Research And Development Activities And Productivity Growth At The Firm Level.

Citation

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Research and development activities and productivity growth at the firm level

Zhao, Qinghui, Ph.D.

Lehigh University, 1991

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Research and Development Activities and Productivity Growth at the Firm Level

By

Qinghui Zhao

A Dissertation
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Doctor of Philosophy
in
Business and Economics

Lehigh University
April 1991

Approved and recommended for acceptance as a dissertation in partial fulfillment of the requirement for the degree of Doctor of Philosophy.

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Acknowledgments

The author wishes to express his appreciation to the dissertation committee for their guidance, suggestions, and encouragement throughout the course of this research project. In addition, the author specially thanks:

Dr. Alden S. Bean for initiating and directing this research project, coordinating the dissertation committee, helping me edit my dissertation, and gaining support from the sample firms, without which this project would not have been possible;

Dr. Arthur E. King for coordinating the dissertation committee and important suggestions for improving my writing style and the text presentation and clarity;

Dr. Thomas T. Hyclak for helping me focus on the research topic and valuable suggestions on research methodologies, especially in estimating an operational measure of total factor productivity;

Dr. Edwin Mansfield for important suggestions on defining the current sample and key variables that ensured the current research has been conducted in a sensible and meaningful way; and

Dr. Donald T. Campbell for his inspiration about scientific research which has influenced the process of this investigation in many ways.

The author also would like to sincerely thank:

Mr. Roger L. Whiteley, Associate Director of the Center for Innovation Management Studies (CIMS), Lehigh university, for sharing his special insight into the manufacturing industries, especially in areas of technical services and productivity;

Mrs. Diane M. Bean, Mrs. Esther E. Speziale, and Mrs. Nancy A. Speck, the staff of CIMS, for their hospitality, encouragement and assistance throughout the course of this dissertation;

the nine corporate R&D managers and economists who provided special guidance and suggestions about the organization of R&D and technical service activities, and about economic adjustments at the firm level; twelve firms also provided verified data for use in this study;

Professor June A. West, Associate Director of the Philip Rauch Center for Business Communications, Lehigh University, for her assistance in editing this dissertation; Dr. William G. Wells, Visiting Scientist at Lehigh University's Center for Innovation Management Studies from George Washington University, for his comments; and Mr. Chia-Ying Ma, my fellow graduate student at Lehigh, for his assistance in data collection and computation;

the Center for Innovation Management Studies, Lehigh University, for a research grant (CIMS #0132) and College of Business and Economics of the University for financial support; and finally,

my parents for their patience and understanding; and my wife, Weifang, for her help and encouragement during all these years.

Qinghui Zhao
April, 1991

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Abstract

The importance of research and development (R&D) activities in the firm's productivity growth has long been recognized, and because of their heterogenous characteristics, research on the interrelations and the individual productivity impact of these activities has also been constantly suggested in the literature of R&D productivity studies and by corporate R&D management. This study examined systematically the productivity effects of all four R&D activities. It also extended the analysis into the 1980s and made considerable effort to improve the data accuracy by adjusting the firm's data at the SIC four-digit level.

Results from this study indicate that, in the last two decades, firms in the chemical industry have focused primarily on competition in existing markets and their R&D programs have concentrated on product and process developmental activities. This study has concluded that these development activities strongly contributed to the firms' total factor productivity growth. Further, this study suggests that applied research of the chemical firms actively supported the developmental programs and, when combined with these programs, contributed to the firm's growth. Finally, it was found that basic research in the chemical firms has been very weak and no direct effect on productivity could be found based on the current analysis.

This study also provided the first empirical assessment of the productivity impact of technical services, another main component of the firm's total technical effort. Results of this study indicated that this activity has not contributed to the firm's long-term productivity growth and that the amount of technical services might have grown beyond an "optimal level."

Introduction

Economists, as well as historians, political scientists, and sociologists will generally agree that one of the major forces shaping human destiny has been technological change. For example, the discovery of grain cultivation was responsible for the agricultural surplus that made the existence of urban society possible. The introduction of gunpowder and the printing press was a major factor that changed the political system in Europe. Technological knowledge delineates the manner in which resources can be combined to yield output of goods and services, and thus it is one of the most important factors responsible for economic growth.

Interest in and perceptions of technological change have undergone considerable variation in the past. Eighteenth- and nineteenth-century economists could not fail to notice some of the consequences of the acceleration in economic growth then taking place, but they regarded technology as *exogenous* to the economic system (Mathias, 1984). This economic treatment of technological change has been very persistent among economists and economic historians. Not until the early 1930s did their perceptions of technological progress begin to change (Kuznets, 1930; Schumpeter, 1934). However, most changes in the analysis of technological change took place after World War II. An important stimulus was the significance of post-war economic growth and the attempt by economists to evaluate its causes. In recent decades, studies responding to the persistence of slowdown in economic growth and the increase in international competitiveness further promoted research on the relationship between technological change and economic growth. These studies, as described below, have helped both to re-establish the importance of technological change as a source of economic growth and to show the limits of the existing approach to the analysis of technological change.

In the late 1950s, Abramovitz (1956) and Solow (1957) noted the substantial magnitude of the residual difference between rates of growth of real product and weighted rates of growth of labor and capital inputs as conventionally measured. Abramovitz termed this residual a "measure of our ignorance." The search for factors that would explain changes in productivity growth and thus reduce the residual has been a major challenge since then. Several influential studies (Schmookler, 1952; Fabricant, 1954; Abramowitz, 1956 and Solow, 1957) suggested that the historical growth in labor productivity was predominantly due to the application of new production technology. Solow (1957) reported that about 90 percent of the long-term increase in output per capita in the United States was attributable to technological change, increase in education levels and variables other than labor and capital factors. Denison (1962) concluded that about 40 percent of the total increase in national income per person employed during 1929-1957 was attributable to the "advance of technology."

Studies of technological change were aimed not only at analyzing its effects, but also at its internal structure of the process. Since the 1960s, an important connection has been discovered between the direction of technological progress and the extent and nature of research and development (R&D) spending of individual firms. For example, Comanor (1965) and Mansfield (1968) found, for a given firm size, a close relationship in the long run between the rate of R&D spending and the total number of important inventions forthcoming. Scherer (1965), Schmookler (1966), Comanor and Scherer (1969) reported the close relationship between patents and R&D expenditures. Pavitt and Wald (1971) found a high correlation across 13 U.S. industries between R&D intensity and rates of technological innovation. As a result, the relationship between R&D and productivity growth has been well established and documented by Terleckyj (1960, 1974), Minasian (1962, 1969), Mansfield (1965, 1968b, 1980), and Griliches (1973, 1981).

These studies of technological change could not have been done within the existing model of technological progress, mainly based on neo-classical economics, and thus formed the basis for the endogenous theories of technological change. These theories state that the supply of technological change is an endogenous force acting within the economic system and is determined by the amount of resources (R&D expenditures) allocated to the modification of existing techniques or the production of new techniques (Nelson, Peck and Kalachek, 1967; Mansfield, 1968; Nordhaus, 1969).

Based on the theories of endogenous technological change, this dissertation will investigate the productivity issue of R&D activities, and further the conventional analysis of R&D productivity at the firm level by decomposing total R&D into appropriate elements, including basic, applied research and developmental activities. The productivity impact of technical services is also examined in this study. Major efforts will be made in deriving price deflators at the SIC four-digit level.

There are six chapters in this dissertation. Chapter 1 will introduce the theories and concepts which form the basis of this study and will discuss the recent patterns of industrial R&D funding and performance in the United States. Chapter 2 will review the major literature on R&D productivity studies. Model specifications and variable definitions of this dissertation will be presented in Chapter 3, and the sample profiles of this study will be described in Chapter 4. The estimates and tests of the model will be discussed in Chapter 5. In the last chapter, Chapter 6, suggestions for future research on R&D productivity will be proposed.

Chapter 1
The Economics of Technological Change

The process of measuring the contribution of technological change (R&D) to productivity gains basically involves three steps: measuring technological change; measuring productivity gain; and establishing the relation between these two measures. This chapter will discuss these three steps separately but the scope of the discussion is limited by the following considerations:

1. Efforts at measurement have proceeded at four levels: the single innovation (case study), the level of the firm (or business unit), the level of the industry, and the level of the national economy. Each level of measurement has its unique problems and issues. Because this study is at the firm level, the following discussion is limited to concepts and issues at this level. Also, analytical frameworks and estimation techniques at each level of measurement may differ and interpretation of estimates obtained may vary. The terms "R&D productivity studies" and "empirical research" in this dissertation specifically refer to the econometric studies using production functions.

2. Technological change affects many economic and financial variables, such as productivity growth, the firm's market value and the firm's knowledge stock. Because this dissertation is the study of productivity growth, the following discussion on technological change will be confined to economic matters. Consequently, the phase "technological change" refers to the change of technological *input* in the production process, and the *impact* of technological

change is measured by "productivity gains" or "productivity growth"

1.1 Technological Change

Based on Mansfield's (1968, 1990) definition, technology is society's pool of knowledge regarding industrial, agriculture and medical arts. Industrial technology consists of knowledge regarding physical and social phenomena that is applied by industry to guide day-to-day operations. Technological change is the advance of technology and takes the form of *new* methods of production, organization and marketing. It differs from a change in technique and from scientific advance. A change in technique is an alteration of the character of the *existing* products, equipment, and organization. Scientific advance has had a great impact on technological change but theoretically, it is directed toward *understanding*, whereas technology is directed toward *use*.

Of particular interest to this study are two issues about technological change which are concerned with how technological change influences productivity and what impact it has on other factors of production. First, technological change can be either a change affecting an entire set of existing techniques or a change via the introduction of new techniques. In the first case, new technological knowledge affects the efficiency of known techniques in a disembodied fashion. In the latter case, new technological knowledge is embodied in a new technique that either is added to the existing pool of techniques or displaces some old techniques.

Disembodied technological change means that all technological changes consist of improvements in knowledge and organization and are independent of capital and labor. With disembodied technological change, the same quantities and types of labor and capital will produce more output. Examples of such technological change are the development of time and motion studies in industrial engineering, the development of linear programming in operations research, and the change from U-form to M-form organizational structures.[1] On the other hand, embodied technological change is technique specific and requires new investment in physical goods such as plant and equipment for the new knowledge to be utilized. This embodiment may require only conventional factors of production, and it results in an incremental improvement in output growth.

The assumption of the embodiment of technological change is critical in estimating the economic impact of technological change because it requires a different form of model specification and leads to different estimation results. For example, by assuming embodied technological change, Solow (1959) obtained a higher estimates of the rate of technological change in the private economy during 1919-1953 than his previous estimates that assumed disembodied technological change. Mansfield (1968) also reached the same conclusion, as will be reviewed in Chapter 2. Conventionally, most R&D productivity studies have assumed disembodied technological change partly because this assumption simplifies the analytical framework and thus allows researchers to explore their research objectives more thoroughly.

The second issue about technological change is that it may be "biased," i.e, it can be either labor-saving or capital-saving. Given the rate of output and the relative prices of factors of production, if technological change results in a greater percentage reduction in capital input than labor input, it is capital-saving (or labor-using). If it results in a greater percentage reduction in labor

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[1] One of the differences between the U-form and M-form is that the U-form is centralized and has a pyramidal structure while the latter is decentralized (Williamson, 1981).

input than capital input, it is labor-saving (or capital using). If it results in an equal percentage reduction in both capital and labor inputs, it is termed a "neutral" technological change. However, technological change may alter the relative demands for factors of production, and through the market mechanism, alter the equilibrium price ratios. This further complicates the issue of biased technological change.

Empirically, there is no agreement on the precise definition of bias in technological change. The most cited measure of biased technological change is changes in relative shares of output going to an input, including the Hicksian definition, the Harrodian definition, and Solow's definition.[2] If technological change is "embodied" in labor or/and capital, the bias in technological change also will depend on the elasticity of factor substitution and the differential rates of growth of labor and capital embodiment.

In neo-classical theory of production, technological change is exogenously determined and thus, there is no need to pre-suppose the nature of technological change. However, if technological change is an endogenous process, relative factor endowment may serve as determinant of the type of technological change. It can be hypothesized that labor-saving innovations will be favored in countries (or firms) relatively well endowed with capital, whereas capital-saving innovations will be favored in countries (or firms) relatively well endowed with labor. Many economists have speculated that technological change in the United States has been oriented toward labor-saving, but there is no direct evidence supporting it (Salter, 1960; Mansfield, 1968).

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[2] The mathematical expression of these definitions is given in End-Note 1, page 27.

1.1.1 Measurement of Technological Change

Ideally, technological change should be measured by the change in the firm's technological assets (knowledge stock) such as patents, inventions and innovations. But, such intangible stock is difficult to measure in ways that are consistent across fields of knowledge and areas of use. However, as mentioned earlier, the close relationship between the firm's technological progress and the firm's R&D investment has been established (Comanor, 1965; Scherer, 1965; Mansfield, 1968). This makes it possible to measure the firm's technological change through its R&D investment.[3]

According to the National Science Foundation (NSF) definition, the term research and development "includes basic and applied research in the sciences (including medicine) and in engineering, and design and development of prototypes and processes. It does not include quality control, routine product testing, market research, sales promotion, sales service, research in the social sciences or psychology, or other nontechnological activities or technological services."[4]. This definition categorizes R&D into three activities. First, there is basic research, the original investigation for the advancement of scientific knowledge.[5] Second, there is applied research which aims at a specific practical payoff; and third there is development, which is to reduce research finding to practice.

A considerable amount of resources have been devoted to R&D in the U.S.

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[3] As any other research subject, there are many issues and problems related to the measurement of technological change through R&D expenditures. There is no reason why the estimates of the economic impact of technological change and of R&D should be the same. Mansfield (1977b) suggested that the latter estimate be smaller than the former. Other issues relate to this measurement will be discussed both in Chapter 2 and Chapter 3.

[4] "Methodology of Statistics on Research and Development", NSF 1959, p.124.

[5] More complete definitions and discussions of the R&D components will be presented in Chapter 3.

Estimated total R&D investment reached $132 billion in 1989, or 2.6 percent of GNP.[6] Real R&D expenditures have more than doubled during the last three decades, rising from about $44 billion in 1960 to an estimated $105 billion in 1989. Four major sectors provide financial sources for R&D: the Federal government, private industries, colleges and universities, and nonprofit institutions. The federal share of total national R&D expenditures in 1989 was about 47 percent, falling from 65 percent in 1962; the industrial share was 48 percent in 1989, rising from 33 percent in 1960; universities and colleges supported about three percent of the R&D in 1989, up from one percent in 1960.

Private industries, the Federal government, and universities and colleges are the three largest R&D performing sectors. In 1989, the private industrial sector performed 71 percent of total national R&D; the Federal government 11 percent; and universities and colleges 10 percent.

Among these three R&D activities, basic research, applied research and development, the broad national patterns of the relative emphasis of R&D investment have hardly changed at all.[7] Since 1960, the proportions of total R&D devoted to these three types of activities have shifted only marginally: basic research has fluctuated between 9 percent and 14 percent; applied research between 21 percent and 24 percent; and development between 63 percent and 69 percent. In 1989, the private sector performed only 18 percent of total basic research but most of the total applied research (72%) and total development (85%).

In the private industrial sector, individual industries show very different trends in both their R&D expenditures and in the sources of support of these

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[6] All statistics reported here are from the National Science Board (1989).

[7] This pattern is important to this dissertation, as will be elaborated in Chapter 3.

expenditures. The National Science Board thus divides industries into three groups: high-technology manufacturing, other manufacturing, and nonmanufacturing, based on the ratio of their R&D expenditures to their net sales.[8]

1.2 Measurement of Productivity

In the neo-classical theory of production, productivity gains resulting from technological change take place in the form of shifting the firm's production possibility frontier toward a higher level of production. If the production function were readily observable, a comparison of production at two points in time would provide a simple measure of the productivity gain of technological change. In reality, however, this relationship is complicated because the production function is not directly observable.

Productivity often is measured as a ratio of output to input. Two such measures are used the most: the partial productivity index and the total factor productivity index (TFP). Labor productivity is the most often used partial index.[9] The most common measure of TFP in R&D studies[10] is Solow's index (1957). Based on the Cobb-Douglas production function with constant returns to scale and both disembodied and neutral technological change, Solow derived his measure as:

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[8] The group memberships are given in End-Note 2 (page 27). See National Science Board (1989), page 352.

[9] This index is "partial" only when it is used *alone*, such as to compare productivity per worker over time. However, in the econometric studies of R&D productivity using the production function approach, The terms "total" and "partial" are misleading because under the production framework and with certain assumptions, these two indices are mathematically equivalent.

[10] Another common measure of TFP in studies of productivity, but not in R&D studies, is Kendrick's index (1961), as described in End-Note 3, page 28.

$$\frac{d\Pi}{\Pi} = \frac{dQ}{Q} - [\alpha\frac{dL}{L} + \beta\frac{dK}{K}]; \qquad (1.1)$$

$$\beta=(1-\alpha)$$

where Π is productivity and $\frac{d\Pi}{\Pi}$ is productivity growth. Q, L, and K denote output, labor, and capital, respectively; α and β are the respective prices of labor and capital (under the assumption of perfect competition, α and β are equal to the respective output share of labor and capital) and dQ, dL, and dK are the time derivatives of Q, L, and K.

