due to high marginal costs.

Good, *et al.* (1993a, 1993b, 1995) found that the European airlines are highly inefficient compared to the U. S. airlines. For the period 1976–1986, the European carriers, specifically the three major carriers, Air France, British Airways and Lufthansa were less technically efficient than all the American carriers including Pan Am and Eastern, which have since exited the U. S. market. A possible explanation for these inefficiencies (and the high marginal costs) is the powerful labor unions in Europe negotiating wages above competitive levels.

## 6.2 Extensions of the Model of Cartel Behavior to a Dynamic Setting

Endogenous market structure and production decisions can be analyzed using the dynamic programming techniques discussed in section 4 with modifications to handle conjecural variations. We base the following discussion on recent work by Captain, Good, and Sickles (1996) which is based on the intertemporally nonseparable dynamic model of Hotz et al. (1988). We use the dynamic model to analyze long-run strategies of firms and to simulate the optimal profit-maximizing levels of the strategic variables for different scenarios.

Assume that the firm chooses the level of employment ($X_L$), network size ($X_N$) and capital ($X_K$) to maximize the flow of expected profits,

$$\max \mathcal{E}_t \sum_{t=\tau}^{\mathrm{T}} \beta^{\tau-t} \Pi_t(X_{Lt}, X_{Nt}, X_{Kt}) \tag{97}$$

subject to a per-period asset accumulation constraint

$$A_{t-1} = \gamma_t(A_t + p_t Y_t - w_{Lt} X_{Lt} - r_t I_t)$$

where

$$Y_t = F(X_{Lt}, X_{Nt}, X_{Kt}, \ldots),$$

where $A_t$ are the firm's real assets in the beginning of period $t$, $\beta^t$ is the discount factor, $\gamma_t = (1 + r_t)$, $r_t$ is the real interest rate, $p_t$ is the price of output, $I_t$ is the level of investment. The time horizon (T) is assumed to be finite and exogenous. Other inputs, such as materials, are assumed to be state variables in the simulations and *thus are not* directly introduced through the production function. Assume that $T$ is finite and $Y_T = 0$ when the firm exits the industry. Capital accumulation is written in terms of a perpetual inventory model:

$$X_{Kt} = I_t + \alpha a_t$$

where the law of motion for $a_t$ is :

$$a_t = (1 - \eta)\, a_{t-1} + X_{Kt-1}$$

Here $\eta$ measures the rate of depreciation of past levels of capital stock to its current level, while $\alpha$ is the capital depreciation rate. Temporal non-separability in the dynamic optimization problem comes in through the distributed lag of current and past investment decisions. The dynamic programming problem is characterized by the value function which at time $t$ is:

$$V_t(A_t, a_t, p_t, w_{Lt}, w_{Kt}) \tag{98}$$

$$= \max_{X_L, X_N, X_K} \{\Pi_t(X_{Lt}, X_{Nt}, X_{Kt}) + \beta \mathcal{E}_t \left[V_{t+1}(A_{t+1}, a_{t+1}, p_{t+1})\right]\} \tag{99}$$

The three Euler equations for the control variables are:

$$
\begin{aligned}
(X_L) \qquad & 0 = \Pi_{X_L}(t) - \beta\gamma_t\mathcal{E}_t\Pi_{X_L}(t-1)\{[w_t + w_L(t)X_L(t) \\
& -p_tY_L(t) - p_Y(t)Y_{X_L}(t)Y_t] / \\
& [w_{t+1} + w_L(t+1)X_{Lt+1} - p_{t+1}Y_{X_L}(t+1) \\
& -p_Y(t+1)Y_{X_L}(t+1)Y_{t+1}]\} \qquad (100)
\end{aligned}
$$

$$
\begin{aligned}
(X_N) \qquad & 0 = \Pi_{X_N}(t) \\
& +\Pi_{X_L}(t)\frac{p_tY_{X_N}(t) + p_Y(t)Y_{X_L}(t)Y_t}{w_{Lt} + X_{Lt} - p_tY_{X_L}(t) - p_Y(t)Y_{X_L}(t)Y_t} \qquad (101)
\end{aligned}
$$

$$
\begin{aligned}
(X_K) \qquad & 0 = \Pi_{X_K}(t) \\
& -\Pi_{X_L}(t)\frac{w_{Kt} + w_K(t)X_{Kt} - p_tY_{X_K}(t) - p_Y(t)Y_{X_K}(t)Y_t}{w_{Lt} + w_L(t)X_{Lt} - p_tY_{X_L}(t) - p_Y(t)Y_{X_L}(t)Y_t} \\
& +\alpha\beta\mathcal{E}_t\Pi_K(t+1) + [(1-\eta+\alpha)\beta] \\
& \cdot\mathcal{E}_t\left(w_{Kt+1} + w_K(t+1)X_{Kt+1} - p_{t+1}Y_{X_K}(t+1) - Y_{X_K}(t+1)Y_{t+1}\right) \\
& \cdot\left(w_{Lt+1} + w_L(t+1)X_{Lt+1} - p_{t+1}Y_{X_L}(t+1) - p_Y(t+1)Y_{t+1}^{-1}\right) \\
& \cdot\mathcal{E}_t\Pi_{X_L}(t+1) - \mathcal{E}_t\Pi_{X_K}(t+1)] \qquad (102)
\end{aligned}
$$

where $p_Y(t) = \frac{\partial p_t}{\partial y_t}$,and $\Pi_{Xi}(t) = \frac{\partial \Pi_t}{\partial X_{it}}, Y_{Xi}(t) = \frac{\partial Y_t}{\partial X_{it}}, w_i(t) = \frac{\partial w_i}{\partial X_{it}}$ for $i = K, L$.