Many factors contribute to the firm's productivity growth. In addition to technological change, productivity growth is generally considered to be influenced by scale effects, improvement in the quality of goods and services, and the movement of the relative input prices[11]. Scale change and technological change have a similar impact on the production function. An increase in the scale of operations of the firm will either result in the saving of both labor and capital (similar to neutral technological change) or a decline in unit requirements of labor compared with those of capital (similar to biased technological change), given all other technological properties of the production process. Consequently, scale effects are highly interdependent with technological change and they cannot easily be distinguished empirically. For analytical purposes such as in R&D productivity studies, various assumptions must be made in order to separate the scale effect. Second, productivity measures are affected by quality improvements in products and services. Neither partial nor TFP indices discussed above properly account for such

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[11] The influence of the movement in relative prices on productivity growth will be described in Section 1.3.1.

improvements[12] (Mansfield, 1977b) and thus, understate productivity growth.

Each of these indices has additional merits and problems. Labor productivity is the simplest, oldest and most frequently developed measure of productivity. Change in labor productivity is of importance because of its close relationship with the change in a nation's standard of living, and because of the existence of labor costs in almost all endeavors. However, technological change is not the only source of the growth of labor productivity. Other important factors that influence labor productivity include the movement of relative factor prices, the elasticity of factor substitution, and the rate of technological diffusion.

The TFP index alone is intended to measure the joint effects of all factors of production and, theoretically, it is more realistic than the partial index. Since the work of Solow (1957) and Kendrick (1961), there has been growing interest among economists in the theory and measure of TFP. However, in practice, the derivation of this index requires extensive amounts of information and computation. First, either explicitly or implicitly, the TFP index is based on some specification of a production function and some simplifying assumptions.[13] Second, TFP includes the effects of all excluded factors of production and many aspects of the economic environment. For example, in the short run, business cycles could affect the rate of capacity utilization. Input and output price movement, foreign exchange, and product mix have significant impact on the output measure when value rather than physical measurement unit is used for

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[12] These measures are based on the neo-classical theories which exclude the quality issue. This issue will be discussed in Section 1.3.1, page 17.

[13] For example, in practice, the TFP index assumes that the firm has been operating in a perfectly competitive market. Further discussion on this index is given in Chapter 3. The Solow-Stigler controversy (Stigler, 1961) also illustrates problems associated with this index.

multi-national multi-market segment firms. In the long run, gradual change in market imperfections and managerial and organizational efficiency could also influence the movement of the TFP index. Responding to these limitations, several approaches have emerged. For example, one approach focuses on the theoretical formulation of TFP (e.g, McFadden, 1963; Hilderbrand and Liu 1965; Brown and Conrad, 1967; and Nerlove, 1963). Another approach — the growth accounting approach — concentrates on the scope and accuracy of measurements of inputs and outputs (Griliches and Jorgenson, 1967).

Technological change itself cannot lead to a gain in productivity. It is the proper combination of technological change and tangible factors of production that results in mid- and long-term productivity growth. This implies that the analysis of the R&D/productivity relationship should be made in the production framework which allows the explicit specification and testing of the relationship between technology and other tangible inputs. In order to derive a production function which includes R&D as a factor of production, existing theory involving the neo-classical theory of production provides a starting point.

1.3 R&D and Productivity Growth

R&D productivity studies, in a broad sense, are studies of intermediate-term[14] economic growth on the supply side. The production frontier is shifting outward through factors such as technological change rather than increases in output demand or in the quantity of inputs. In order to model the sequential process linking R&D to productivity, this study will rely on the economic concept of a "production function" and make use of the mathematical

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[14] Economic growth is classified into three stages, short-, intermediate- and long-term. An economy is in the short-term when it is moving towards the production possibility frontier. Long-term growth occurs when the economy is at the steady-state. In between these two growth paths, it is in the intermediate-term stage of growth.

theory of optimization. The underlying theory for modeling this process is the endogenous theory of technological change which is developed from the neo-classical theories of production and economic growth. This section will introduce these three theories in sequence.

1.3.1 Neo-classical Theory of Production

The neo-classical theory of production analyzes the relationships between quantities of inputs and outputs in the production unit, and in so doing makes certain simplifying assumptions about the nature of firms and markets. The underlying assumptions are:

1. The firm produces one homogeneous product;
2. The firm has perfect information concerning inputs and outputs;
3. The firm is a price-taker; its decision to buy or sell inputs or outputs will not affect the price of those commodities;
4. Demand and supply are in equilibrium in relevant markets;
5. The firm is owner-managed;
6. The firm maximizes profit.

Production in the firm is viewed as the contribution of input factors of production, the most common of which are capital and labor. At the same time, there is a given level of technology which determines the techniques available for production. This in turn determines the maximum level of output which can be obtained from a given level of inputs.[15] Among the infinite techniques available, the firm will choose the one which, given existing factor prices, minimizes total costs.

The assumptions and relationships described above can be presented in

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[15] That is, mathematically, there exists an infinite number of convex factor production sets in which these factor combinations are both financially as well as technologically feasible.

analytical form with a production function and a total cost function. Conventionally, the production function is written as:

$$Q = f(K, L) \tag{1.2}$$

where Q is output; and K and L are capital and labor inputs, respectively. The total cost function can be expressed as the linear equation:

$$C^0 = \alpha L + \beta K + b \tag{1.3}$$

where C^0, α, β denote the given total cost of production, unit cost of labor and unit cost of capital, respectively; b represents fixed costs. The ultimate aim of the firm in the neo-classical world is to maximize profit, and this objective can be modelled as:

$$\pi = p \cdot f(K, L) - \alpha L - \beta K - b \tag{1.4}$$

where π and p are profit and the unit price of product in a competitive market, respectively. Setting the partial derivatives of π with respect to K and L equal to zero, the following equations can be obtained:

$$\frac{\partial \pi}{\partial L} = p \cdot f_L - \alpha = 0$$

$$\frac{\partial \pi}{\partial K} = p \cdot f_K - \beta = 0$$

where $f_L = \frac{\partial Q}{\partial L}$ and $f_K = \frac{\partial Q}{\partial K}$. After rearranging terms, these two equations yield:

$$p \cdot f_L = \alpha \quad \text{and} \quad p \cdot f_K = \beta \tag{1.5}$$

Equation (1.5) states that, under the current level of technology, the profit-maximizing firm will choose an output level (Q) so that each input is used up to the point at which the value of its marginal product ($p \cdot f_{L\ or\ K}$) equals its price.[16]

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[16] Second order conditions require that the production function be strictly concave in the relevant range.

This is the point of maximum economic efficiency.[17]

When there is a change in the ratio of factor prices because of a change in the economic environment, a rational firm would choose the technique and level of output which satisfy the condition in Equation (1.5) in the new situation. However, the possibility of substituting one factor of production for another is not infinite because as more and more of one factor replaces another, the process of substitution becomes increasingly more difficult.[18] Neo-classical theory of production assumes that this type of change in the economic environment would not cause any technological change.

There are limitations to the neo-classical theory of production. First, it assumes that each firm faces a production function and makes a choice of techniques on the basis of prevailing factor prices; and the number of techniques available are assumed to be infinite. Second, labor and capital are the only two factors of production incorporated into the theory, and given the technology, they are assumed to be perfect substitutes. Third, the theory can only describe changes in process technology and cost-reducing technology, but product technology, improvement in performance and appearance of new products and services find no place in this theory. Finally, changes in the spectrum of available techniques are assumed to be exogenous. These assumptions about the nature of the firm and the market lack realism both in general terms and in terms of the process of technological change. As a consequence, they affect the value of the theory as a framework for explaining technological change. However, the neo-classical theory of production provides the foundation for an important body of research on economic growth.

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[17] That is, it is technologically efficient, allocatively efficient, and scale efficient.

[18] This is because the production function defined above is strictly concave.

1.3.2 Neo-classical Theory of Economic Growth

Similar to the neo-classical theory of production, the neoclassical theory of economic growth also concentrates on only a small number of variables as the key features of the growth process. It builds on production function (1.2) but imposes the additional assumptions of constant returns to scale and diminishing marginal productivity. The neo-classical model of economic growth has allowed for changes in labor as well as in capital and the mutual substitution of labor and capital.

In neo-classical theory, economic growth will take place either through an increase in inputs along a given production function or through a shift to a more efficient production function. Technological change can be expected to shift the production function towards the direction of more efficient utilization of inputs. To derive an expression for the growth rate of output in terms of the growth rates of inputs, the production function (1.2) is first differentiated with respect to time as below:

$$\frac{dQ}{dt} = \frac{\partial F}{\partial K}\frac{dK}{dt} + \frac{\partial F}{\partial L}\frac{dL}{dt}; \tag{1.6}$$

multiplying both sides by $(1/Q)\times(K/K)\times(L/L)$, and simplifying; equation (1.6) becomes:

$$\dot{Q} = \frac{\partial F}{\partial K}(K/Q)\frac{dK}{dt}(1/K) + \frac{\partial F}{\partial L}(L/Q)\frac{dL}{dt}(1/L) \tag{1.7}$$

where $\dot{Q} = \frac{(dQ/dt)}{Q}$, the rate of growth in output. Each of the two terms in the right-hand side of equation (1.7) is the product of the output elasticity and the rate of growth. If we define ε_K and ε_L as the output elasticities for capital and labor, and $\dot{K}$ and $\dot{L}$ as growth rates, expression (1.7) can be re-written as:

$$\dot{Q} = \varepsilon_K \dot{K} + \varepsilon_L \dot{L}. \tag{1.8}$$

This expression states that the growth rate of output equals the sum of the growth rates of inputs, each weighted by its elasticity. Under the assumption of competitive pricing of factor inputs, the elasticity coefficients also equal the shares of labor and capital in output, respectively. This relationship holds with any production function that is homogeneous of degree one in a competitive economy. The works of Denison, Kendrick, Solow, and Jorgenson and Griliches in the late 1950s demonstrated that if factors of production are correctly measured and the production at any given moment is homogeneous of degree one, any unexplained growth in output (residual) would come from the existence of technological change.

Technological change has been shown to shift the production function upward over time in the following three fashions:[19] 1) as better organization and methods that improve an entire set of existing techniques; 2) as an improvement in the quality of the labor force; and 3) as an improvement in capital services. Each of these three sources will affect both the rate of technological change and the sensitivity of output growth to change in input growth. Consequently, each will result in different specifications for equation (1.8). These specifications can be described as follows:

First, when technological change affects economic growth through better organization and methods of production, production function (1.2) can be rewritten as:[20]

$$Q = A \cdot F(K, L) \tag{1.9}$$

where A is an autonomous technological change shift factor. Following the same

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[19] In the literature, these are categorized as embodied and disembodied technological change; see Section 1.1, page 6.

[20] The rationale for this expression is that disembodied technological change is independent of other factors of production and can be factored out from the expression of a production function, as discussed in page 6.

mathematical manipulation that was applied to equation (1.2) to develop equation (1.8), the expression (1.9) becomes:

$$\dot{Q} = \dot{A} + \varepsilon_K \dot{K} + \varepsilon_L \dot{L} \tag{1.10}$$

where $\dot{A}$ is the growth residual. This specification has been used as the theoretical basis in most of the studies of R&D productivity.

Second, the production function in the case of improvements in labor force quality is:

$$Q = F(K, E) \tag{1.11}$$

where E is effective labor and is defined as $E = L \cdot e^{\lambda_L t}$. The growth rate of E is given by $\dot{E} = \dot{L} + \lambda_L$, where λ_L is the technological change parameter. Following the similar steps, the equivalent expression to equation (1.8) is:

$$\dot{Q} = \varepsilon_K \dot{K} + \varepsilon_E (\dot{L} + \lambda_L). \tag{1.12}$$

Finally, the production function in the case of capital embodied technological change is specified similarly to the second case above, as follows:

$$Q = F(C, L) \tag{1.13}$$

$$\dot{C} = \dot{K} + \lambda_K$$

where $\dot{C}$ is the growth rate of technologically enriched capital and λ_K is the technological change parameter. Equation (1.13) then becomes:

$$\dot{Q} = \varepsilon_C (\dot{K} + \lambda_K) + \varepsilon_L \cdot \dot{L} \tag{1.14}$$

The production function in all these three cases is assumed to be homogeneous of degree one in *K (C)* and *L (E)*. With different assumptions about technological change, the operational specifications of equation (1.8) differ considerably, and, as has been reported in the literature, the econometric estimates of λ vary as well.

Solow's 1957 study is one of the best known neo-classical studies of economic growth. The aim of Solow's study was to find an elementary way of segregating variation in labor productivity due to technological change from variation due to changes in the availability of capital per worker. He incorporated time as a variable into his model to represent technological change. That is, any kind of shift in the production function over time represents "technological change" or a "residual." With the assumption of constant returns to scale and neutral technological change,[21] Solow reported that about 85 percent of the long term increase in output per capita in the United States was attributable to this "technological change" residual. Note that technological change in Solow's model is defined by exclusion rather than by modeling it explicitly. However, his results demonstrated the need for a better understanding of the nature of the residuals, and one such study was made by Denison.

Denison (1962) attempted to decompose the residual by identifying a list of sources of growth both qualitatively and quantitatively. Denison found five main sources that contributed to U.S. economic growth between 1929 and 1957 — increased education (23%), increased employment (34%), increased capital input (15%), the advance of knowledge (20%) and economies of scale (9%). Note too that by accounting explicitly for these sources of growth, the size of Solow's residual had decreased.

Landau (1990) further decomposed the growth of capital and labor inputs into the growth of quality and quantity of each input and relaxed the assumption that the aggregated inputs are homogeneous. His results show that technological change contributes less than 30 percent to the long-term economic growth, as oppose to the 85 percent estimated by Solow (1957). Landau

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[21] For definition of neutral technological change, see page 8.

concluded that in the expansion of the U.S. economy between 1947 and 1985, growth in capital was the most important source of growth in output, followed by growth in the labor input; technological change was found to be the least important source of the three. Despite this conclusion, his study does confirm Solow's finding that technological change is one of the important sources of economic growth.[22]

In summary, neo-classical models of production and economic growth achieved great analytical clarity by concentrating on a small number of variables. Consequently, the impact of relevant but excluded variables was measured in the residual term. Technological change has been one such variable measured implicitly in the residual. This limitation also has prevented the use of this theory to effectively analyze mid- and short-term economic growth. Thus, in order to reach a better understanding of the economic effects of technological change, it has been explicitly introduced as one of the economic forces on productivity growth and has been integrated into a theory of endogenous technological change.

1.3.3 Theory of Endogenous Technological Change

Since the mid-1950s, the economics of technological change has progressed from interpreting technological change as an un-explained residual to considering technological change as the result of an accumulating R&D capital stock.[23] Within this framework, technological change is determined within the economic system and can be studied within the context of the efficient allocation of limited resources under institutional and market constraints.

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[22] This finding has generated some controversy discussed in End-Note 4, page 28.

[23] R&D expenditures have been identified as the indicator of technological change by various researchers (e.g, Mansfield, Nelson, Schmookler), as introduced earlier (page 3).

The inclusion of R&D capital stock into the economic system is based on the characteristics of R&D behavior as an investment-type activity. The firm re-invests a fraction of its present profit in R&D for the purpose of gaining future benefits through improvements in the efficiency of its production and in the quality of its products and services. Studies of industrial organizations have shown that the cost relationship of R&D to output follows a U-shaped pattern, as do the cost relationships of other factors of production. The average cost of R&D declines as output increases to some minimum point where it levels off or rises. This pattern indicates that R&D can be viewed as one of the factors of production, and that one can apply the production function approach in the theory of endogenous technological change.[24] Based on this theory, equation (1.2) can be modified to include technology (R&D) as an intangible factor of production:

$$Q = f(K, L, T) \tag{1.15}$$

where T represents technological stock. Specification of this model depends on the assumption of the embodiment of technological change, the measurement of productivity, and an appropriate functional form, which will be discussed in Chapters 2 and 3.

In practice, the process linking technological change to productivity growth is that technological change, represented as the generation of a stream of innovations[25] and their diffusion, leads to new and improved products, processes, and services. It is innovation that results in observable technological change and economic growth. Innovations may influence productivity in

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[24] In empirical research, this approach takes on many forms. Various production functions which have been specified will be reviewed in Chapter 2 and derived in Chapter 3 of this dissertation.

[25] Broadly speaking, the first commercial use of an R&D outcome can be referred to as an innovation.

different ways. *Product* innovation leads to an increase in the value-added of the product which helps the firm obtain a higher price for it, particularly if it leads to product differentiation. This would be reflected in productivity increase because a higher price leads to higher revenue for a given quantity of goods and services. *Process* innovation may lead to cost efficiency or quality enhancement in the product. In the case of increased cost efficiency, the firm would achieve a gain in productivity in the traditional sense of reduced resources per unit of output. In the market, process innovations leading to quality enhancement would have a similar effect on productivity as to new products. Also, because the result of successful R&D projects resembles a public good, the R&D outcome from R&D performing industries has been found to increase productivity in R&D using industries (Terleckyj, 1974, 1980; Mansfield, 1980).

The incorporation of an R&D input as an endogenous variable has a number of consequences. First, the process of invention and innovation no longer can be consider as exogenous to the economic system. Resources have to be allocated to particular R&D projects and therefore, the direction of inventive and innovative activity is based on economic criteria from the very outset. Second, because R&D generates new knowledge as well as new uncertainty, its existence in the production function is incompatible with the assumptions of perfect information and equal technology possessed by each neo-classical firm. As a result, market competition is more likely to be Schumpeterian — innovative and entrepreneurial. Third, the fact that firms choose among R&D projects implies that there is a spectrum of R&D strategies which have become important components of overall corporate strategy.

Extensive empirical studies, e.g, Schmookler (1966), Mansfield (1968), have shown that the rate of technological change depends on the extent and nature of R&D.[26] Research results from Mansfield, Griliches, Scherer and others indicate that R&D growth has contributed to about 20 percent of the productivity growth in the U.S. economy.[27]

1.4 Summary

R&D productivity studies are based on theories of endogenous technological change. Neo-classical theories of production and economic growth have considered technological change to be exogenous to the economic system, and have attempted to explain or to account for it as a residual in empirical estimation. The theory of endogenous technological change has explicitly included technology in the analysis of economic performance and resource allocations within the endogenous framework. Technological change is assumed to influence economic performance in either an embodied or a disembodied fashion. The choice between these two forms of technological change leads to different estimation frameworks. Empirical studies have used R&D investment as a proxy for technological change, and the outcome of technological change is measured indirectly through its impacts on labor productivity or TFP.

Private industry has been both the major R&D financial source and performer. National patterns of emphasis on components of R&D (basic research, applied research, and development) have changed only marginally since 1960. Individual industries have shown very different trends in both R&D expenditures and in sources of support, and they can be divided into groups according to R&D intensity for analytical purposes.

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[26] The rate of technological change in an industry depends mostly on the amount of resources devoted to R&D by firms, by independent innovators, and by the government. It also depends on the nature of R&D — basic and applied research and development.

[27] These results will be reviewed in detail in the next chapter.

Based on the theory of endogenous technological change, and under different assumptions on the embodiment of technological change, considerable efforts have been devoted to study the impact of R&D on productivity growth at both macro and micro levels. Those major and recent studies of R&D productivity will be reviewed in Chapter 2.

End-Notes to Chapter 1

1. The Hicksian definition measures the bias along a constant capital-labor ratio:

$$\frac{\partial\,(F_K\,K)/(F_L\,L)}{\partial\,t}\bigg|_{K/L\ constant}. \tag{1}$$

The Harrodian definition measures the bias along a constant capital-output ratio:

$$\frac{\partial\,(F_K\,K)/(F_L\,L)}{\partial\,t}\bigg|_{K/Q\ constant}. \tag{2}$$

Solow's definition measures the bias along a constant labor-output ratio:

$$\frac{\partial\,(F_K\,K)/(F_L\,L)}{\partial t}\bigg|_{L/Q\ constant}; \tag{3}$$

where *Q*, *K* and *L* are output, capital, and labor input, respectively. When these measures are greater than zero, they indicate labor-saving technological change; when less than zero, capital saving technological change, and when equal to zero, neutral technological change.

2. The National Science Board (1989) divides the private industrial sector into three groups, based on the industry's R&D spending and financing, as follows:

Industries	**SIC's**
High - Technology Group	
Chemical and allied products	28
Machinery (including computers)	35
Electrical equipment	36
Aircraft and missiles	372, 376
Instruments	38

Industries	SIC's
Other manufacturing	
Food, kindred products and tobacco	20, 21
Textiles and apparel	22, 23
Lumber, wood products and furniture	24, 25
Paper and allied products	26
Petroleum refining	29
Rubber products	30
Stone	32
Primary metals	33
Fabricated metals	34
Motor vehicles	371
Other transportation	373-375, 379
Nonmanufacturing Industries	

3. Under the assumption of a homogeneous production function and the Euler condition, the Kendrick's measure is defined as

$$\frac{d\Pi}{\Pi} = \frac{Q_1/Q_0}{(wL_1 - rK_1)/(wL_0 - rK_0)} - 1 \qquad (4)$$

where w and r are the wage rate and the rate of return on capital, respectively, and variables with subscript 1 refer to the current period and those with 0 refer to the base period. Under the assumption of competitive equilibrium, and if the changes in the quantities of inputs and outputs are small, it can be shown that this measure is equivalent to Solow's measure (Levhari, Kleiman and Halevi, 1966).

4. It should be noted that Landau advocated the assumption of capital embodied technological change, although he assumed disembodied technological change in his study. If this were the case, the estimate of rate of technological change would be higher at both micro and macro levels (see footnote ^{40}, page 40 in Chapter

2). Perhaps, due to the problems and differences in data and methodology as well as assumptions, the relative importance among these three sources of economic growth may not be the key issue in the studies of economic growth. What *is* important is to identify the dominant driving forces of economic growth and to recognize the inter-relationship among them. Landau's findings do raise the important issue that an increase in R&D investment alone does not necessarily lead to long-term economic growth. However, new technology has to come first before new capital investment can be enriched (embodied technological change) to produce economic growth. The experience of the major industrialized as well as the centrally planned economies seems to demonstrate this interrelationship.

Chapter 2
Literature Review

Chapter 1 has introduced the endogenous theory of technological change that links R&D to productivity growth. Based on this theory, various forms of production functions have been specified and models have been estimated in empirical research. Chapter 1 also has shown that the analysis of R&D performance and the appropriate estimation framework depend critically on methods used to construct an R&D input measure[28] and the choice of indicators for R&D output.[29] Because the source of R&D contribution has been a major focus of research on economic growth over the last several decades, there is a rich literature on this issue. This chapter will survey those major and recent studies in R&D productivity. However, it is not intended to be exhaustive and only topics closely related to this dissertation will be reviewed. Note that only a few studies in the literature have been found which explore the issue of productivity effects of specific R&D components. The objective of this review on studies of total R&D[30] productivity is to establish the appropriate analytical and estimation framework for studying the productivity effects of individual R&D components.

Technical-service is one of the important technical activities in the firm's R&D labs and this dissertation will examine its productivity effects along with

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[28] The issues associated with the estimation of the R&D input are important to R&D productivity studies and they will be discussed throughout this chapter, starting with Section 2.2.2.

[29] Three major R&D output indicators have been identified in the literature: number of patents granted to a firm, stock market value of the firm, and productivity growth of the firm. Because this study will focus on the productivity issue, this review will primarily concentrate on studies in this area. Studies using other R&D output indicators will be briefly surveyed in End-Note 1 (page 52) to provide a general overview of R&D studies.

[30] The term "total R&D" refers to *all* company-funded expenditures on R&D as a whole.

those of the traditionally defined R&D components (basic research, applied research, and development). However, no study has been found so far which analyses the performance (contribution) or efficiency of the firm's expenditures on technical services.

This review will be organized by the assumption of the embodiment of technological change because it affects the analytical framework and econometric results of R&D productivity studies.

2.1 R&D Productivity Studies Assuming Embodied Technological Change

Embodied technological change means that new technical knowledge is embodied in new techniques and either is added to the existing pool of techniques or displaces some old techniques. It requires new investment in physical goods such as plant and equipment for the new knowledge to be utilized. The work of Kaminen and Schwartz (1969) is an attempt to deal with the problem of endogenous technological change at the firm level. The technical progress functions in their study are differential equations which relate the rates of augmentation of the two factors of production through a concave innovation possibility frontier (IPF),[31] and are determined by the rate of expenditures on R&D. R&D investment is viewed as a decision variable in the entrepreneur's profit maximizing decision process. This approach assumes embodied technological change, and the production function takes the following form:

$$Q = H\,[B_1(m_1)\,K, B_2(m_2)\,L] \tag{2.1}$$

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[31] IPF is defined as the locus of all techniques available at a given time (Kennedy, C. 1984. "Induced Bias in Innovation and the Theory of Distribution." Economic Journal. September: 74(295)).

where Q is output; H is assumed to be a linearly homogeneous production function; B_1 and B_2 are factor augmenting coefficients resulting from R&D investment for capital (K) and for labor (L); m_1 and m_2 are the amount of R&D spending devoted to capital and to labor, respectively.

With this framework Link (1978) used a cross-sectional data base of 45 manufacturing industries selected from the 1958 National Science Foundation (NSF) survey of R&D activity to study the productivity effects of R&D. Because of data limitations he was forced to make additional assumptions. First, induced technology[32] was assumed to be neutral and process augmenting rather than partly factor augmenting. Second, each firm's specific technical or entrepreneurial ability was assumed to be the same across industries. Finally, neither the time lag of the impact of R&D investment on output nor rate of technological obsolescence of R&D was considered. Despite these shortcomings, he estimated an overall industrial average rate of induced factor augmentation of 9.52 percent, and an annual rate of return to R&D of 18.8 percent. This estimate of the rate of return is considered below those of other studies, as reviewed below.

Equation (2.1) is not the only way of modeling embodied technological change in an R&D productivity study. Mansfield (1965) employed the Cobb-Douglas model to study the rate of return on R&D of ten chemical and petroleum firms and ten manufacturing industries during 1945-1958. He assumed: (1) various annual rates of technical obsolescence for both tangible and intangible capital, regardless of vintages; (2) the efficient allocation of the firm's labor force among various vintages of capital; (3) an exponential growth of

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[32] The term "induced technology" refers to technology that is invented or innovated within the firm. Alternatively, the firm can purchase technology from an inventor or innovator outside the firm (external technology).

R&D expenditures; (4) constant returns to scale; and (5) capital embodied technological change. With these assumptions, the Cobb-Douglas model can be written as:

$$Q(t) \;=\; A\,L^{\alpha}(t)\,\{e^{-\delta t}\int_{-\infty}^{t} e^{[a_1/(1-\alpha)+\delta]\,v}\,(\int_{-\infty}^{v} e^{-\lambda(v-g)}R(g)dg)^{a_2/(1-2)}I(v)dv\}^{1-\alpha}$$

where $Q(t)$ is the output rate at time t; L(t) and R(t) are, respectively, the labor input, and the rate of R&D expenditures, at time t; a_1 and a_2 are, respectively, the natural rate (trend) of technological change and the elasticity of output with respect to accumulated past net R&D expenditures. δ is the annual rate of technical obsolescence. A and α are estimated parameters. $I(v)$ is the gross investment in plant and equipment by the firm at time v ($v \leq t$). Mansfield obtained estimates of marginal rates of return to R&D between 40 and 60 percent in the petroleum firms, and around 30 percent among the chemical firms. However, the estimates for the ten manufacturing industries were all below 10 percent with the assumption of capital-embodied technological change. Mansfield concluded his study with cautions about his estimates because of his simplifying assumptions and errors in the measurement of variables.

In general, this approach implicitly assumes "biased" technological progress. Kamien and Schwartz (1969) proved mathematically that technological change of the firm will asymptotically approach Hicksian neutral technological change if the elasticity of factor substitution is less than one. However, this assumption is regarded as extremely tenuous in empirical research. Many problems are still associated with this framework such as the definition of technical bias and issues involved in constructing a measure of the R&D stock. Mansfield (1968) noted that the assumption of embodied technological change tends to yield higher estimates than the assumption of disembodied technological change.

2.2 R&D Productivity Studies Assuming Disembodied Technological Change

When disembodied technological change is assumed, a different estimation framework is required. As described previously,[33] disembodied technological change means that all technological change consists of improvements in knowledge and organization and is independent of the factors of production. This implies that disembodied technological change can be factored out of the expression for the production function. Furthermore, because technological change (R&D) possesses the characteristics of an investment activity in the production process, its influence on productivity can be treated in the same fashion as that of other factors of production. Of the many functional forms founded in the literature, the extended Cobb-Douglas production function and total factor productivity approach are the two most common, and they will be reviewed in this section.[34] Although these models employ the same estimation technique—regression, each is associated with different assumptions.

2.2.1 Total Factor Productivity Model

The Total Factor Productivity (TFP) model is widely used in R&D studies. Theoretically, it measures the joint effect of all interrelated factors in the production process. The TFP index used in most R&D productivity studies is

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[33] pages 6 and 19.

[34] Other functional forms have also be used in the literature, such as the modified Constant Elasticity of Substitution production function (CES), a simultaneous equation system, and the distributed lag model. To provide a general view of the research on R&D productivity, studies using these functional forms will be reviewed in End-Note 2, page 53. The findings on R&D productivity studies are not confined to the U.S. economy. Similar results have also been found from a number of international studies as briefly surveyed in End-Note 3, page 55.

Solow's TFP index.[35] This index is based on the assumptions of a perfectly competitive market, unitary elasticity of factor substitution and constant returns to scale.

The general form of a TFP model can be expressed as:

$$\left(\frac{d\Pi}{\Pi}\right)_{it} = a + \psi \cdot I_{it} + \sum_{j}^{J} \beta_j X_{jit} + e_{it} \qquad (2.2)$$

$$\begin{array}{ll} (\mathit{firm} & i=1, \dots I) \\ (\mathit{time} & t=1, \dots T) \\ (\mathit{variable} & j=1, \dots J) \end{array}$$

where $\frac{d\Pi}{\Pi}$ is Solow's TFP index; I is the R&D intensity—the ratio of annual R&D expenditures to sales or value-added; ψ is the marginal rate of return to R&D. The X's are productivity related independent variables such as material inputs, business environmental variables and dummy variables for the inter-industry or inter-firm differences.

With this model, Terleckyj (1974) explored the effect of R&D on productivity growth of various industries, based on NSF statistics for 1958. He followed Kendrick's definitions of input, output and productivity and adopted Kendrick's (1973) estimates of productivity growth. Terleckyj also took into account the technology spill-over among industries and estimated separately the productivity return to R&D that was financed and conducted by its own industries ("own" R&D), and to R&D that was transmitted from other industries through purchase of R&D intensive inputs ("purchased" R&D). His estimates of the rates of return were 30 percent to "own" R&D in manufacturing industries, and 45 percent to R&D "purchased" from other industries. His study also provided evidence which ruled out government financed R&D as a factor directly influencing productivity growth in those manufacturing industries that

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[35] See Chapter 1, page 11.

conducted this R&D. His findings seem to support the argument that the direct diffusion of technology from federal R&D to those manufacturing industries that conducted the R&D has been very slow or insignificant. However, if the "purchased" R&D is divided into government- and company- financed components, the indirect effects of government-financed R&D, i.e, transmitted through R&D intensive inputs, were estimated to be almost twice that of company-financed R&D (78% vs. 45%) in manufacturing industries. Because R&D can also be embodied in capital stock,[36] Terleckyj then estimated that the effect on productivity growth in the purchasing industries is greater when R&D is embodied in capital goods than when it is embodied in intermediate materials. He cautioned, however, that the estimates obtained may have been inflated because human capital was not included in the models. Terleckyj (1980) later corrected for this bias in a subsequent study.

The purpose of Terleckyj's study (1980) was to test for the independence of the estimates of his early work (1974, above) from possible effects of increased use of human capital and other inputs. The TFP index employed in this study was the one prepared by Gollop and Jorgenson (1980) which was already adjusted for the use of human capital and other characteristics of input. Terleckyj's estimated results are, for the most part, consistent with those from his earlier 1974 work. The main exceptions are that the statistical significance of the estimated direct effect of privately financed R&D was lower, and there was some indication of possible indirect effects of government-financed R&D.

This positive and statistically significant relationship between R&D and TFP at the industry level seemed to vanish in the 1970s. Another study for this period was made by Griliches and Litchenberg (1984). They examined R&D

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[36] See discussion in Chapter 1, page 19.

effects on productivity growth by product groups as defined by NSF and used data at the SIC four-digit level from the Annual Survey of Manufactures. Because the industrial level they studied is below the two-digit SIC breakdown, they constructed their own TFP index from 1959-76 and conducted a number of careful analyses to control for short-term variations in the data. Their findings indicated that the relationship between an industry's R&D intensity and its productivity growth did not disappear. Also, they found that the overall decline in national productivity growth occurred in R&D intensive industries, but to a lesser extent. Another study of the relationship between productivity growth and R&D in the 1970s — but at the business level — was made by Clark and Griliches (1984). Their sample covered 924 U.S manufacturing business units during 1970-1980 in the PIMS[37] database. They estimated the TFP index from their sample data and concluded that the average annual rate of return to R&D was about 20 percent.

The TFP index is intended to measure the joint effect of all interrelated factors in the production process. Because factors of production no longer are included in the TFP model as independent variables, the TFP model has an advantage of simplicity and appears to bypass or lessen econometric estimation problems such as multicollinearity. However, the estimation of the TFP index requires sufficiently detailed data. This is one of the reasons that many studies have used the extended Cobb-Douglas production function, as will be discussed next.

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[37] Profit Impact of Market Structure database. Descriptions of this database were given by Schoeffler (1977).

2.2.2 Extended Cobb-Douglas Production Function

The extended Cobb-Douglas production function (ECD) differs from the TFP model in that it uses the partial productivity index as its dependent variable. It takes the following form:

$$Q_t = Ae^{\lambda t} L_t^{\alpha} K_t^{\beta} R_t^{\gamma} \tag{2.3}$$

where Q_t is measured output; A is an output argumentation factor (constant); λ is an external disembodied rate of productivity growth; and, α, β, and γ are elasticity parameters for labor (L), capital (K) and R&D (R), respectively. Among many issues related to the estimation of this model, the construction of an R&D input measure and tests of economies of scale are of particular importance to R&D productivity studies because of their potential influence on the estimated parameters of interest. In this section, these issues along with various assumptions and econometric problems will be reviewed and illustrated with reference to specific studies.