Let the production function be specified as a Cobb-Douglas stochastic frontier (Cornwell, et al., 1990) of the form:

$$
\ln Y_{ft} = \ln X_{ft}\beta + \ln Z_f\gamma + \ln Q_{ft}\delta_f + \epsilon_{ft}
$$

$$
\delta_f = \delta_0 + u_{ft} \qquad (103)
$$

were the subscripts $f = 1, \ldots, N$ and $t = 1, \ldots, T$ refer to firm and time, respectively, $X_{ft}$ is a vector of inputs, $Q_{ft}$ is a vector of other firm characteristics, and $Z_f$ is a vector of explanatory variables which have different effects for different firms. The unobservable effects, $\delta_f$, can be correlated with other explanatory variables and can interact with selected slope and intercept terms. This allows for the endogeneity of variables such as load factor and network size with respect to the firm specific statistical error. The $u_{ft}$ are assumed to be an i.i.d. zero-mean random vector with covariance matrix $\Sigma_u$. The disturbances $\epsilon_{ft}$ are taken to be i.i.d. with zero mean, constant variance $\sigma_\epsilon^2$, and to be uncorrelated with both the regressors and

$u_{ft}$. Total revenues can then be calculated at time $t$ by specifying the factor market demand equation and total profits at time $t$ can be obtained by specifying a total cost function.

To close the dynamic model we need to specify the demand and cost equations by bringing in equations (89-96). Estimates from the model outlined in the previous subsection, the system of five equations – translog cost, labor share, capital share, demand and behavior – treating $p$, $Y$, $C$, $S_L$, $S_K$ , and $w_L$ as endogenous and all others as exogenous, were used to calibrate the system of Euler equations and simulate the optimal levels of employment, network size, and capital (number of planes) during the sample period. These were then compared with the observed levels employment, network size, and capital. The simulations were carried out for four different sets of values for $\alpha$, $\beta$, and $\eta$. Details of the simulations can be found in Captain (1993) and Captain et al. (1996). Because of bilateral agreements in the European airline industry cabotage rights were limited for carrierrs not in the bilaterals. As such the internal scale of operations was very restricted, evidenced from their relatively small network sizes and small fleets. British Airways and Lufthansa are the largest European carriers in terms of numbers of planes and personnel, and rank after Air France in terms of the size of the network. The results indicate that an increase in the network and fleets sizes was warranted for the other carriers for the bulk of the period 1979-1990 and suggest substantial allocative distortion in the size of the European networks as well as in their labor allocations. European networks on average were too small and employment levels on average were too large.

# 7 Measurement and Econometric Estimation Issues

## 7.1 Measurement

It is clear that modeling the determinants of total factor productivity and estimating the contributions of various factors that affect TFP growth in the economy, its component industries, and particular firms has advanced considerably in recent years. However, two other issues which affect measurement and analysis of productivity growth are the quality of data used and the econometric techniques employed in the estimation process. We adress the issue of measurement error in this subsection and consider econometric issues in the next subsection.

Griliches (1994) has summarized the potential measurement issues pertaining to productivity analysis. He lists the following eight causes of measurement error:

1. Coverage issues, definition of the borders of a sector, and the relevant concept of 'output' for it. For example, is illegal activity included? Are pollution damages counted against the 'output' of an industry?

2. The difficulty in measuring 'real' output over time as prices and the quality of output change.

3. Improper measurement of inputs over time when there are changes in the skill-mix of the labor force, changes in the quality of the machinery and equipment used, and changes in the utilization of the labor force and of the existing capital stock.

4. Exclusion of certain inputs involving such items as research and development and of public infrastructure expenditures in the total input concept.

5. Missing data on hours worked by people, machines, and other specific inputs.

6. Improper 'weights' used to construct a particular index which often ignore the divergence of market prices from 'shadow prices' and the impact of various disequilibria.

7. Formula differences, the unknown shape of the underlying production possibilities frontier, and gross versus net concepts.

8. The consequences of aggregation over heterogeneous individuals and industries.

These topics have been subject to long continuous effort by serious researchers at universities and statistical offices here and abroad. The measurement issues are highly problematic, costly, and often subject to serious controversies. These issues affect how productivity is measured and what are the legitimate contributors to TFP growth. Often it is not one of these issues but a combination of them that influence the causes of productivity growth. Their importance varies across countries, industries, and time. Therefore, it is extremely important to continue and increase effort to improve the quality of data often used in productivity study. In recent years, as Griliches(1994) has noted, the major problems have been associated with measurement of real output and real input growth, i.e., the correct measurement of prices and associated adjustment for quality changes. Measurement of capacity utilization of capital and labor is a measure issue in the context of the short run comparisons. In the long run, the quality improvement of the labor force through education and experience, the amount of resources devoted to discovery of new knowledge through R&D effort, and organizational restructuring of industries and productive units to absorb new and advanced production techniques, are likely to be both major sources of true productivity growth and also present a continuous and major challenge for analysts of productivity behavior.