The contribution of R&D to output obtained empirically will depend on the R&D input measure used. R&D stock is in many ways similar to tangible capital stock, e.g, in its depreciation over time and time lag effects on productivity growth. Earlier studies chose to disregard the depreciation issue based on the argument that the total amount of R&D was very small prior to 1930's and that R&D growth actually began on a major scale after World War II. Also, the rate of growth of R&D expenditure in the 1950's was so high that even if the depreciation rate was high, the amount subject to depreciation would not have had time to build up during the period covered by the data. One such early study using the ECD model was made by Minasian (1962), in which he tested the hypotheses that productivity increase is associated with investment in the improvement of technology; and, that the greater the expenditures for R&D, the greater the rate of growth of productivity. Using 1947-1957 data from 17 firms in the chemical and allied product industry and five firms in the drug and pharmaceutical industry, he tested for the productivity effects of five rival explanatory variables — economy of scale in production, diversification, profitability, tangible capital investments, and pricing. He concluded that R&D expenditure was a highly significant independent variable, explaining not only the rate of growth in productivity but also the profitability of those firms in his sample.

In another study of 17 chemical firms, Minasian (1969) explicitly used the ECD form and reported an estimated output elasticity for R&D of 0.11. Given that the real value added per firm averaged 171.8 million dollars annually and the real accumulated R&D expenditure per firm averaged 35.2 million dollars annually, the estimated marginal product of R&D averaged 54 cent annually.[38] Thus, the gross marginal return on investment in R&D was 54 cents for each dollar increase in the stock of R&D. However, Minasian's definition of R&D stock did not assume a lag structure or rate of depreciation for R&D stock. Furthermore, he excluded the influence of external technological change from his model.

These assumptions were revisited by Mansfield. In his study of ten petroleum firms and ten manufacturing industries during 1946-1962, Mansfield (1965) allowed past R&D investments to depreciate and included the external influences of technological change. Assuming constant returns to scale, he estimated the output elasticity of R&D to be 0.12 for his own sample and 0.08 for Minasian's sample, and argued that an average of these two estimates, 0.10,

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[38] That is, 0.11 x \$171.8 / \$35.2 = \$0.54. In addition, his calculation of the marginal product for tangible capital was only \$0.09.

more accurately reflected reality. By assuming four different sets of values on the cost and rate of depreciation of R&D stock, he obtained an average[39] marginal return to R&D of 8 percent for five chemical firms and of 40 percent for five petroleum firms in his sample. His estimates of the rates of return to R&D in some manufacturing industries — apparel, food and furniture — exceeded 15 percent under conservative assumptions about R&D costs and depreciation rates.

From this study, two important points are relevant to this dissertation. First, Mansfield investigated the effect of different types of technological change on the return to R&D by assuming capital embodied technological change and then, disembodied, using the same sample. This made it possible to evaluate the impact of different assumptions on the embodiment of technological change. Mansfield found that capital embodiment yields higher estimates of the return to R&D than disembodiment.[40] Thus, statistical results which assume disembodied technological change would be conservative estimates. Second, Mansfield observed evidence of diminishing returns to scale from accumulated past R&D expenditures in the chemical and petroleum firms. These two findings provide important guidelines for interpreting statistical results about the R&D productivity relationship in a production function framework.

In Mansfield's model, the influence of external technological change was expressed as a time residual ($e^{\lambda t}$). This inter-industry technological flow is an important issue for R&D studies because an industry's rate of productivity growth depends not only on its own rate of technological change, but also on

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[39] They are averaged over 20 alternative estimates: four different set of assumed values for each of the five firms in every industry.

[40] This result had also been demonstrated by Solow (1959) as in Chapter 1, at the macro-economic level. The reason for this outcome can be seen in End-Note 4, page 55.

technological change in other industries. Most R&D studies have to make certain assumptions about such industrial inter-dependency, presumably because of the lack of data. Scherer (1984) is one of several researchers[41] who attempted to consider such technical flow. He examined more than 1,500 patents and detailed data on R&D expenditures in order to determine both the industrial "origin" of technology and its intended ultimate industrial "use." From these data, he estimated a technology flow matrix for the U.S industrial economy. He reported that, during the 1970s, a two-standard-deviation increase in an industry's use of R&D was associated with an annual increase in labor productivity of 1.1 to 1.5 percentage points. He also estimated the rates of return on investment in used R&D ranged from 74 to 104 percent. However, the issue of industrial inter-dependency is a complicated one. As pointed out by Mansfield (1984), Scherer's approach suffered from many other problems such as the definition of R&D, and from simplifying assumptions which require caution in the use of Scherer's results.

The studies reviewed above explicitly assumed constant returns to scale. This assumption certainly simplifies the estimation process and has enabled researchers to concentrate on their respective topics. However, some researchers have advocated an assumption of increasing returns to scale (Arthur, 1990). Others have empirically tested this assumption, and their results have suggested decreasing returns to scale (Mansfield,[42] 1965; Griliches and Mairesse, 1984). In their investigation of the return to R&D at the firm level, Griliches and Mairesse (1984) assessed the impact of this assumption on

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[41] Similar attempts have also been made by Mansfield (1980) and Terleckyj (1974) using the TFP framework.

[42] Mansfield's results have been reviewed in page 40.

estimates of returns to R&D. Their study was based on a sample of 157 large R&D performing companies drawn from the COMPUSTAT data base, covering the 12-year period, 1966-1977. By alternatively imposing or relaxing the assumption of constant returns to scale (CRS), they estimated the rate of return to R&D separately. They adopted a two-error component specification[43] and further separated their estimates into total, between-firm, and within-firm, regression. With this methodology, the hypothesis of CRS was accepted in their between-firm regression (with output elasticity of R&D [$\hat{\gamma}$] = 0.07), but was rejected in the within-firm regression in favor of significant decreasing returns to scale (with $\hat{\gamma} = 0.08$). Further tests of the assumptions on economies of scale are reviewed below.

The second objective of their study was to test the hypothesis that large inter-industry differences exist in funding, performance, and efficiency of R&D. In order to test the hypothesis, Griliches and Mairesse divided their sample into two groups: the "R&D-intensive" group versus "others." Their statistical evidence strongly supports this hypothesis that inter-industry differences are significant. The average ratio of R&D to sales in the "R&D intensive" group was twice that in the "others" group, and the estimate of γ from the total-regression was ten times higher than the "others" group, regardless of the CRS assumption.

The third objective of their study was to shed some light on the debate that one of the causes of the productivity slowdown in the U.S. may be due to the slowdown in R&D investment as well as the decrease in the efficiency of recent R&D. Griliches and Mairesse divided their sample into two six-year subperiods, 1966-1971 and 1972-1977, and proceeded using the same estimation

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[43] The two-error component model decomposes the disturbance term into two dimensions: variances in the time series dimension (within-firm regression) and in the cross-sectional dimension (between-firm regression). This model will be described in detail in Chapter 5.

approach described above. With the additional assumption about the efficiency of physical capital over time, they found that γ did not decline over time. Their results did not provide sufficient evidence to support the debate, regardless of the choice of the CRS assumption.

Many researchers have cautioned that their results are of limited use because their sample size was small and not "randomly drawn." To overcome this problem, although it was not the sole purpose of his study, Griliches (1980) matched the 1957-65 annual NSF-Census R&D surveys and the 1958 and 1963 Census of Manufactures and Enterprise statistics to explore the rates of returns to R&D in the private sector.[44] His sample consisted of 883 companies with large R&D expenditures, accounting for 77 percent of the R&D performing companies with 1,000 or more employees, 89 percent of the total sales and 92 percent of the total R&D expenditures. His estimates, based on both 1963 levels and rates of growth over 1957-1965, indicated an average elasticity of output[45] with respect to R&D investment of about 0.07. This was derived by averaging results for the R&D intensive industries (0.10) and less intensive industries (0.05).

Despite differences in assumptions and problems with the data, studies reviewed here under the ECD framework yield reasonably consistent estimates of the output elasticity with respect to R&D stock. As suggested by Mansfield in 1965, an output elasticity of 0.10 can be assumed with reasonable confidence. Statistical results of studies reviewed in this chapter are summarized in Table 2-1.

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[44] His data were provided in moment-matrices form for all confidential variables. His analysis was confined on two dimensions of his data—average rates of growth over the whole period (1957-65) and levels in 1963. All variables were in nominal historical prices in his analysis.

[45] Griliches's productivity index was measured by net sales per worker.

2.2.3 Studies on R&D Components

Those studies of R&D productivity surveyed above concentrated on the firm's total R&D expenditures. However, R&D encompasses activities of many kinds. The NSF classifies R&D into basic research, applied research, product development and process development.[46] These components differ from each other in many ways including their nature, characteristics and impact on productivity growth. Although very limited, the literature on this subject is important to this dissertation because it focuses on the issue of the contribution of those R&D components to productivity. Studies addressing this issue will be reviewed separately in this section.

It has been generally agreed that aggregate data do not reveal many insights unless one examines the components with respect to such issues as how they are constructed, what their functions are and how they interact. With respect to the objectives of this dissertation, the productivity impact of each component and the inter-relationships among them are of importance. However, very few studies of the R&D components have been made, presumably due to data limitation.[47] An attempt to fill this void was made by Mansfield (1980), in which he investigated the relationship between basic research and productivity increases in manufacturing at both the firm level and the industry level. Based on Kendrick's TFP index, published data on basic and applied research from NSF, and the Department of Commerce data for 20 two-digit SIC manufacturing industries during 1948-66, Mansfield obtained a strong

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[46] Technical-service is an important activity that has also consumed a large portion of the firm's technical efforts. Detailed definitions of all these R&D activities will be given in Chapter 3.

[47] Two sources of problems seem to contribute to this data limitation. First, R&D performing firms do not consistently and thoroughly measure their R&D expenditures and performance (Schainblatt, 1982). Second, confidentiality considerations have also limited data availability.

statistical relationship between the amount of basic research conducted by an industry and the industry's rate of productivity increase during his sample period. The estimated rates of return to basic research ranged from 60 percent to 166 percent, but it was less than ten percent for applied research.[48] Because the distinction between industrial basic and applied research is very vague, these estimates, along with other statistical evidence, led Mansfield to suggest that the basic research in his sample may represent long-term R&D and applied research may represent short-term R&D. To test the robustness of his estimates, he analysed various other factors in his models, such as technology spill-over from other industries and sources of the firms' R&D financing. The inclusion of these factors did not significantly change his results. At the firm level, Mansfield estimated the same model using data from 10 major petroleum firms and six major chemical firms during 1960–76, and obtained results similar to those estimated at the industry level. By combining the amounts of R&D on basic and applied research and regressing the total on the firm's TFP index,[49] he estimated a 27 percent annual average rate of return from all research expenditures.

Mansfield's findings were supported by additional evidence from Link's study. Link (1981) used data from 51 major R&D performing manufacturing firms during 1973-1978 and confirmed that company-financed basic research was a significant determinant of firms' productivity growth.[50] His results also suggested that government-financed basic research does have significant impact

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[48] For some specifications, the estimated rates of return to applied research are negative in Mansfield's study.

[49] This TFP index at the firm level was estimated from his sample.

[50] The rate of marginal return (ψ) = 2.31.

on industry productivity growth,[51] in contrary to the findings in Terleckyj (1974).[52]

With a large and more recent sample of firms, Griliches (1986) examined the productivity issue of basic research at the firm level in the 1970's. He employed labor productivity as his dependent variable and again matched the NSF R&D survey with data from the Census of Manufactures and Enterprise statistics. He obtained three samples for his study: 652 firms for the period of 1966-67; 386 firms for 1967, and 491 firms for 1977. This study singled out basic research as the most important source of the firm's productivity growth. Differences in the levels of productivity and profitability were also found to be directly related to differences in the basic research intensity of the firm.

While the importance of basic and applied research in productivity growth has received attention from Mansfield, Link,[53] and Griliches, little quantitative effort has been made to examine the productivity issue of the development expenditures at the firm level, namely product and process development. In the study of Clark and Griliches (1978), the productivity impact of product and process development was assessed but in a very limited way. The data on product and process development were available only in ratio form from the PIMS data base, a ratio of product R&D to total R&D expenditures. Their results suggested that an increase in product R&D's share of total R&D investment was associated with a negative rate of productivity growth[54]. Because of measurement errors in their variables, the authors warned that little

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[51] $\psi=1.17$

[52] See page 35.

[53] Link (1981) has also included the development expenditures in his model.

[54] The regression coefficient of this variable on average is (−1.21).

meaning could be attributed to this finding.

Another early study which indirectly examined development expenditures was made by Mansfield, et al. (1977a). They investigated social and private rates of return[55] to 17 cases of product and process innovations. They found that product innovation has a wider difference than process innovations between these two rates, which is consistent with the hypothesis that the degree of appropriability of technology was an important factor affecting the rates of return to R&D.[56]

2.3 Difficulties in R&D Productivity Studies

Studies reviewed above have found a strong relationship between an increase in R&D and productivity growth at both the industry level and the firm level. However, as repeatedly stated by most authors (Mansfield, Griliches, Terleckyj, etc.), the magnitude of the productivity impact of R&D has to be interpreted with caution and, in some cases, conditionally. These caveats have resulted from the difficulties in empirical R&D productivity studies which include the lack of theoretical guidance, econometric problems and data availability. Mansfield (1977b) and Griliches (1979) have summarized these difficulties for the studies at both micro and macro levels.

First, the underlying theory is still developing. For example, treating technological change as endogenous to the economic system means that some firms could take the advantage of their technical advances and the resulting market structure will not be perfectly competitive in the neo-classical sense. In this case, it is likely to be more Schumpeterian — innovative and

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[55] The concept of social and private rates of return to R&D will be defined in Chapter 3.

[56] See Chapter 5 for more discussions.

entrepreneurial. However, the assumption of perfectly competitive markets is still a basic condition in the empirical research. Second, there are econometric problems in the modeling of the dynamic and simultaneous relationship among input factors and among R&D components. Third, there are difficulties in the measurement of the R&D stock and output, including the assumptions of the lag structure and rate of depreciation of technology, spill-over of technology, and double counting.[57] Studies by Schankerman (1980), Pakes and Schankerman (1984) and Reiss (1990) have shown that ad hoc assumptions to deal with these problems tend to give upward bias to the estimates of returns to R&D.

Finally, data availability and the requirement of data confidentiality present a major obstacle to most researchers. For example, in some studies of total R&D, data were provided in ratio form or "moment matrix" form (Griliches and Mairesse 1984; Griliches and Litchenberg 1984). Disaggregated R&D data have been scarce, and this has prevented detailed study of the R&D productivity relationship, especially at the firm level. Those studies surveyed (Mansfield, Griliches, and Clark and Griliches) are limited to basic and applied research. Very few econometric studies have examined the productivity issue of the R&D components in a systematic way, although such a study is considered an important direction for future research (Mansfield, 1977b).

Results of extensive research[58] on R&D have led Mansfield and Griliches and others to conclude that a firm's success depends not only on the *extent* but

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[57] Labor and capital expenses used in R&D are included in the overall input labor (L) and capital (K) once, and then counted again as part of R&D (R) expenditures. Note that R&D expenditures are treated as operating expenses. However, double counting and actual accounting practice have been shown to bias the estimated R&D coefficient in opposite directions (Schankerman, 1980). This point will be further elaborated in Chapter 3.

[58] Mansfield (1968, 1977a, 1977b, 1980); Griliches (1981, 1989); Link (1981).

also on the *nature* of the R&D.[59] They emphasized that only when the extent and nature of each R&D component are examined can the understanding towards R&D and its performance be furthered. At the firm level, an examination of the R&D components not only concerns the sources of the firm's productivity growth but also its competitiveness and R&D strategies (Bean, 1989a). This is the primary purpose of this dissertation which will examine the productivity of various R&D activities.

This dissertation will attempt to overcome some of the problems discussed above, mainly in the measurement of relevant variables and R&D decomposition. Chapter 3 will present an econometric model and define the variables for this dissertation.

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[59] "Extent" and "nature" refer, respectively, to the amount of expenditure and the types of R&D activities, i.e., basic and applied research, and product and process development.

Table 2-1: Statistical Summary of the Literature Survey

Author(s)	*Year Pub.*	*No.*	*Level*	*Period Study*	*Model*	*Results*	*Notes*
Link	1978	45	industry	1958	(2.1)	ψ=0.188	cross sectional study
Mansfield	1965	5	firm	1946 - 1962	ECD	ψ=0.4-0.6	on petroleum firms
		5	firm	above	ECD	ψ=0.3	on chemcial firms
		5	firm	above	ECD	ψ=0.07	on chemical firms
		10	industry	above	ECD	ψ=0.15	on apparel, food,furniture industries
Terleckyj	1974	33	industry	1948-1966	TFP	ψ=.3	using Kendrick's TFP index
Terleckyj	1980	33	industry	1948-1966	TFP	ψ=.37	using Gollop's TFP index
Griliches & Litchenberg	1984	27	industry	1959-1976	TFP	ψ=3-32	under various assumpt.
Clark & Griliches	1984	924	bus.unit	1970-1980	TFP	ψ=.2	using the PIMS database
Minasian	1962	17	firm	1948-1957	ECD	γ=.11	ψ of his sample = .54
Griliches & Mairesse	1984	157	firm	1966-1977	ECD	γ=0.08	
Griliches	1980	883	firm	1958-1963	ECD	γ=0.07	
Mansfield	1980	22	industry	1948-1966	TFP	ψ=1.55	to basic research; average (t>2)
Mansfield	1980	22	industry	1948-1966	TFP	ψ=0.07	to applied research; average (t>2)

Author(s)	Year Pub.	No.	Level	Period Study	Model	Results	Notes
Mansfield	1980	16	firm	1948-1966	TFP	$\psi=1.78$	to basic research; average (t>2)
Mansfield	1980	16	firm	1948-1966	TFP	$\psi=0.10$	to applied research;
Mansfield	1980	16	firm	1948-1966	TFP	$\psi=0.275$	to industrial research;
Link	1981	51	firm	1973-1978	TFP	$\psi=2.31$	to basic research
Link	1981	51	firm	1973-1978	TFP	$\psi=0.19$	to appliedresearch and development
Griliches	1986	>380	firm	1966,67,77	ECD	0.6-4.5	as premium on basic research
Mansfield	1988	200	firm	1948-66	TFP	$\psi=1.49$	to basic research in the U.S.
Mansfield	1988	200	firm	1948-66	TFP	$\psi=0.07$	to applied research in the U.S.
Mansfield	1988	200	firm	1960-79	TFP	$\psi=-1.34$	to basic research in Japan, avg
Mansfield	1988	200	firm	1960-79	TFP	$\psi=0.57$	to applied research in Japan, avg

Notations

- Pub. = Year of publication
- No. the number of cross-sectional units (industries or firms)
- Level the level of aggregation (business units, firms, or industries)
- Model Econometric models used in the study
- Results ψ = the rate of marginal returns, γ = output elasticity of R&D

End-Notes to Chapter 2

1. There is a rich body of literature on R&D studies using patents and value of the firm as the R&D output indicators. These studies implicitly assume disembodied technological change.

   Systematic study of patenting behavior has led Mansfield, Schmookler, Scherer, and others to conclude that the number of patents granted to a firm is an usable indicator for inventive output. Scherer (1965) reported a linear relationship between the number of R&D personnel in 1955 and the number of patents issued to a firm in 1959, using a sample of the 500 largest U.S. industrial firms in 1955. In another intensive study of patents and patenting, Schmookler (1966) found a close relationship between change in the number of scientists and engineers and change of patents over 1870-1950, and the close relationship between patents and R&D expenditures in 1953 for 18 major industry groups. This positive relationship between R&D input and patents was also reported by Mansfield (1968) and by Comanor and Scherer (1969).

   However, there are several deficiencies in the use of patents as an R&D output indicator. First, patented inventions are of unequal importance, i.e., patents are issued for minor as well as for major innovations. Second, patents generally represent inventions rather than innovations which have a commercial connotation. For example, some important inventions and many innovations go without patents, and many patented products and processes are never commercialized. Third, patent policy for firms in different industries are different due to various competitive factors; even firms in the same industry have very different patent policies for competitive and strategic reasons.

The stock market value approach rests on the perfect market hypothesis that the stock market value of a firm should reflect the firm's ability to invest in opportunities that will generate earnings, dividends or cash flows. Griliches (1984), Pakes (1984), Abel (1984), Ben-Zion (1984), and Mairesse and Siu (1984) — each with differences in data, methods and focus — have found significant effects for both R&D and patent variables in their market value models. Bean and Guerard (1987, 1989) concluded that R&D is a decision variable in corporate financial decision-making. The stock market value approach opens up an interesting research area but still leaves many issues unresolved such as the appropriate functional forms and measurement of the R&D impact on the stock market.

2. There are studies that assume disembodied technological change but use analytical frameworks other than the TFP and ECD models. For example, Brown and Conrad (1967) estimated the influence of research and education using an extended CES production function for ten manufacturing industries for the period 1950-60. In their model, they relaxed the assumption of unitary elasticity of substitution between labor and capital, and permitted research and education to influence all parameters in the system. Among their results, they reported a relatively large effect of these two variables in the durable goods industries. The sum of the

output elasticities with respect to these two variables is 1.535 in durable good industries and 0.382 in nondurable goods industries. The distributed lag model is another analytical framework in the R&D productivity studies. Statistical results similar to those under the ECD and TFP models were obtained by Branch (1974) and Ravenscnaft and Scherer (1982), using different distributed lag models.

A simultaneous equations system approach has also been specified as the model of R&D productivity. R&D productivity behavior as in many other economic behaviors cannot escape the problem of simultaneity, i.e., the possible confusion in the direction of causality between R&D and productivity (profitability). Nadiri and Bitros (1980) investigated the determinants of R&D in a general dynamic model of a set of input demand functions for 62 firms during 1965-1972. Their results confirmed that R&D significantly influences both the short and long term behavior of labor productivity. Also, changes in output and in relative input prices significantly affect both the firm's demands for input factors and R&D in the short and long term. The simultaneity problem was also considered by Griliches and Mairesse (1984).[60] They estimated a semi-reduced form of their simultaneous equation system and concluded that the results obtained in this semi-reduced form are comparable to those reported earlier,[61] with higher estimates of the importance of R&D relative to physical

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[60] Sample of this study has been surveyed early in page 41.

[61] As reported in page 41.

capital. It should be noted that, due to the lack of data, input prices were omitted from both studies.

3. Several international studies, using the ECD and the TFP models, have also reported the positive and significant relationship between R&D growth and productivity growth. For example, Griliches and Mairesse (1983) compared R&D efficiency between U.S and French manufacturing industries and firms. Their study attempted to clarify the controversy over the causes of the significant slowdown in the growth of productivity in both countries. Using the same analytical model as Griliches and Mairesse (1984), Cuneo and Mairesse (1984) analyzed a data base of 182 French firms over 1972-1977, and reported similar results. Mansfield (1988) compared industrial R&D performance in Japan and the United States, and suggested that the rate of return to applied research investment is much higher in Japan than in the U.S. However, the return to basic research in the U.S. is nearly twice as that of Japan. Goto and Suzuki (1989) studied the R&D productivity in Japan's manufacturing industries and reported a marginal rate of return to R&D of 40 percent. They also observed the direct and indirect effects of industrial R&D in some industries in Japan, as initially found by Terleckyj (1974, 1980) in the U.S industries.

4. The assumption of capital embodied technological change yields some rather high estimates of the rate of returns to R&D. The reason for such a result can be seen from the analytical frameworks of technological change described in Chapter 1, using

the growth rates of the U.S. economy. Since World War II, the capital stock and output have been growing annually, along a trend of about 3.5 percent, with 1.5 percent growth in the labor force. The respective labor and capital share of national income has been about 75 percent and 25 percent. Referring to equation (1.8) in Chapter 1 (page 18), $\dot{Q} = \dot{K} = 0.035$, $\dot{L} = 0.015$, $\varepsilon_L = 0.75$, and $\varepsilon_K = 0.25$, and the residual is thus 1.5 percent. The rate of disembodied technological change can be estimated from ($\dot{A}$) in equation (1.10) at 1.5 percent. The rate of capital embodied technological change (λ_K) is given in equation (1.14). Because ε_C is less than one (about 0.25) and λ_K works on $\dot{Q}$ only through this small capital elasticity, ε_C, λ_K must take on a larger value than $\dot{A}$ to explain the same residual (1.5 percent from equation (1.8)). With $\varepsilon_K < \varepsilon_E$, λ_K will be greater than λ_L too. Terleckyj (1974) has shown that λ_K is greater than its counterpart under the assumption that technological change is embodied in intermediate materials.

Chapter 3
Model Specification and Variable Measurement

Based on the theory of endogenous technological change presented in Chapter 1, major R&D productivity studies under various forms of production functions were reviewed in Chapter 2. Among these forms, the total factor productivity model and the extended Cobb-Douglas production function (ECD) are the most commonly specified models. Previous studies favor the TFP model as more "realistic" because it captures all physical inputs as described in Chapter 1. This dissertation employs the TFP model to examine the contribution of R&D components to productivity growth. The model will be derived in Section 3.1. Variables included in this model will be defined in Section 3.2.

3.1 The Econometric Model of This Dissertation

The general model for the analysis of the contribution of R&D to productivity growth can be derived from equation (1.15) (as equation (3.1) below) and summarized as follows (Griliches, 1973):

$$Q = F(K, L, T) \tag{3.1}$$

$$T = N(R, E) \tag{3.2}$$

$$R = C(I) \tag{3.3}$$

where Q is an output measure; K and L are measures of tangible capital and labor input; T is the firm's current level of technological stock which consists both of internally accumulated and productive technological stock (R) and of technological change spilled over from other firms (E). Internal technological stock is defined in equation (3.3) as a function of past R&D investment (I). In order to use this model in empirical research, technological change is usually assumed to be disembodied and neutral and can be factored out from the expression of the production function. Equation (3.1) then becomes:

$$Q = T \cdot F(K, L) = N(R, E) \cdot F(K, L). \tag{3.4}$$

For analytical purposes, the *F* and *N* functions usually are specified in the Cobb-Douglas production functional form and *E* is approximated by an exponential trend. The system (Equation (3.1) to (3.4)) then can be written as:

$$Q = A \cdot K^{\alpha} \cdot L^{\beta} \cdot R^{\gamma} \cdot e^{\lambda t} \tag{3.5}$$

where A is a constant; α, β, and γ are, respectively, elasticity measures of output with respect to tangible capital, labor, and R&D stock;[62] λ is the rate of external disembodied technological change (E); and time is t.

If the terms K^{α} and L^{β} in the right hand side of equation (3.5) are moved to its left hand side, equation (3.5) can be re-written as:

$$\frac{Q}{K^{\alpha} \cdot L^{\beta}} = A \cdot R^{\gamma} \cdot e^{\lambda t}. \tag{3.6}$$

The ratio in the left hand side of this equation can be immediately identified as Solow's TFP index, as introduced in Section 1.2 of Chapter 1.

Equation (3.6) can be expressed, in log form, as:

$$ln(Q) - \alpha \cdot ln(K) - \beta \cdot ln(L) = ln(A) + \gamma \cdot ln(R) + \lambda \cdot t. \tag{3.7}$$

This model explicitly states that the firm's efficiency (TFP) depends on its internal technology stock and external invention and innovations.

Because intermediate materials have been identified to transmit technology from R&D performing industries to those of use (technology spill-

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[62] The parameter γ will be transformed into a marginal measure (ϕ) and variable R into the R&D to output ratio (y) in equation (3.10).

over), many studies have suggested that material inputs be included in the model (Terleckyj, 1974).[63] Following this suggestion, materials (such as feedstocks in the chemical industry) will be modeled in equation (3.7) as:[64]

$$ln(Q)-\alpha \cdot ln(K)-\beta \cdot ln(L)-\xi \cdot ln(M) = ln(A) + \gamma \cdot ln(R) + \lambda \cdot t. \qquad (3.8)$$

where M is material costs.

By taking the time derivative of all terms on both sides of the equation, rearranging terms, and using the lower case letters to represent the growth rates of their corresponding terms, equation (3.8) becomes:

$$q-\alpha \cdot k-\beta \cdot l-\xi \cdot m = \gamma \cdot r + \lambda \quad or$$

$$\pi = \lambda + \gamma \cdot r + e \qquad (3.9)$$

where $\pi = q-\alpha \cdot k-\beta \cdot l-\xi \cdot m$, the growth rate of total factor productivity. The last term, e, is an additional disturbance for the purpose of statistical estimation and is assumed to be log-normal and satisfies all assumptions of the classical normal linear regression model. This model (3.9) is the most used specification of the theory of endogenous technological change (Equation (1.15)) in the literature.

With this basic model (3.9), other variables that influence either output or R&D performance also can be analyzed in the model. R&D stock will be disaggregated into four R&D components—basic and applied research, and product and process development.[65] Technical-service will also be analyzed using this model. Therefore, the general model of this dissertation is, in the notation of (3.9), as follows:

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[63] See Section 2.2.1 of Chapter 2 for more discussion.

[64] This specification has been used in the literature, e.g., Clark and Griliches (1984), to estimate the contribution of R&D to the firm's productivity growth. The TFP index so defined is also consistent with the TFP definition of the Bureau of Labor Statistics (BLS).

[65] In practice, distinctions between research activities and between development activities are not always clear. See Chapter 4 and 5 for more discussions.

$$\pi = \lambda + \sum_{i=1}^{I} \gamma_i \cdot r_i + \sum_{j=1}^{J} \varepsilon_j \cdot X_j + e \tag{3.10}$$

where r_1 to r_4 represent the growth rates of the four R&D elements and r_5, technical services. Other variables (X_j's) include measures of corporate business objectives, competitive pressure on R&D, the rate of capacity utilization, and various dummy variables to capture differences among firms and across time. Note that the parameter of interest, γ, is the output elasticity of R&D stock ($\gamma = \frac{\partial Q}{\partial R} \cdot \frac{R}{Q}$) from equation (3.5) and r is the rate of growth of the firm's technology stock ($\frac{dR/dt}{R}$). This two terms are conventionally transformed into a measure of marginal return to R&D (ϕ), as follows:

From equation (3.10), the term $\gamma \cdot r$ can be re-written as:

$$\gamma \cdot r = \frac{\partial Q}{\partial R} \cdot \frac{R}{Q} \cdot \frac{dR/dt}{R}. \tag{3.11}$$

Let $y = \frac{dR/dt}{Q}$,and $\phi = \frac{\partial Q}{\partial R}$. This expression then can be simplified as:

$$\gamma \cdot r = \frac{\partial Q}{\partial R} \cdot \frac{R}{Q} \cdot \frac{dR/dt}{R} = \frac{\partial Q}{\partial R} \cdot \frac{dR/dt}{Q} \cdot \frac{R}{R} = \phi \cdot y,$$

and equation (3.10) becomes (3.12), the analytical model used in this dissertation.

$$\boxed{\pi = \lambda + \sum_{i=1}^{I} \phi_i \cdot y_i + \sum_{j=1}^{J} \varepsilon_j \cdot X_j + e} \tag{3.12}$$

This transformation is based on the argument that the marginal rate of return to R&D is distributed more uniformly than output elasticity across industries (Griliches, 1980), and on the assumption that the rate of growth in the firm's R&D capital stock can be approximated by the R&D investment intensity in a given period (Mansfield, 1965). This transformation greatly simplifies the estimation process and has become the conventional model in R&D productivity studies. Instead of estimating the R&D stock, R&D input can be modeled by the its investment intensity.

In empirical research, some concepts associated with this specification (equation (3.12)) must be clarified. (1) The effects of R&D usually occur with a lag. Although some work has been done in estimating the lag structure on total R&D, previous R&D productivity studies usually have ignored them. However, when total R&D is decomposed into various components, this issue becomes important because the lag between the performance of research activities and the appearance of their productivity effects could be very long. Little is known about the length of the lags of the various components of R&D, and the estimation of these lags is beyond the scope of this study. Nevertheless. Mansfield (1980) suggested that if the ratios, y_{it}, are stable over time (t) and the correlation coefficients among y_i's are high, the validity of the estimates of interest (ϕ) can be established. This issue will be elaborated on later in this chapter and in Chapter 5.

(2) There are two sources of returns (ϕ) to a successful innovation—social return and private return. There is no agreement of the precise definitions on these two concepts, especially on that of social return. The definition of social return depends on the assumption of a specific market structure and the definition of consumer surplus. The definition of private return depends mainly on the choice of a specific measure of the R&D output. Adopting neo-classical assumptions of the firm and markets,[66] Mansfield, *et al.* (1977) defined social

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[66] These assumptions are as follows: (1) The innovator is a profit maximizing entrepreneur. (2) The industry (market) using the innovation is competitive. (3) The firm's supply curve is horizontal in the relevant range.

return to an innovation as the sum of the consumer's surplus arising from the price reduction, plus the resource saving resulting from the use of the innovation. In addition, he defined private return as a function of the cash flow to the innovator from the innovation in each year. The estimates of average annual returns to R&D reviewed in the previous chapter (except Mansfield, *et al.* (1977)) are estimates of private returns.[67] The procedure estimating social return is a very complex one. The general perception is that the social rate of return to an innovation is higher than the private rate (Griliches 1958; Mansfield, 1977). Mansfield, *et al.* (1977) obtained an estimate of the social rate of return of 56 percent and the private rate of return of 25 percent for 17 innovations in manufacturing industries. A much higher rate of social return was reported by Griliches (1958). Noted that the estimate obtained from Griliches's (1958) study is for commercially successful innovations only.

(3) The (private) rate of return to R&D is in fact an *excess* one in econometric studies using production functions. Using this approach, both output (Q) and technical stock (R) are products of tangible capital (K) and labor (L). Theoretically, the increments of capital (K) and labor (L) used to produce output (Q) and those used to produce technological stock (R) should be distinguished. However, totals of K and L are used in most R&D productivity studies due to difficulties in measuring and obtaining data on those portions of L and K going only to R&D. Consequently, the results from such studies have to be interpreted carefully. "Returns", in fact, represent the excess amount returned to R&D, above and beyond the "normal" remuneration of the

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[67] Because the issue of social return is beyond the subject of this dissertation, the term "return" used in this dissertation is referred to private returns only, unless otherwise explicitly indicated. Note that these two concepts are defined in the context of intermediate-run economic growth and derived from the assumption of perfect appropriability of the fruits of the innovation. End-Note 1 (page 92) provides reference on these two concepts under different assumptions.

conventional factors of production[68] (Griliches, 1980).

(4) The rate of return to R&D represents its *direct* economic impact because the estimate is obtained from a single equation regression model. This estimation process (mostly the Least Squares approach) ignores the *indirect* economic impact of R&D through other relevant variables in the model. This procedure raises another implication. If the returns to some other inputs (e.g, education, enriched capital investment) depend on the rate of technological change, part of technology's contribution to the productivity increase will be attributed incorrectly to those inputs (Mansfield, 1977b). A simultaneous equations model might offer a solution[69] to this problem but the lack of data on all the relevant factor prices discourages its use in this study, as it has in most others.