## 7.2 Econometric Issues

Not only accurate measurement of the underlying data is critical for understanding the problem of productivity growth but so are the estimating scenarios used to bring order to the data in line with theoretical and practical insights provided by economic and engineering theory. We have touched on several broad themes involving econometric treatments used in empirical productivity research. Clearly, the nature and scope of data allow for richer statistical paradigms to be used. Panel data models have become increasingly popular in productivity studies in multivariate (Sickles, 1985) and univariate (Ahn and Schmidt, 1996) models as such panels as the Longitudinal Establishment Files monitored by the Census Department's Center for Economic Studies and the U.S. Airline Panel Data Sets (Caves, Christensen, and Tretheway, 1984; Good and Sickles, 1986) have been made available to researchers. As new panels, as well as time series and cross sectional firm/industry/country data are becoming available for productivity analysis, so too are the tools of non- and semi-parametric estimation. One particularly interesting class of model holds promise for estimating dynamic structural models of production in the presence of arbitrary heterogeneity.

A rich set of alternatives exist to the generic dynamic specifications using Bellman's equation and close-form solutions to the Euler equations that have been pursued above. For example, firm specific heterogeneity can be included in the production or utility function directly. Heterogeneity can be specified in terms of a set of observable individual specific variables. Simulated method of moments can be used to effectively integrate out the unobserved heterogeneity (McFadden, 1989; Pakes and Pollard, 1989, McFadden and Ruud, 1994). This essentially means that population orthogonality conditions are averaged over draws from the heterogeneity distributions and these averaged orthogonality conditions are used in the GMM procedure on the Euler equations. This is a computationally intensive procedure but one that promises to be more widely used as computing cycles become increasingly less expensive.

Often, a control variable may be measured categorically or may have limit observations (e.g. a value of zero to an output in a multiple output model). In this case dynamic discrete methods can be employed as well as Kuhn-Tucker constraints or explicit construction of virtual prices that correspond to the observed limit observations (Ransom, 1987; and Lee and Pitt, 1986). In different contexts, exact and approximate solutions for the dynamic discrete model have been explored by, among others, Gotz and McCall (1984), Wolpin (1987), Miller (1984), Pakes (1987), Rust (1987, 1989), Eckstein and Wolpin (1989), Hotz and Miller (1993), Manski (1991), Hotz, Miller, Sanders and Smith, (1994), Berkovec and Stern (1991), Keane (1994), Stern (1994). Keane and Wolpin (1994) have recently also pursued simulation approaches to solve the dynamic discrete choice model using a combination of Monte Carlo integration and regression based interpolations as alternatives to the polynomial approximations suggested in Bellman, Kalaba, and Kotkin (1963). These and other alternatives, such as those proposed by Judd (1995) which utilize orthogonal polynomials or other series approximations for Bellman's equation, appear particularly attractive for future research on productivity using highly structured models which consider such issues as heterogeneity, discrete state and control variables, and constraints.

# 8 Concluding Remarks

In this paper we have discussed two basic approaches to measurement of productivity growth: the index number approach and the approach adopted by econometric modeling analysis. Considerable advances in both theory and measurment techniques of index number analysis has been achieved in recent years. Its basic appeal is simplicity and that it provides a first approximation to productivity growth measurement. However, it is based on restrictive assumptions, among which are the absence of non-constant returns to scale, perfect competition in both input and output markets, and optimization behavior by the firms. This approach cannot distinquish between a shift in the production function (the pure technical change effect) and movement along the function due to scale and relative price changes. Such a distinction is crucial to understanding the forces that shape the very process of productivity advancement.

The basic appeal of the econometric modeling strategy is its flexibility to incorporate in a consistent framework both theoretical considerations and institutional factors that influence productivity growth. We discussed in this paper a number of econometric modeling techniques that have been pursued in the literature which explicitly incorporate specific factors that influence the rate of technical change and productivity growth at the firm, industry, and aggregate economy level. They indicate how it is possible to account for the influences of scale, relative price movement, rate of innovation due to R&D effort, and regulatory constraints and non-optimization due to disortions in factor markets or other relevant determinants on productivity growth. We also have discussed how technological spillovers, public sector capital, and alternative market structures can affect productivity performance. The overall conclusions that arise from the studies reported in this paper are (1) that econometric modeling methods allow the contribution of a complex and often competing set of forces that shape productivity growth to be distinguished in a general framework and that their significance can be tested statistically and (2) that aside from the usual supply side forces that shape productivity performance, it is important to identify the contributions of the "extent of the market", particularly the growth of aggregate demand, to the trend as well as in the acceleration or deceleration of total factor productivity. If changes in demand influence productivity, the role of monetary and fiscal policies which affect the level and growth of aggregate demand becomes a central issue in the debate on and measurement of total factor productivity growth.

However, accurate measurement of productivity growth, as it is the case for any other field of applied economics, depends crucially on the quality of data used for estimation purposes and the advancements in estimation methodologies. We have outlined briefly some of the considerations with respect to the quality of data that require substantial effort and technical expertise by economists and statistical agencies. Further advancement in measurement of productivity growth critically depends on whether new and more accurate data are available to estimate the dynamic forces that govern the movement of productivity growth. Another crucial advancement that also will play an important role in accurately measuring technical change and productivity growth is development of new estimation techniques. We have also discussed, albeit briefly, some of the progress in this area in the last section of the paper. Further advancement in this area is not only desired but is necessary to exploit the increasing availability of panel data and new theoretical analyses with which to capture the effect of dynamic factors that undoubtedly influence productivity growth.

Aside from these considerations a number of other unresolved issues require further effort: (1) There is a basic problem of heterogeneity of plants, firms, industries, and countries. Often these units are assumed to behave in the same way to changes in exogenous variables assuming that their production or cost functions are the same; (2) There is also the problem of consistent aggregation from the firm to the industry and to the national level. The evidence reported in various studies cannot easily be generalized to the next level of aggregation because of the lack of acceptable aggregation rules and the availability of data; (3) Much more emphasis is required to develop models that capture the dynamic forces that link past technologies and operations to those currently in operation or in the planning stages; and (4) Advancement in statistical estimation technology to capture the complexity of dynamical forces that characterize economic growth is a further challenge that cannot be ignored.

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# 10 Tables and Figures

Table 1: Decomposition of TFP Growth 1947–1976 †

| | Source (%) | | | | | |
|---|---|---|---|---|---|---|
| Period | Technical change Direct (a) | Technical change Indirect (b) | Factor prices (c) | Exogenous demand (d) | Net scale effect (e) =(c)+(d) | $\dot{TFP}$ (average annual rate) |
| 1947-1957 | 13.7 | 1.3 | -32.3 | 117.1 | 84.8 | 0.0350 |
| 1958-1967 | 23.8 | 2.2 | -14.5 | 88.8 | 74.0 | 0.0365 |
| 1968-1976 | 44.0 | 4.2 | -13.7 | 65.5 | 51.8 | 0.0496 |
| 1947-1976 | 30.6 | 2.9 | -17.6 | 84.1 | 67.2 | 0.0409 |

† $\eta_r = -0.8$. Columns (a) through (e) are computed from (19) in the text.

Several years for which the measured TFP growth was negative were deleted; these include the Korean War period (1952-1953) and 1948-194

Table 2: Sources of Output Growth for the U.S. and Japanese Electrical Machinery Industries: Average Annual Rates of Growth (in %)

| | Gross Output | Labor Effect† | Materials Effect† | Capital Effect† | R&D Effect† | Adjustment Cost | | Technical Change | Residual |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Capital | R&D | | |
| United States: | | | | | | | | | |
| 1968–73 | 4.2 | -.24 | 1.83 | .87 | 1.18 | .06 | .12 | .73 | -.32 |
| 1974–79 | 4.9 | .39 | 1.06 | .69 | .31 | -.09 | .04 | .86 | 1.67 |
| Japan: | | | | | | | | | |
| 1968–73 | 16.9 | .94 | 14.32 | 2.12 | .7 | -.26 | -.34 | 1.55 | -2.11 |
| 1974–79 | 6.4 | -.66 | 2.08 | 1.10 | .72 | .09 | -.12 | 2.55 | .69 |

† Growth rate of input weighted by average output elasticity

Table 3: Decomposition of Labor Productivity Growth in the U.S. and Japanese Electrical Machinery Industries: Average Annual Rates of Growth (in %)

| | Labor Productivity | Labor Effect | Materials Effect† | Capital Effect† | R&D Effect† | Adjustment Cost | | Technical Change | Resi |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Capital | R&D | | |
| United States: | | | | | | | | | |
| 1968–73 | 4.68 | -.04 | 2.07 | .91 | 1.28 | .06 | .12 | .73 | |
| 1974–79 | 3.56 | .15 | .43 | .37 | .12 | -.07 | .04 | .86 | |
| Japan: | | | | | | | | | |
| 1968–73 | 12.63 | .81 | 10.24 | 1.33 | .56 | -.13 | -.26 | 1.55 | - |
| 1974–79 | 8.95 | -.47 | 4.48 | 1.54 | .86 | .05 | -.16 | 2.55 | |