(5) As is well known, the Cobb-Douglas production function implicitly assumes a unitary elasticity of substitution ($\delta = 1$) between labor and tangible capital. As in the case with any assumption, there is a risk of committing a specification error of an unknown magnitude and consequence. However, in this case, two sources of evidence support this assumption of unitary δ. The first is from empirical results in the productivity research literature (Griliches 1967; Nerlove 1963). Cross-sectional estimates of δ in U.S. industries at the two-digit SIC level (Solow, 1964) and at the four-digit SIC level (Ferguson, 1964) and

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[68] Schankerman (1980) demonstrated that this interpretation of excess returns is essentially correct in the growth accounting framework, but resulted in downward bias in the measured contribution of R&D to growth. However, a number of other studies have argued that, since the capital and labor inputs used to produce the technological stock are a very small proportion of their respective totals, the downward bias would be insignificant.

[69] The simultaneous equation model does not provide estimates of the indirect effects of independent variables on dependent variables neither; but, it does disentangle the complexity of the relationships among the various inputs. Griliches and Mairesse (1984) and Nadiri and Bitros (1980) have used this approach, but only in a limited way due to the lack of factor prices, as surveyed in Chapter 2, page 54.

other studies (e.g., O'Neil, 1965; and Bell, 1964) present no strong evidence that δ is significantly different from unity. Time-series estimates of δ in the manufacturing industries by McKinnon (1962, 1963a), Lucas (1963), and Ferguson (1965) reach, in general, the same conclusion. Griliches (1967) investigated various topics concerning δ and also provided no strong evidence against the Cobb-Douglas production function as an appropriate analytical framework in manufacturing industries.

The second source of evidence supporting a unitary δ is derived from the fact that δ is a second-order parameter for estimating sources of productivity growth from production functions. This is because δ influences productivity growth indirectly through changes in the capital-labor ratio over time. This relationship can be approximated with the following form[70](Nelson, 1964):

$$q = t + \beta l + (1-\beta)k + (1/2)\beta(1-\beta)[(\delta-1)/\delta](k-l)^2. \tag{3.13}$$

where q, l, and k are output, labor and capital in log form. The impact of δ on q is given in the last term of equation (3.13). Because β is less than one in general, the value of the last term should be very small and the impact of δ on q is insignificant unless the capital-labor ratio $(k-l)$ changes substantially. Bell (1964) used the capital-labor ratio in the ACMS[71] framework to estimate δ and concluded that his estimated δ's were clustered around the value of one.

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[70] See Equation (3.5) for more notation definitions.

[71] An analytical framework used by Arrow, Chenery, Minhas and Solow.

3.2 Variable Definition and Measurement

Variables in Equation (3.12) consist of two sets. The first set of variables are tangible factors of production which are used to estimate the TFP index. The second set are the R&D elements. Each of these sets of variables will be defined and discussed in this section.

3.2.1 Output Measure

Productivity usually is measured as a ratio index of output to input(s). The output of an R&D innovation is defined broadly as flowing from the commercialization of the results of technological advances in the form of commercialized products, processes, and services.[72] In this context, the firm's sales revenue can be and has been taken as the measure of R&D outcomes in econometric studies of R&D productivity. In manufacturing industries such as the chemical industry, the inventory of finished goods also represents the firm's output although it is small in quantity.[73] To more accurately measure the firm's R&D outcome, the finished goods inventory is added to net sales to represent the firm's output.[74]

An innovation not only leads to an increase in sales, but it also can result in the reduction of manufacturing and marketing costs. In addition, as reviewed in Section 2.2.1 of Chapter 2, results of innovations have an indirect impact, through intermediate materials, on the productivity growth of those firms that

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[72] For more precise definition of innovation and its output, see Mansfield (1968).

[73] This portion of inventory is about seven percent of total sales for firms in the sample of this study.

[74] There are problems in using the finished goods inventory. First is the change of the accounting methods (LIFO vs FIFO) during the study period. Second is the change of company inventory policy. Last, this portion is not measured in "market value." However, since the percentage of finished goods inventory in total sales is small, these problems do not seem to have statistical significance. It is added to sales to measure the firm's output in attempt to reflect more accurately the firm's production output in that year.

purchase the intermediate materials. This is called "technology spill-over." Thus, costs of materials and services can be another measure of R&D outcome.

By combining these two measures of R&D outcomes, value-added, which is defined as the difference between output and material inputs (costs), has been considered a more appropriate measure of the firm's R&D outcome (output) than the output measure alone. This study will use value-added to derive the firm's productivity index.

Nominal data on the firm's net sales, finished goods, and material costs have been obtained primarily from the COMPUSTAT data base.[75] Note that material costs do not include depreciation and labor expenses.[76]

The use of value-added as the measure of output in R&D productivity studies requires economic adjustments because most firms are multi-national and multi-product corporations operating in the dynamic business environment. In such an environment, many non-production factors (other than labor, tangible capital, and R&D) also influence the output measure over time. Failure to appropriately control for these non-production factors will result in the introduction of bias into the estimates of interest. Because of the lack of "company-specific" data in the current study, data for these economic adjustments will be estimated from public sources.

Four major non-production factors have been identified to influence the output measure: changes in products/services mix, price movement of products/services sold and of feedstocks purchased, fluctuations in foreign

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[75] These data items are also available from company annual reports to their stock-holders. However, these data items in the COMPUSTAT data base have been filtered so that the same data item is consistent across different firms. For definition and content of each data item, see COMPUSTAT manual, 1990.

[76] It was calculated as the difference between "costs of goods sold" and "labor expenses," both from the COMPUSTAT data base. Note also that "costs of goods sold" shown in company annual reports include depreciation expenses, whereas those in the COMPUSTAT data base do not.

exchanges, and changes in plant capacity utilization. These non-production factors and the corresponding economic adjustment are described in the following sections.[77]

3.2.1.1 Product Line Mix

Firms often change production levels of their product lines or market segments over time, possibly because of market demand, the firm's R&D and innovation efforts, cost considerations, or the firm's competitive strategies. These changes in production levels lead to the changes of "weights" of each product line in the firm's overall indices of sales price, costs, and plant capacity utilization. If these indices cannot be obtained directly from the firm, but data are available on an aggregated basis across all product lines, the real output deflated by a single price index at the product line or higher level will be distorted. Such a price index will fail to capture price movement due to the changes in product mix. Such distortions will also be present in estimation of deflated costs and capacity utilization. As a result, such changes in product mix distort the firm's measure of productivity.[78]

One way of correcting this distortion is to decompose the firm's businesses into product lines or market segments and then adjust for price changes and the rate of capacity utilization over time at the segment level. This decomposition and the corresponding adjustment require very detailed data and a great deal of computational effort. Few studies have taken this approach. However, this is the approach that has been taken in this study. Efforts have been made to

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[77] In deriving the productivity index, the ideal measures of inputs and output are in their physical units. Factoring out changes in price and currency exchange is in essence to convert the dollar value of output into "physical" unit. The adjustment of capacity utilization is required in the context of R&D productivity studies which examine the movement of the firm's production frontier.

[78] There are other problems when the firm is assigned with one single SIC code, as will be discussed in next section.

decompose each firm's businesses into major product lines or market segments based on annual company reports to stock-holders, company reports (FORM 10-K) filed with the Security Exchange Commission, the Moody's Industrial Manual and COMPUSTAT financial database of Standard and Poor's.[79] Given this decomposition, appropriate weights can be assigned to each segment and distributed over the time period for which the overall indices were derived.

Most of indices in this study will be estimated as weighted indices, weighted by segment shares. These indices include the output price index, cost index of materials, price index of capital expenditures, labor hourly earnings index, and index of plant capacity utilization. All of these estimated indices have been sent to the sample firms for verification. The detailed estimation process and results have been documented as a technical supplement to this dissertation.[80] The methods used to adjust each of these indices are described in the subsequent sections of this chapter.

3.2.1.2 Price Deflators

The firm's sales revenue is directly measured as a product of its *physical quantity* sold and the *selling price*. Obviously, an increase in the *selling price* due to market forces would increase the firm's sales volume, and therefore, the productivity measure. The material costs are measured in the same fashion. The

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[79] The actual business segments are grouped by the SIC codes at SIC four-digit level. That is, if two business segments are in the same SIC category, they are summed and assigned a single SIC code. This grouping method is corresponding to the data availability of price indices, rates of capacity utilization and adjustment indices for labor input, which are available at the SIC four-digit level.

[80] This technical supplement has about 400 pages and is placed at the Center for Innovation Management Studies, Lehigh University, PA 18015. It consists of the following sections: (1) introduce the major businesses of each sample firm; (2) break down the firm's businesses into the SIC four-digit industries and geographic segments; (3) estimate price indices for output, cost, labor expenses, and capital expenditures; (4) estimate the capital stock; and (5) use these estimated indices to adjust output, materials, R&D, and labor expenses. All these estimated indices and deflated data are tabulated in the supplement.

conventional way of removing this price impact is to convert the current sales price into a constant one. This task could be easily accomplished by obtaining and converting sales price of all products/services into their respective constant prices. Unfortunately, sales (transfer) prices on the product lines or market segments are considered by the firms in this study to be confidential and were not obtained. Companies are not willing to divulge this information because it enables profit margins of individual product to be imputed.

In the R&D productivity literature, price indices of sales and costs have been used at the SIC two-digit level. This convention has been considered problematic because most major R&D performing firms have multiple product lines, many of which cut across the SIC two-digit classification. Data sources such as the COMPUSTAT data base assign the firm to a single SIC code based on the firm's product line with the largest sales value. For example, if a firm has been manufacturing products of coatings and resins (SIC 2851), rubber products (SIC 3011), and machinery (SIC 3559), and the sales volume of these product lines are, respectively, 40 percent, 35 percent and 25 percent of the firm's total revenue, this firm will be assigned in SIC 285. Obviously, the sales price index for SIC 285 will deviate from that for SIC 2851 and does not represent the indices for SIC 3011 and SIC 3559. In other words, the use of the price index at SIC 285 to deflate the firm's overall sales will introduce bias into the estimation process. This would be in addition to biases associated with changes in the firm's product mix over time, as discussed in the previous section. This is also true in deflating material costs.

As mentioned above, efforts have been made in this study to decompose the firm's businesses into appropriate product lines or market segments at the SIC *four-digit* level. The sales price index for the firm was estimated by first obtaining the producer price index (PPI) from the U.S. Bureau of Labor

Statistics (BLS) at the SIC four-digit level for each product line or market segment . Then an overall price index was computed as a weighted average of those segment price indices, weighted by the segment's shares in the firm's total sales on a year to year basis. This weighted price index is used to deflate net sales.[81]

The price index for material costs was estimated in the same fashion. The kinds of materials and their delivered costs used to produce each segment's products and services (at SIC four-digit level) are obtained from the table of "Materials Consumed by Kind" of the Census of Manufactures of the U.S. department of Commerce. First, an appropriate PPI at four-digit SIC level was obtained from the BLS for each kind of material consumed. Then, a cost index was derived for each segment by weighting these PPI indices. The weights are the percent of each kind of materials in the total delivered costs in 1977, 1982, and 1987.[82] Finally, an overall cost index is estimated as a weighted average of each segment's cost index, weighted by the segment shares in total sales.[83]

3.2.1.3 Foreign Exchange

All firms in the sample of this study are U.S.-based international companies. In published records, sales abroad had been converted into U.S. dollars and reported together with domestic sales. Thus, fluctuations of foreign exchange from year to year would distort the real sales volume. The method used in this dissertation to adjust for this factor was to divide the U.S.-dollar value of sales outside the U.S. by an index of foreign exchange for the firm.

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[81] These overall price indices were returned to the firm for verification for possible errors.

[82] The changes of these weights represent the changes of technological, economic, and other considerations in producing products and services in a segment. The weight of 1977 is used for years 1970-1977, weight of 1982 for years 1978-1982, and weight of 1987 for 1983-1988.

[83] When data on the segment's costs are available, the weights here should be the segment shares in total costs.

However, few firms have published their own foreign exchange index. Therefore, such an index has to be obtained from the appropriate public sources.[84]

There are many public indices of foreign exchanges, and the critical issue in adjusting for changes in foreign exchange rates becomes that of choosing an appropriate exchange index. The most widely used indices are the index published in the World Financial Markets by Morgan Guaranty Trust Company (Morgan index) and the Federal Reserve Board index (Fed index). The discussion of the choice made for this dissertation is limited to these two sources.

The Fed index is constructed by computing a geometrically weighted average of the exchange values of the dollar against the ten major foreign currencies.[85] The weights used in this index reflect shares in world trade in *all* goods, both "manufactures" and "primary commodities," including petroleum. This index is considered[86] inappropriate for use in studies of manufacturing productivity because it introduces first the distorted agricultural prices through support and subsidy programs and restriction of agricultural trade that limits exchange rate influences. Second, the undifferentiated petroleum trade markets also limit the influence of exchange rates. This index seems best suited for studies concerning international trades across many sectors of the economy. For studies, such as this dissertation, focusing on only the manufacturing sector, it

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[84] Most companies have reported their foreign sales and currencies gains and losses over time. Mathematically, a foreign exchange index can be estimated using this reported information, provided that the foreign sales can be deflated correctly. The derivation process is shown in End-Note 2, page 93.

[85] These ten countries are German, Japan, France, United Kingdom, Canada, Italy, Netherlands, Belgium, Sweden, and Switzerland. This method started in 1977. Prior to 1977, this index was computed as an arithmetic average which was criticized to impart a systematic bias to the measurement of changes in the dollar's average exchange value. See The Federal Reserve Board Bulletin, 1977, p. 700,

[86] See "Dollar index confusion", World Financial Markets, October/November 1986.

seems to be too broad and thus inappropriate.

The Morgan index also has concentrated on valuing the dollar in terms of the currencies of other industrial countries. However, it differs from the Fed index in two important aspects. First, it is weighted against 15 industrial countries (ten countries for the Fed index).[87] Second, and most importantly for the current purposes, the Morgan index uses weights derived from data on trade in manufactured goods alone. In addition, the Morgan index is available in both nominal and real terms. The Morgan *real* trade-weighted average, or "effective," index adjusts for inflation differentials between the United States and its trade partners. These differences certainly make this index more appropriate than the Fed index for this dissertation, and it was therefore used to adjust the international sales data reported for the sample firms.

3.2.1.4 Capacity Utilization

Capacity utilization creates another problematic issue for any productivity study of manufacturing firms. Underutilization of capacity often results from unanticipated fluctuations in demand or in relative prices, forcing firms to operate their plants and organizations at sub-optimal levels, i.e., below the production possibilities frontier. Rates of capacity utilization have been consistently found to be associated positively with rates of productivity growth (e.g, Mansfield 1980). This variable is important because it affects the validity of the estimates of the rate of technological change. Because R&D, representing technological change, is intended to shift the production frontier, the impact of R&D on productivity growth is obscured when the firm operates below the frontier. This means that the observed operating efficiencies of the firm do not

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[87] Additional countries are Australia, Austria, Spain, Denmark and Norway, addition to the ten countries mentioned above.

reflect its true potential.

Unfortunately, data on capacity utilization at the firm level cannot be easily obtained. Similar to the price indices, such data are considered very sensitive. Many R&D productivity studies have used average data for the industry as a proxy for the firm level data. This study has made considerable efforts to obtain capacity utilization data at the SIC four-digit level from public sources and has returned these estimated indices to the sample firms for verification.

Capacity utilization indices have been estimated by many organizations. One of the most popular sources is the Department of Commerce, which uses two different concepts of capacity in its *Current Industrial Reports*, Survey of Plant Capacity. Capacity first is defined broadly as the practical capacity which is the greatest output that the plant could achieve within a realistic work scheme. Second, capacity is defined as the preferred level of operation which the firm would prefer not to exceed due to economic and other considerations. The ratios of the actual level of production to each of these two capacity measures make up the two capacity utilization indices published by the Department of Commerce.

The difficulty in estimating a capacity utilization index is that the concepts of "capacity" and "utilization" are not well defined. In the Survey, the participating firms are instructed to report preferred capacity by "assum[ing] the number of shifts and hours of plant operation that can be reasonably attained by your plant," and "assum[ing] the availability of labor, materials, utilities, etc., sufficient to utilize the machinery and equipment that was in place ..." The practical capacity, on the other hand, can be based on the maximum number of work hours of the labor force, in a past peak performance period, or by any combination of other methods. These difficulties have led the

Department to warn readers that "there is a distinct element of subjectivity" and that "not all plants have defined practical capacity in realistic terms." Thus, any estimated capacity utilization index is expected to deviate from the true one.

As a first approximation, the capacity utilization index of this study was estimated from the Survey. An overall index was computed for the firm as a weighted average of the segments' indices, weighted by each segment's share in the firm's total sales. In addition, the unpublished capacity utilization index estimated by the Federal Reserve Board at the industry level (SIC two-digit level), seasonally adjusted, has been obtained from the Wharton Econometric Forecast Associates (WEFA).