† Growth rate of input weighted by average output elasticity

**Figure 1**
**Comparisons of Alternative Productivity Indices**
**(Industry Level Data)**

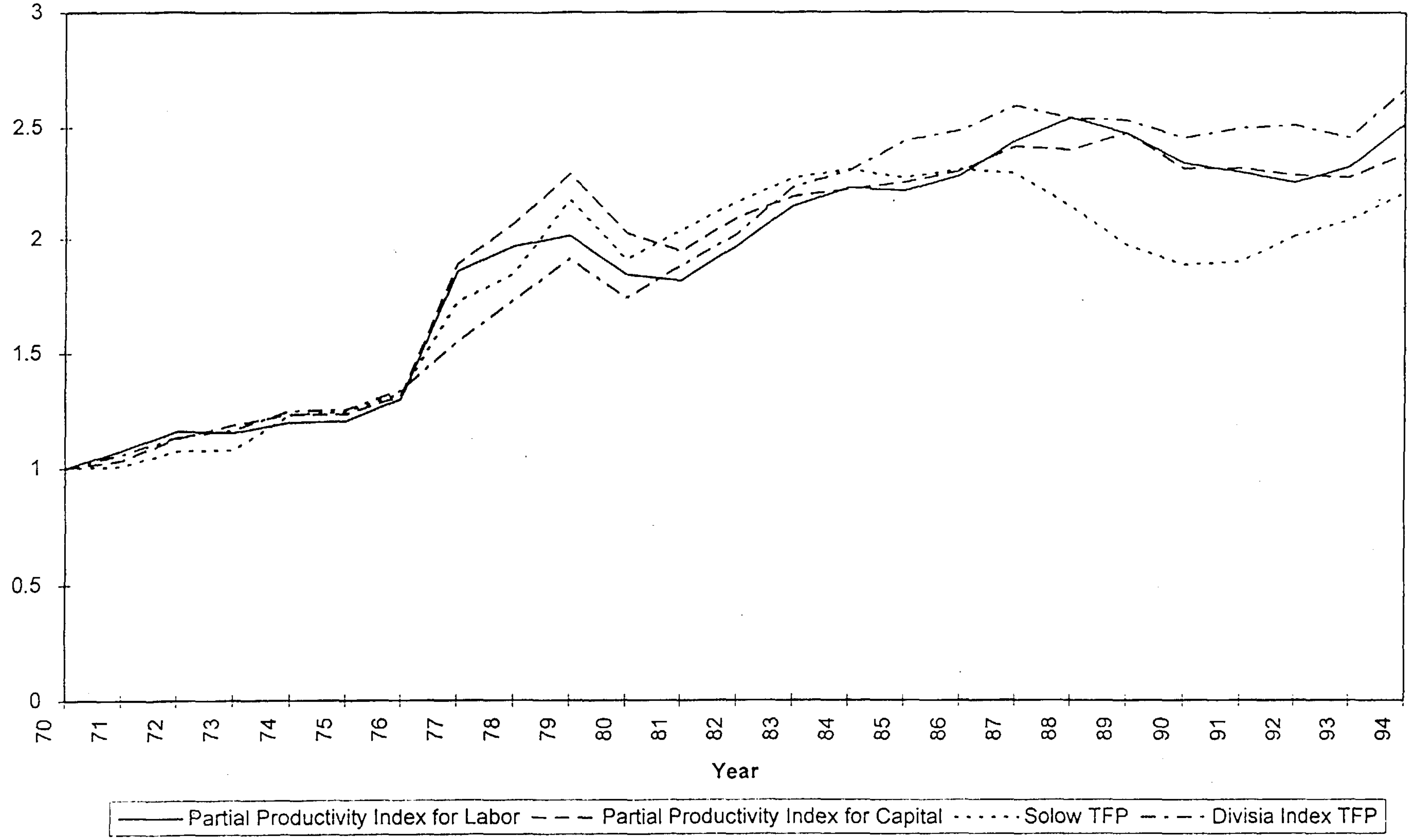


Figure 2
Distribution of Total Factor Productivity Index (Divisia)
(Firm Level Data)

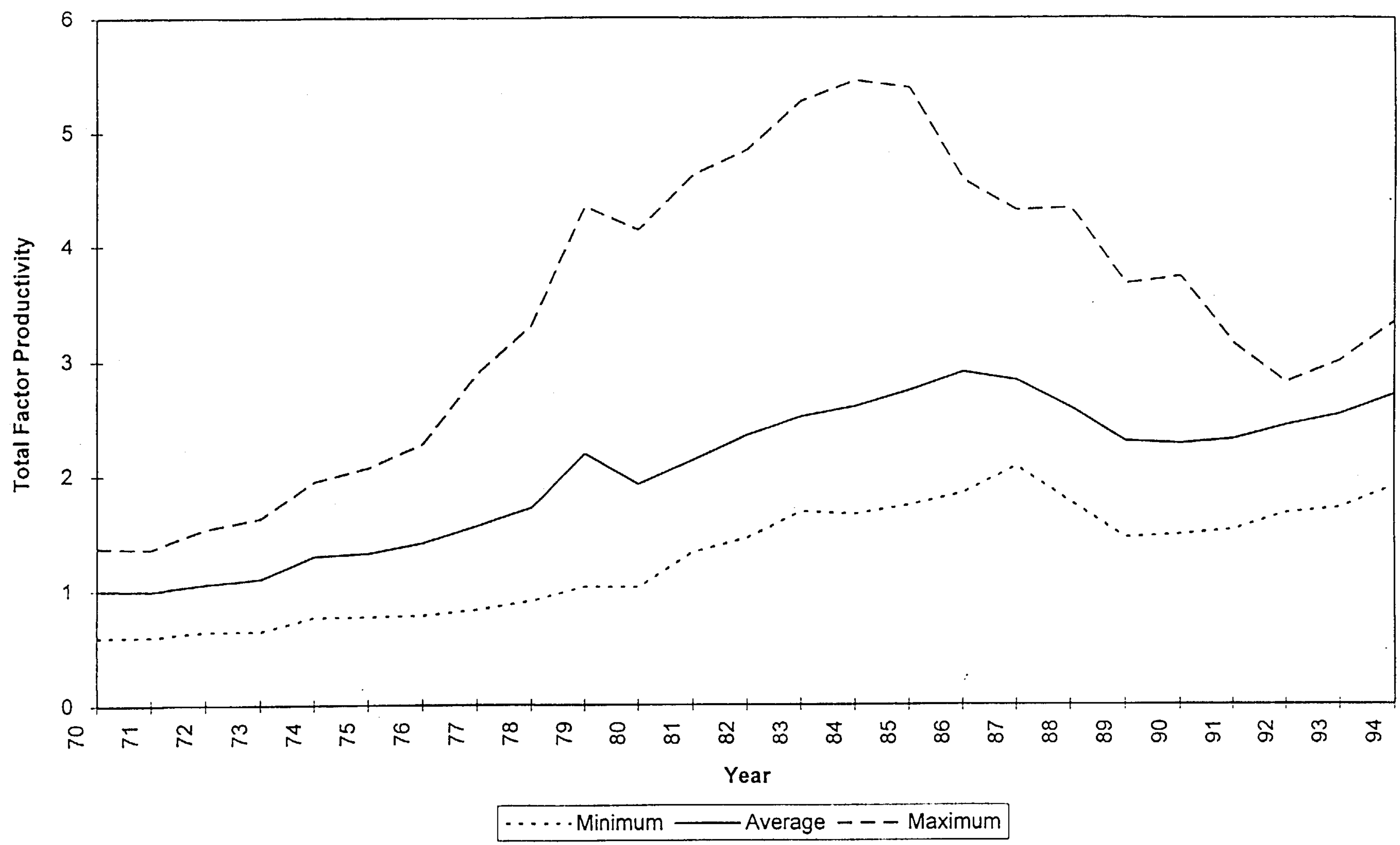


**Figure 3**
**Temporal Pattern of Airline Industry Concentration**

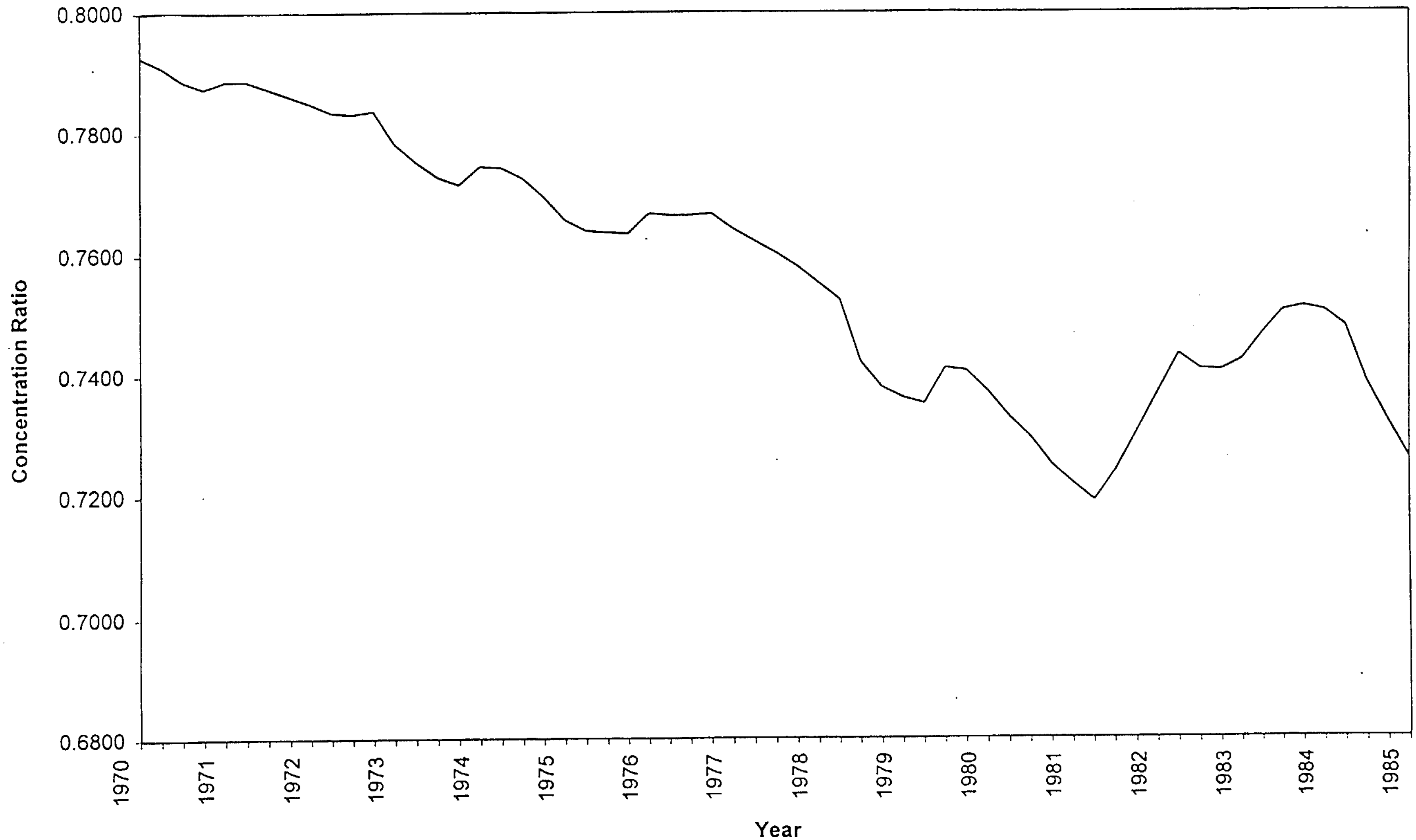


**Figure 4**
**Employment and Decomposition of TFP