3.2.2 Tangible Capital

Tangible capital[88] represents tangible fixed property — property, plant and equipment used in the production of revenue. Various measures of tangible capital have been proposed in the literature of productivity studies, including gross capital stock, adjusted gross stock, net stock, market value, depreciation, and flow of services. These various measures rest implicitly on some technological conditions. The measures can be divided into two classes: measures of stock and measures of flows. The value of the stock of capital at any point in time is the present valuation of current and all future services expected from this stock, while the flow of capital measures changes in the services of capital flowing from the stock. In practice, they both measure changes in the value of the stock of capital in "constant" prices, assuming that the flow of services is proportional to the stock of capital and that the relevant measure of

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[88] The term "capital" in this subsection represents tangible capital, as distinguished from R&D capital, which is intangible.

stock for this purpose is the net value of capital stock in "constant" prices.

Several issues are involved in estimating tangible capital. One is the quality issue, especially under the assumption of embodied technological change because it has to be modeled in terms of capital vintage (Solow, 1959). Landau (1990) has shown that the growth of capital quality is one of the key factors contributing to economic growth. Another problem in assessing capital quality is the issue of a price deflator. For productivity studies at the firm level, no price deflator is available to account for changes in the quality of capital. Also, because the deflator for the firm is usually approximated by deflator for the industry or by the GNP deflator, estimates of tangible capital are likely to be biased.

3.2.2.1 Measures of Capital Stock

In the literature, measures of tangible capital stock have been based on economic and/or accounting information, as mentioned in the previous section.

Gross capital stock is a simple and less ambiguous measure of tangible capital stock. However, this measure does not consider depreciation of the capital over time and evaluates capital at its original value (historical cost) until it is replaced or retired. There are two major variants of this measure. The first writes off all the capital over time, based on increments derived from the expected life span of the asset. This measure can be approximated by a moving sum of past investment expenditures. A second variation of this measure adjusts for the variance around the expected life span and retires items on the basis of survival curves, machine mortality tables, and other factors.

Adjusted gross stock differs from gross stock in that it takes into account the degree of durability. It deflates gross investment for differences in expected life spans by giving the more durable machines and equipment the same weight as standard ones but carries them for a longer period.

Net stock, market value and depreciation are three related measures of tangible capital, although they belong in distinctly different classes. Net stock and market value use the concept of a stock while depreciation was the concept of a flow. These three measures take into account the fact that the value of capital declines with age and/or usage, due to its exhaustion (decline in its life expectancy), deterioration (decline in its physical productivity), and obsolescence (decline in its market value due to technical progress). So far, no single index is available to measure all three dimensions.[89] However, because the productivity of machines and equipment actually declines with age, net stock can be measured using a purely physical deterioration depreciation scheme. This approach has been widely used. The measure of the market value of capital stock (devaluation) can be approximated by using estimated depreciation rates based on used machinery prices.

Each of these measures of tangible capital is useful in answering particular questions but is very limited in representing tangible capital stocks/flows for use in productivity studies. Furthermore, these measures are derived from the firm's published financial information and are based on accounting depreciation schemes, which, as is well known, are for the purposes of external financial reporting and taxation.

To avoid this problem, the measure of capital stock of this study is estimated from the accumulative deflated and depreciated annual capital expenditures of the firm, based on methods developed and used by the U.S. Bureau of Labor Statistics (BLS) and the U.S. Bureau of Economic Analysis (BEA). The estimation procedure involves four steps: (1) computing a price

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[89] In practice, it is difficult to separate these three dimensions. It is conceivable that as time passes, all these three dimensions may change in the same direction for conventional machines and equipment.

index for the annual capital expenditures for each firm; (2) deriving two replacement functions, one for industrial structures (buildings) and another for chemical equipment and machinery; and (3) deflating and depreciating the firm's annual capital expenditures; and, (4) estimating the capital stock from the deflated and depreciated (discarded) annual capital expenditures using the perpetual inventory method. These steps and the estimated replacement functions are described in Appendix B.[90]

In general, this approach results in an estimated value of capital stock that it is greater than (but follows closely) the levels of capital stock (both gross and net) reported by each firm. This is because the time frame of sample firms' accounting depreciation schedules were shorter than those used to estimate capital stock.[91] Note that there are some potential problems associated with such estimated data. First, some firms indicated that a depreciation schedule of 27 years for industrial structures was "a bit" too long. Second, the estimated stock is based on the past annual capital expenditures and, due to the lack of sufficient information, this estimated series was not explicitly adjusted when firms divested their businesses. This adjustment relies implicitly on the firms' restated series of annual capital expenditures, which reflects changes in past investments prior to the date when the firm's divestiture occurred.[92]

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[90] page 169.

[91] The service lives are 16 years for machinery and equipment and 27 years for industrial structures.

[92] It may be more accurate to measure the capital input of the firm by the weighted average of the three common measures of capital stock: company reported gross capital stock, reported net stock, and the estimated stock.

3.2.3 Labor Input

In the literature of productivity studies, at least three measures have been used to represent labor input in production: the total number of employees, labor expenses, and the number of hours worked by production workers.

Each of these measures has its merits and problems. The labor expense measure has intuitive value because labor expenses are among the major costs of the employer. This is the measure used by the BLS in collecting data for its estimates of average hours worked per week. However, productivity measures are concerned with real input-output relations. Since World War II, time paid for but not worked has increased markedly. As a result, labor expenses inflate the measure of labor input.

The total labor hours worked is a direct measure of labor input. However, changes in weekly hours do not have a proportionate effect on output per person, especially when hours per week are very long. Total labor hours can be derived directly from total labor expenses by an appropriate index of average hourly earnings, which deflates increases in hourly compensation (including time paid but not worked). Although the Department of Commerce (Census of the Manufactures) publishes historical data on both total work hours and earnings per hour by production workers at the SIC four-digit level, the measure of labor hours worked cannot be estimated for the firm because labor expenses reported by each firm include both production and non-production workers.

Because of those problems above and the lack of data on the other two measures, this study uses the number of employees as the measure of labor input, excluding significant portions of seasonal or part-time employees. The adjusted labor expenses will only be used to calculate labor shares of the firm's production when the productivity index is estimated.

Data on labor input for this dissertation are from both COMPUSTAT and company annual reports. Data on the number of workers[93] include all employees of consolidated subsidiaries, and workers from both domestic and foreign operations. Efforts were made to exclude those years when ten percent or more seasonal or part time employees were included in the firm's reports.[94]

3.2.4 R&D Capital Stock

Besides capital and labor inputs, the growth of intangible knowledge (R&D) stock is another source of productivity growth of the firm. This section will define various R&D and technical service activities.

3.2.4.1 Characteristics of R&D

As was the case with tangible capital stock, the contribution of intangible R&D stock to productivity growth depends on the characteristics of specific R&D activities. These characteristics can be described as follows:

1. Early studies (Nelson 1962; Mansfield, 1968) have shown that industrial R&D is closely associated with uncertainty. This can be seen in the difficulties in predicting the results of development projects, and in the rates of failure. First, Marshall and Meckling (1962) concluded from their RAND studies that the predictability of the costs, time and success of military development has been quite inaccurate. Costs increased on the order of 200 to 300 percent over budget and development times were extended by one-third to one-half of the original estimates. In addition, the size of error in estimates has varied widely

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[93] Data on this data item may differ between the COMPUSTAT tapes and the company annual reports. Decisions on the choice of these two data sources are based on the actual business of the firm in the year. This data item represent average or year-end number.

[94] The footnote of the COMPUSTAT data base identifies those years when the reporting firm includes seasonal or part time employees for ten percent or more.

from one weapons system to another.[95] The errors in estimation in the civilian economy also are quite large, particularly when major technological advances are attempted (Mansfield, 1968). Second, because chance plays a crucial role in inventions and innovations, any success usually is achieved after a series of failures. Further, because R&D productivity studies also concern the market performance of R&D projects, there are two kind of risks involved — technical risk and commercial risk. A survey of 120 large R&D performing companies revealed that in half of these firms, more than 60 percent of the R&D projects never resulted in commercially used products and processes. The survey estimated that the smallest failure rate for the sample firms was 50 percent. For those projects that led to commercially used products or process, the profitability of their use was likely to be quite unpredictable.[96]

2. The contribution of R&D to productivity growth is characterized by its lag structures. There are several lags involved in the R&D to productivity linkage. First, R&D projects may take more than one year to complete; second, it may take some time before a decision is made to commercialize successful projects; and lastly, it takes time to generate the revenue stream. Two separate studies of 14 selected projects estimated that the time lags from the first idea to the first commercial deliveries of these products ranged from 2.9 years to 7.3 years, with an average of 4.7 years.[97] Empirical analysis of research lags by Pakes and Schankerman (1984) suggests that the mean lag ranges from 1.2 to

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[95] They pointed out that some human factor also is involved in the defense R&D. Military contractors are anxious to have their proposal accepted by the military and the military itself is anxious to have development proposals supported by the Congress and the Department of Defense. This tended to lead the contractors to make over-optimistic estimates. Also, the contractual penalties for such over-optimistic estimates are generally small.

[96] Chemical and Engineering News. July 10, 1957. Also in Mansfield (1968).

[97] Data were compiled by Mansfield (1968). The value of 4.7 reported here is calculated (averaged) from the table that Mansfield compiled.

2.5 years.

3. Like tangible capital stock, R&D investments depreciate and become obsolete, because better products and processes become available, and the knowledge itself begins to lose its specificity.

These characteristics influence the contribution of R&D stock to productivity growth in many ways. First, the uncertainty associated with R&D investments requires the appropriate aggregation of R&D expenditures on all projects as a measure of R&D input.[98] Case studies on successful R&D projects thus bias estimates of R&D productivity upwards and distort the risk-return relationship because they fail to account for the R&D investments on unsuccessful projects. Second, the estimation of R&D contributions has to take into account two parameters: the mean lags between the development of research resources and the beginning of the stream of revenues, and the rate of obsolescence of R&D investment. Pakes and Schankerman (1984) have shown that failure to incorporate these two parameters will bias the estimates of R&D productivity upwards.[99]

In this dissertation, data for the firm's annual R&D expenditures were retrieved from the COMPUSTAT data base, deflated by Mansfield's (1987) index for R&D input at the two-digit SIC level, representing all costs incurred during the year that relate to R&D and including amortization of software costs and software expense.

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[98] Aggregation of R&D investments beyond the firm level, especially across industries has been considered problematic (Griliches, 1979).

[99] Early researchers had ignored the depreciation issue. It was argued that the total amount of R&D was very small prior to the 1930s and that R&D growth actually began on a major scale only after World War II. Also, the rate of growth of R&D expenditure in the 1950s was so high that even if the depreciation rate was high the depreciation amount would not have had time to build up during the period covered by these studies.

3.2.5 R&D Components and Their Estimations

R&D consists of many kinds of activities, and has been shown to improve productivity in different ways (Mansfield, 1968, 1977a). First, as the word indicates, R&D consists of "research" and "development". Second, "research" and "development" can be decomposed into separate components. "Research" consists of both basic and applied research; and "development" includes product and process development. Technical-service has been another important activity in industrial R&D labs and consumes a very significant portion of the firm's technical effort. This dissertation will investigate the productivity effects of technical services together with those of the other R&D components. The definition, nature and productivity impact of each R&D component and technical-service will be defined in subsequent sections. Among other issues, their characteristics and impact on productivity are of particular interest because they directly affect the accuracy of the estimates.

3.2.5.1 Industrial Basic Research

The National Science Foundation (NSF) defines *industrial* basic research as "research that advances scientific knowledge but does not have specific commercial objectives, although such investigation may be in fields of present or potential interest to the reporting company."[100] Successful basic research permits changes in the ways that we look at phenomena and activities, identifies and measures new phenomena, and creates new devices and methods (Mansfield, 1968). Once it is successfully applied, basic research will allow the innovating firm to achieve its competitive edge and maintain it for a long

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[100] In this section, all definitions on R&D and its components are cited from National Science Board (NSB) (1989). p. 89.

period.[101]

NSF statistics show that since the 1960s, the proportion of total R&D devoted to basic research has been between 9 and 14 percent and that the principal bastions of basic research in the United States are universities and the U.S. government. In 1989, the national expenditures for basic research were estimated to be 14,694 millions of constant 1982 dollars (or 18,570 millions of current dollars). Half of the basic research in 1989 was performed by universities and colleges; only 18 percent of the remainder was conducted in the industrial sector.[102]

There are considerable difficulties in evaluating the commercial "performance" of basic research efforts. First, the outcome of basic research are highly uncertain because basic research endeavors represent an "exploration" of the unknown. The uncertainty associated with basic research means that the "production" relationship between scientific inputs and the output of new knowledge is not a deterministic one. Second, the nature of basic research is to seek new knowledge without commercial motives. These characteristics of basic research indicate that the relationship between basic research input and any commercial output will be an indirect one and extremely difficult to model. Although basic research has been empirically shown to have a positive and strong impact on the firm's productivity growth (Mansfield, 1980; Griliches, 1980; Link, 1981), there are strong cautions on such findings (Link and Bozeman, 1987).

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[101] This may also appear in such forms as patent protection.

[102] ibid. p. 89.

3.2.5.2 Industrial Applied Research

According to the NSF definition, applied research is directed toward gaining knowledge or understanding necessary for determining the means by which a recognized and specific need may be met. Industrial applied research includes "research projects which represent investigations directed to the discovery of new scientific knowledge and which have specific commercial objectives with respect to products or processes" (NSB, 1989). Examples of applied research projects can be seen in ways of making steel resist stress at particular temperatures or the application of super-conductivity at a given temperature in the making of personal computers.

Applied research differs from basic research in that it is motivated by the prospect of a practical pay-off for the firms. Basic research aims at new knowledge for its own sake while applied research aims at practical and commercial advances. In practice, this distinction is imprecise because in many cases, both motives are present and it is difficult to classify a particular project in this way. Mansfield (1980) suggests that it may be more appropriate to distinguish industrial research as long-term and short-term research.

3.2.5.3 Industrial Development

Development includes both product and process development. It is aimed at the reduction of research findings to practice. NSF defines industrial development as "the systematic use of the knowledge or understanding gained from research directed toward the production of useful materials, devices, systems, or methods, including design and development of prototypes and processes" (NSB, 1989). In practice, this reduction ranges from the construction of entirely new products and processes to relatively minor modification of existing products and processes. Uncertainty is still a factor in development but it is primarily associated with the cost of development, time to completion, and the utility of outcome. The development phase of an R&D project is generally more expensive than the research phase (Mansfield, 1968).

Unlike industrial research, product and process development have been directly linked to the firm's productivity growth. Empirical research on these two types of development efforts are scarce, primarily due to the lack of data.

3.2.5.4 Technical Services

There is no precise definition of technical service nor an official definition given by NSF. The term used in this dissertation has to be defined based on the actual practice and personal interviews with corporate management and field exports.[103] In a broad sense, technical service can be defined as those technical activities excluded by the NSF definition of R&D. These activities include quality control, routine product testing, market research, sales promotion, sales services, and engineering activities in routine, ongoing efforts to define, enrich, or improve the qualities of existing products and processes. These kinds of technical services may conceivably differ among industries and, within an industry, among firms.

Inferred from the NSF definition of R&D, technical service is not directed to technical advances, i.e, new or improved products or processes Rather, it is a maintenance function. Its aim is to ensure that the firm's products and services meet standards and quality as advertized or agreed upon with customers, or its processes perform as designed.

A great deal of technical services are performed by the marketing and

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[103] Discussions in this section are based on interviews with (1) Dr. Alden S. Bean (Director, Center for Innovation Management Studies (CIMS), Lehigh University); (2) Mr. Roger Whiteley (Associate Director, CIMS); (3) corporate R&D managers who participated in the 1990 CIMS's annual corporate-sponsored meeting; and, (4) students of the National Technology University who have been working directly or indirectly with the R&D departments in their respective corporations. These discussions also are based on descriptions of R&D (labs) functions from some corporations.

operations functions in the firm.[104] But occasionally, these functions are limited in their technical capability and/or capacity and require technical backup from the R&D department. This contribution of technical service by R&D is of interest to this dissertation.

The functions of "R&D's technical service" can be broadly divided into three categories. First, R&D's technical service function helps solve product problems that require technical expertise which the marketing department does not possess, such as special product testing or in some cases minor product modification. Second, it provides special technical assistance to the manufacturing department in the firm regarding problems with the manufacturing. Third, the increase in corporate awareness of the importance of technology also increases the involvement of R&D in the corporate decision-making process,[105] and internal control and management. R&D has teamed up with manufacturing, marketing, and other departments in improving product quality, evaluating the firm's product line mix, conducting market tests and in sales promotion, for example.

This classification of technical service in the firm is subject to some reservations. It depends on the size, structure, and lines of business of the firm. In some firms, "R&D's technical service" may not be separated easily from R&D activities because they both involve product and process testing and

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[104] In firms relatively large in size, technical services may be grouped into two categories: technical service in such departments as marketing and manufacturing ("marketing technical service" and "production technical service") and technical service in the R&D department ("R&D's technical service"). "Marketing technical service" primarily handles quality problems of the firm's products and services directly from customers. "Production technical service" solves technical problems in the production process.

[105] The data base of the Center for Innovation Management Studies (CIMS) revealed that the percentage of firms (N=138) *frequently* participating in formulating corporate strategies increases from 17 percent in the 1970s to 37 percent in the 1980s. The description of this survey is given in Appendix G.

modifications. However, in other firms, R&D and technical services are clearly separated, because these corporate R&D managers believe that performing technical services to their marketing and manufacturing departments in their R&D labs will inhibit their ability to function as a research department. In these cases, the marketing and manufacturing departments may be staffed with sufficient technical personnel to perform these services.