Growth Index**

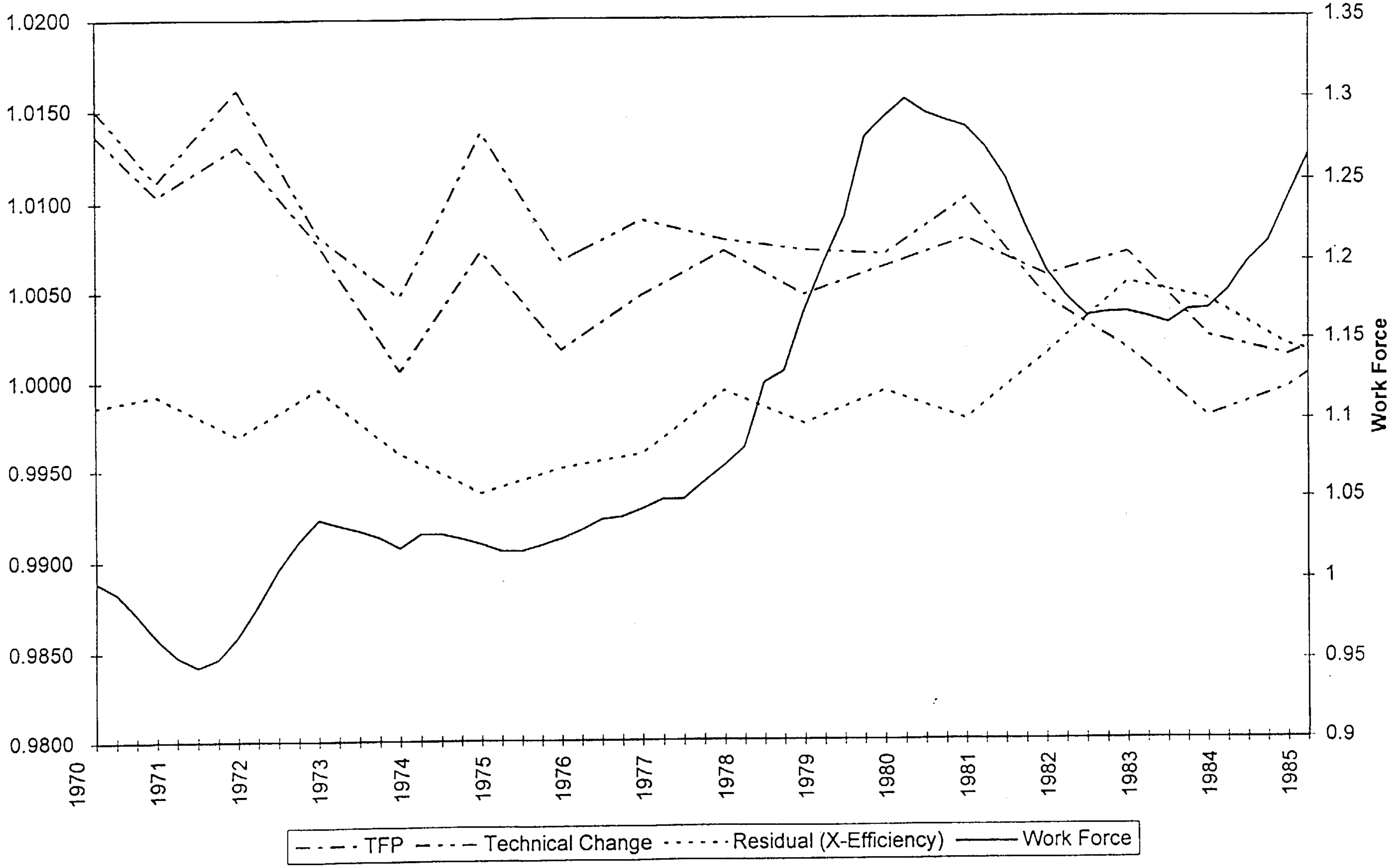


**Figure 5**
**Comparison of Index Number and Cost Fuction Based TFP Growth Rates**

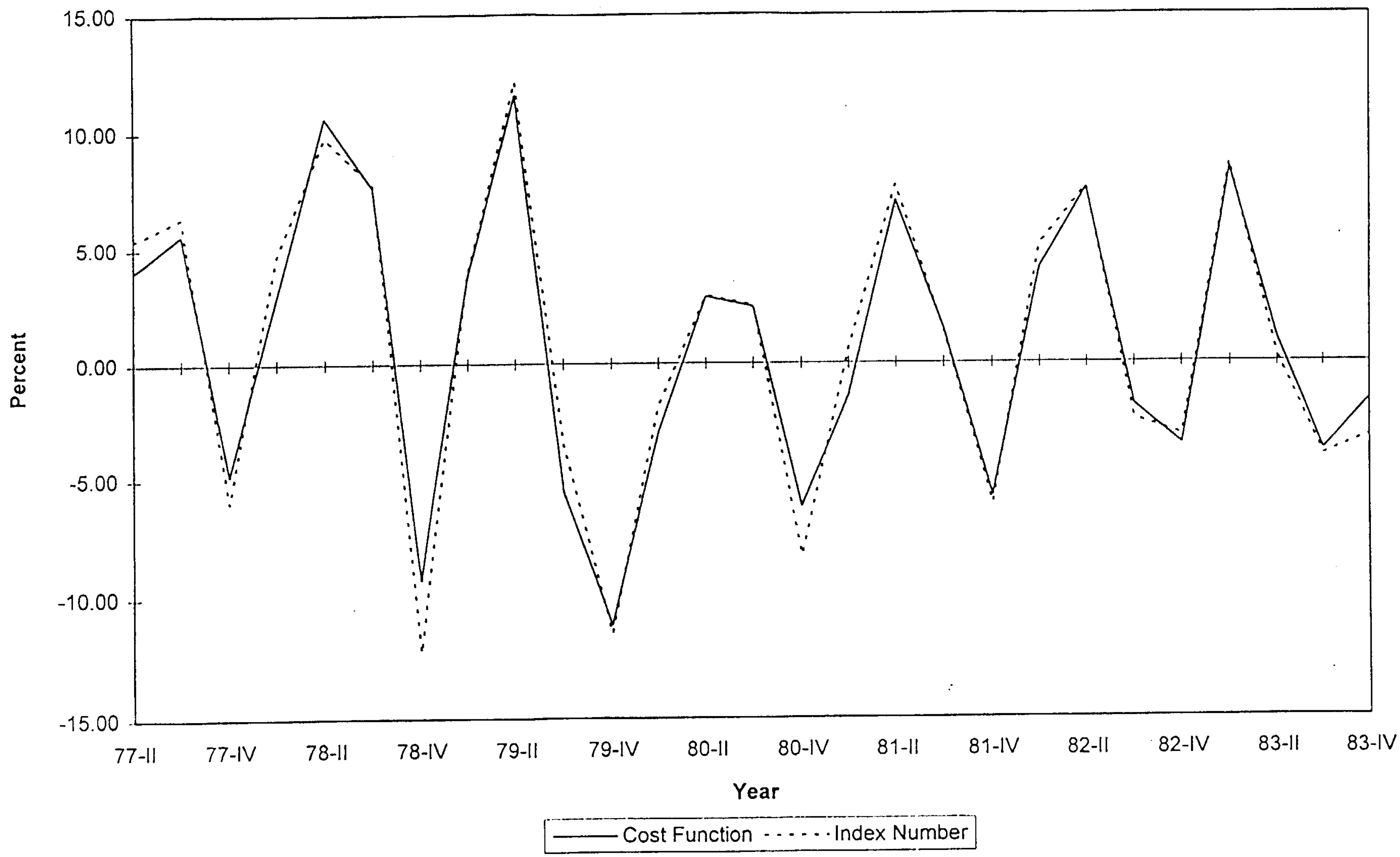
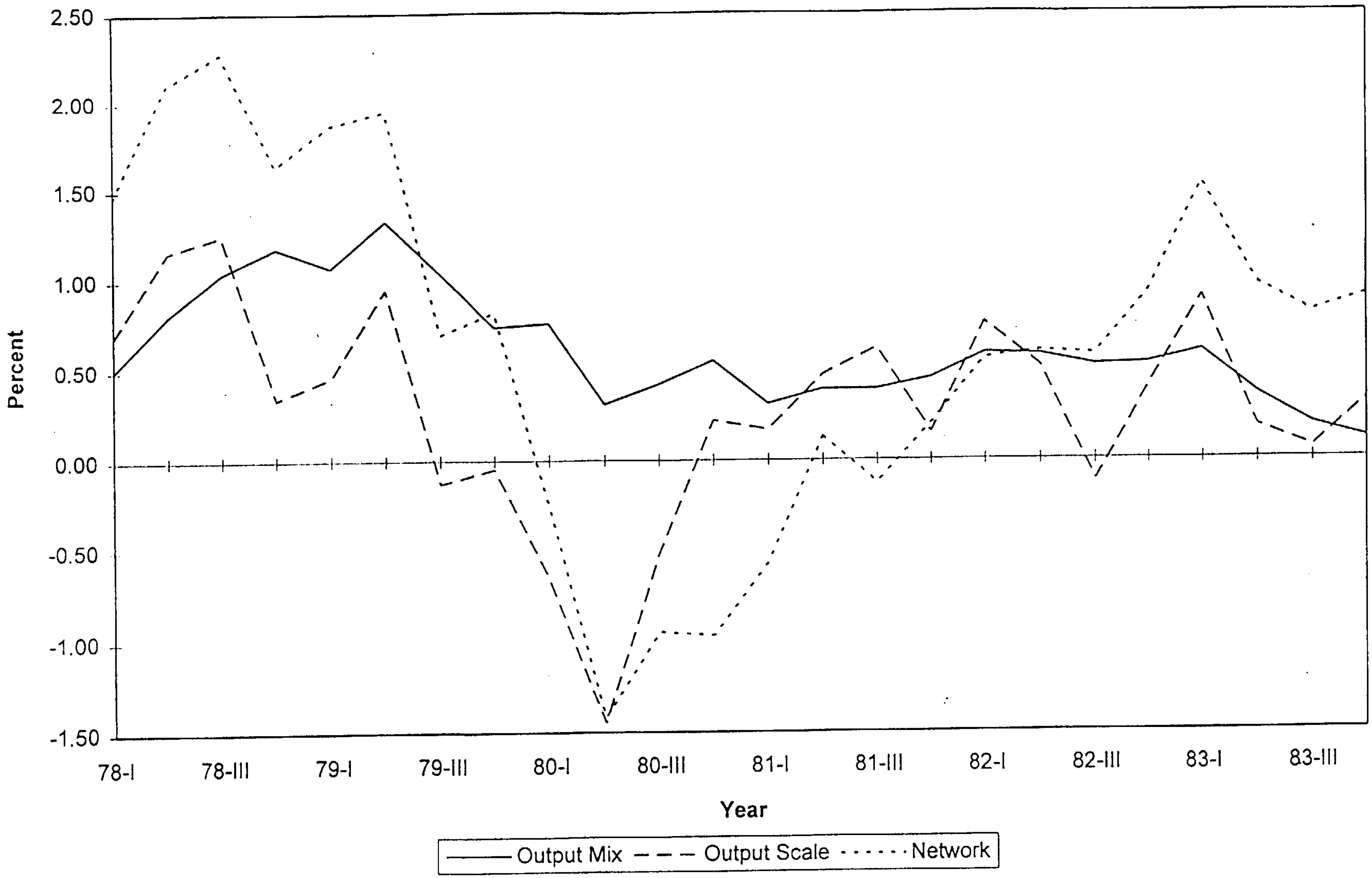


Figure 6
Decomposition of TFP Growth Rates: Output Scale, Output Mix, and Network Characteristics



## Figure 7
## Decomposition of TFP Growth: Input Distortion, Capital, and Technical Change