The accounting and reporting practice of technical service expenditures also differs from firm to firm despite the definition of R&D and requirements for filing such reports. A current CIMS survey (1990) of the R&D and technical service efforts of 44 U.S.-based firms reveals that some firms consider[106] technical services to be part of their R&D efforts while others have not. It appears from the survey that some firms have reported the technical services performed by the marketing and manufacturing departments as part of R&D expenditures. Such accounting and reporting practices will "inflate" the R&D measure and bias the estimates of returns to R&D downward. In this dissertation, the amount of technical service expenditures of the sample firms is separated out from the total reported R&D, based on the 1990 CIMS survey.

The R&D effort spent on technical services appears quite substantial.[107] Increased international as well as domestic competitiveness has prompted many major corporations to allocate more technical effort to technical services and this practice has raised concern (Bean, 1990) because the increase in technical-service may be occurring at the expense of other potentially more productive types of R&D. Thus, the impact of increased technical service activities on the firm's productivity growth has become a question of increasing importance.

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[106] Firms filed annual reports with the Security Exchange Commission on Form-10K.

[107] Chapter 4 will further describe the allocation patterns of the firm's total technical efforts.

3.2.5.5 Estimation of Annual Expenditures for R&D Components

The annual data on each R&D component have been estimated based on two sources: the COMPUSTAT data base that compiles the firm's annual total R&D expenditures and the CIMS data base that indicates the distribution of the firm's total technical effort in basic and applied research, product and process design, development and engineering, *and* technical services in 1987. An estimation of the firm's annual data on each R&D component and technical services was obtained by disaggregating the firm's total R&D expenditures using the firm's funding patterns of technical efforts as weights.[108] This procedure explicitly assumes that the firm's patterns in allocating technical efforts are the same as those in R&D expenditures, and that these patterns of allocation are stable in the period of this study: 1970-1988.

These two assumptions seem reasonable. The first assumption is based on the fact that the firm's R&D efforts are the major portion of its total technical efforts, and that the firm's R&D expenditures are the dollar values of those corresponding R&D efforts incurred. The latter assumption is based on the fact that in the national level, the funding patterns among these R&D components have hardly changed since 1960, as reported in Section 1.1.1 of Chapter 1. More importantly, the sample firms have indicated that, in the 1980s, their funding patterns had not changed in general, as shown in Table 3-1 below. From this table, the funding patterns over the 1980s are virtually unchanged except funding to applied research that increased slightly. In order to ensure the accuracy of these estimates, the estimated annual expenditures on each R&D component and technical services were returned to each sample firm for

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[108] Some data transformations will be made to the data from the CIMS data base, as described in End-Note 3, page 94.

verification. The actual data used in this dissertation are the verified or corrected data.[109]

Table 3-1: Change of Funding Patterns in the 1980s

Period	*Stats.*	*Basic R.*	*Applied R.*	*Product D.*	*Process D.*	*Tech.Serv.*
1980s	N	7	10	10	11	11
	Mean	-0.43	0.64	0.10	0.09	0.00

1. The change of funding patterns is measured in ordinal scale of seven — from (-3) to (+3), with (-3) = significant reduce, (0) = no change, and (+3) = significant increase.
2. The number of observations (N) used to compute the mean is less than 12 due to both missing and not-applicable values.

3.2.6 Other Relevant Variables

In the literature, other variables also have been identified which influence significantly productivity growth, in addition to the factors of production and the R&D variable. The number of variables of this kind varies from study to study. The choice of these variables often depends on the availability of data. These variables include rates of capacity utilization, utilization of intermediate materials and the percentage of labor force unionized.

The first two variables have been described in Section 3.2.1 of this chapter. The third variable, the percentage of unionized workers, has been found to be negatively related to productivity growth in manufacturing industries (Terleckyj, 1974; Mansfield, 1981; Bozeman and Link, 1983), but not in the non-manufacturing industries (Terleckyj, 1974). However, these

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[109] There are missing values for basic and applied research in the current sample. Following Mansfield's (1981) approach, some values are assigned to these missing cases. For firms reported basic research but not applied research, one percent of basic research expenditures is re-assigned as applied research but the largest amount does not exceed $0.1 million. Likewise, for those firms reported applied research but not basic research, the similar amount of applied research expenditures is re-assigned to basic research. There is no missing value for the development and technical service expenditures.

relationships were not statistically supported in Clark and Griliches (1984). The inclusion of the unionization variable in R&D studies has not significantly changed the estimated rates of return to R&D. For R&D studies at the firm level, industrial or sectoral data are commonly used. This variable will not be considered in this dissertation because of the lack of data. However, this dissertation will examine two other business environmental variables that influence R&D productivity.

The first environmental variable has to do with the firm's business goals, which should theoretically and directly influence the outcome of its production. Neo-classical theories assume that firms will maximize profitability and operate according to the conditions of (1.5).[110] However, recent economic research reveals that this is not necessarily the case. One influential view (Marris, 1966; Penrose, 1980) asserts that the the firm's primary business objective is the growth of the firm rather than profitability because of both the incentives of social, psychological, and financial rewards to corporate management and the threat of corporate take-over. Profitability, market share, and other business goals are then the instruments to achieve this primary objective, as further described in End-Note 4.[111] Although the relationship among profit, costs, and revenue is mathematically simple, their use in the estimation of R&D productivity is complex given differences in accounting practices, tax and financial regulations, and problems in measurement. Because the dependent variable — value-added — used in this study is directly influenced by two business priority variables, differences in the importance of these variables in the sample firms could bias the estimates of interest and these should be

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[110] See Chapter 1, page 16.

[111] page 94.

examined (held constant). The CIMS data base identifies the following six business priorities (business goals):[112] maximizing sales volumes, reducing costs, maximizing profits, maximizing market shares, coping with government regulations, market positioning, and increasing competitiveness.

Competitive pressure is another business environment variable that could influences estimates of R&D productivity in ways similar to those mentioned for business priorities. Competitive pressure's influence could differ from business goals, however, in that business goals are concerned with operating results and outcomes, while competitive pressures can influence the current structure and performance of the firm's R&D programs. This variable is important, especially when the estimates of R&D productivity are compared across firms. Another reason for examining this variable is its importance in the modeling strategy. To study the R&D productivity, ideally, one should link the technical outcomes of R&D investments to the firm's commercialized output (sales or value-added). However, due to difficulties in obtaining measures of technical outcome, the technical input (R&D expenditures) is *directly* linked to the marketed output measure instead. Thus, variables that may influence technical outcomes are relevant to R&D productivity studies, and should be examined whenever possible.

Data for these variables are available in the CIMS data base. They were surveyed in the six dimensions mentioned above and measured on the same ordinal scale. The description of these variables are given in Appendix G and statistical summary in Chapter 4. Note that these variables are assumed to be fixed for the study period and, as will be explained in Chapter 5, they will be modeled in a special way.

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[112] Description of these variables is given in Appendix G.

End-Notes to Chapter 3

1. In long-term economic growth (in steady-state), the causality between economic growth and R&D intensity has to be interpreted differently (Nelson, 1986, 1987, 1988). This can be seen from Equation (3.12), in which $\frac{d\Pi}{\Pi}$ and λ are constant in steady-state economic growth. The term $\phi \cdot y$ is also constant, which means that the higher ϕ, the lower must be y as governed by the law of diminishing returns. Given a constant ϕ in all industries, high y goes with high $\frac{d\Pi}{\Pi}$ in cross section. However, it is shown analytically by Nelson (1988) that y and $\frac{d\Pi}{\Pi}$ are both affected by "technological and demand opportunity", and it is this higher "opportunity" that yields both higher y and $\frac{d\Pi}{\Pi}$.

   Nelson (1988) also shows that $\phi = \frac{G\gamma\tau}{\upsilon}$, where G is an equilibrium growth rate of R&D capital stock, γ the output elasticity of R&D stock, τ the time period in which the innovating firm can reap the benefits of its R&D or *appropriability*, and υ the ratio of output price to unit cost. Several points can be observed from this model. First, the rate of returns ϕ depends on the appropriability τ. If the innovating firm can not reap all the benefits of its R&D, ϕ does not measure the private rate of return. Second, ϕ may not be equal across industries because of the difference in their ability to appropriate. Finally, if all the returns to R&D investments accrue to the innovating firm, these returns will flow in over a long period of time. This implies that ϕ may not be a constant over time.

2. The company had made available both its foreign currency gains/losses and its sales revenue. By combining these data items, the constant foreign exchange rates can be derived as follows:

First, let G_t be the currency gains/loses, U_t, the company's reported Europe sales, both in U.S. dollar, E_t the inflation-deflated foreign sales in European currency unit, R_t the rate of foreign exchange, at time t. Then, the foreign sales (E) can be converted into U.S. dollars (U) through the exchange rate, as:

$$U_t = R_t \times E_t \text{ or}$$

$$E_t = U_t / R_t \qquad (1)$$

Second, as most financial reports, the currency gains/loses shown in the company's reports are computed relative to the previous year's exchange rate. That is, these gains/loses are the difference in reported sales (U_t) when they were calculated using the exchange rates of the current and previous periods separately, as follows:

$$G_t = E_t \times R_t - E_t \times R_{t-1} = E_t(R_t - R_{t-1}), \qquad (2)$$

From equation (1) above, substituting $E = (U/R)$, then:

$$G_t = (U_t/R_t) \times (R_t - R_{t-1}), \quad \text{or}$$

$$G_t/U_t = 1 - (R_{t-1}/R_t), \quad \text{or}$$

$$(R_{t-1}/R_t) = 1 - (G_t/U_t) \qquad (3)$$

Equation (3) states that the ratio of the foreign exchange rate in previous period over that of current period can be derived by dividing the currency gains/loses (G_t) over foreign sales (U_t), both in U.S. dollar and available in the company annual reports. Calculating the G_t / U_t ratios from 1969 to 1988 will provide us a chain of series of exchange rate ratios. By setting the exchange rate of the base year (R_{τ}) to one and working backward and forward, we can then derive a series of exchange rates in "constant terms"—constant to the base year when R_{τ} takes a value of one.

This derived constant exchange rates can thus be used to adjust for the impact of fluctuations in foreign currency on the company reported Europe sales. However, this method of derivation is based on the assumption that E_t has been correctly deflated.

3. The data transformation involves two steps. First, in the data base, total technical effort includes both R&D components and technical services. To obtain funding patterns (percentage) for the R&D components, the original funding patterns are re-calculated so that the total percentage sums to one for R&D components only, using the following form: $NP_{if} = \frac{P_{if}}{\sum_{j=1}^{4} P_{jf}}$ where NP_{if} is the new percentage of the i^{th} ($i = 1 \ldots 4$) component of firm f, and P is the original percentage in the data base. Second, the data base uses the interval of every 10 percent to collect information, i.e., the firms were asked to supply information in the form 0-10%, 10-20%, ... 90-100%. The value of P_{if} above is the mid-point of each interval, based on the following facts. First, seven firms had supplied their actual percentages which are mostly the mid-point of these intervals. Second, statistically, the Best Linear Unbiased Estimator (BLUE) of each interval is its average.

4. According to Marris (1966), two factors make growth of the firm the primary business goal. First, the social status, power, and

financial remuneration of the managers are conditioned in some way by the nature and economic success of the firm. Second, the success of the firm will lead to higher valuation ratio (market to book value of assets) which will invite a take-over bid. Marris suggests that higher growth with lower profitability can lower the valuation ratio, because (1) growth in existing market must involve reducing margins; (2) growth in new markets involves higher risk and cost; and (3) rapid growth requires the recruitment and training of new management.

5. There have been considerable efforts to formulate the labor measure using labor "quality" factors, including the effect of increased education, shortened hours of work, the changing age-sex composition of the labor force, employment classes and other factors that changed the quality of labor overtime (Denison 1974, Gollop and Jorgenron 1980). However, after analysing the results of those adjustments by various authors, Kendrick and Vaccara (1980) suggested that it may not be so important to adjust the input quality change as part of changes in the quantity of labor input or as part of the explanation of productivity change, so long as the variables that changed the quality of labor are identified and their contributions to productivity growth are statistically estimated. Landau (1990) further argues that the growth of labor quality should be separated from the conventional economic analysis because, at the macro-economic level, labor inputs are highly aggregated and heterogeneous, and the growth of labor quality is an important linkage between investment in human

capital and economic growth. He defines the growth of labor quality as "differences between growth rates on input measures that take account of heterogeneity and measures that ignore heterogeneity." Growth in labor quality, in his analysis, "results from the substitution of more effective for less effective workers."[113]

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[113] His treatment of quality of input factors has led to quite different estimate of the impact of technological change in the U.S. economy as described in Chapter 1, page 21.

Chapter 4

The Chemical Industry and Sample Profile

Chapters 1 to 3 have established the theoretical and analytical frameworks for estimating R&D productivity at the firm level for this study. This chapter will provide a discussion of the data sample used for estimation. Section 1 will outline the major characteristics of production and research and development activities in the industry of the sample. Section 2 will present estimates for the summary statistics of the sample[114] which provide important background information for estimating the econometric models. Through the analysis of these statistics, the relationship between the current sample and its industry can also be established. The strength of this statistical relationship will determine the extent to which inferences can be made beyond the current sample.

Based on the objectives of this study and evidence from previous work, the current study will focus on the chemical industry only. The main goal of this study is to assess the productivity impact of R&D activities at the firm level. However, the results of previous research have shown that, because the characteristics in businesses and R&D vary across industries, returns to R&D have been different among industries (Mansfield, 1968; Griliches, 1984). The estimates obtained for a single industry should reduce ambiguity and thus will make it easier to interpret results and to compare across firms.

The choice of the chemical industry is based on the fact that this industry

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[114] The production and financial backgrounds of each firm in the sample have been documented in the technical supplement to this dissertation and placed at CIMS, Lehigh University.

is one of the largest in the U.S. private sector and that the chemical industry has been one of the most intensive R&D performing industries. This choice is also partly determined by the availability of sufficient company-specific data on production and R&D activities.

4.1 The Chemical Industry

The chemical industry can be defined as a "segment of the economy which *isolates* very simple, naturally occurring raw materials, *transforms* them through chemical reactions into commercially useful products, and *participates* industrially in the use of these products."[115] The term "chemical industry" or "the conventional chemical industry" refers to "the chemical and allied products industry," defined by the Office of Management and Budget.[116] Any segment of this industry or any individual firm defined as "chemical" operates in at least one of these activities. In some analytical studies, one industry segment or a group of firms may be omitted. Typically in such studies, the segment engaged primarily in making drugs is examined separately because of the unique characteristics of the pharmaceutical firms in such areas as product differentiation, R&D investment intensity, and marketing. The term for such a truncated version of the chemical and allied products industry is "chemical, except drugs." This dissertation will adopt this analytical convention and limit the sample firms to those who are primarily engaged in the production and

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[115] Emerson (1983). p. 1. Emphasis is added here. The specific sectors for which chemicals are a major ingredient include fertilizer, ferrous metals, food processing, glass, industrial gases, natural and synthetic rubber, nuclear energy, personal care products, pesticides, petroleum, pharmaceuticals, photography and copying, plastics and resins, protective coatings, pulp and paper, soaps and detergents, and textile fibers.

[116] Executive Office of the President, Office of Management and Budget. 1987. Standard Industrial Classification Manual.

distribution of chemical products/services.[117]

4.1.1 The Production Characteristics of the Chemical Industry

Chemical production and R&D activities have many unique characteristics. This section will discuss those characteristics relevant to this study.

There are two lines of business (LOB) in the chemical industry: "undifferentiated chemicals" and "differentiated chemicals" [Kline, 1976]. Undifferentiated chemicals are generic in nature, have a specific chemical formula, and carry a chemical name such as sodium chloride, carbon tetrachloride, and benzene. All undifferentiated products are chemically identical, although they may differ in quality (grades), and they can be used in many applications. In this LOB, specifications of chemicals are based on what the product contains, and/or on a specific formula. On the contrary, differentiated chemicals have only a very few applications. There are real, or at least imputed, differences among products in this LOB. Specifications are based on the performance of products. Firms in this LOB differentiate their products by making specific functional chemicals (such as dyes), by making specific formulations (such as adhesives), or by marketing strategies and/or other technological strategies. Chemical products can be grouped into four categories by these two lines of business, as shown in table 4-1 below.

The characteristics of these two lines of business have direct impact on R&D management. For companies producing true commodities ("commodity

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[117] Various data sources, such as COMPUSTAT, assign companies into different SIC industries based on their own grouping criterion. These criteria can be very misleading. Efforts have been made in this dissertation to choose sample firms whose chemical product/service is at least 70 percent of their total business. This is a necessary step to ensure the consistency of the data sample and hence validity of estimated results.

Table 4-1: Chemical Products and Their Characteristics

LOB	*Product Catagory*	*Product Evaluat.*	*Num. of Customer*	*Sales Volume*	*Examples*
Undiff.	True commodities	composition	many	large	gases,fertilizers
	Fine chemicals	composition	small	low	medicinals
Diff.	Pseudocommodities	performance	small	large	tonnage, resins
	Specialty chemicals	performance	many	low	biocides, dyes

firms"), sales are large-volume, usually to a few big customers on contract. Typically, commodities are key raw materials for the customer. The commodity firm cannot differentiate its product from other firms in the same line of business. The true commodities are manufactured in large, centralized plants using complex, sophisticated, automated, continuous, and inflexible equipment. These characteristics imply that the producers have less influence over pricing of their products and thus, the profit-maximizing commodity firms attempt to reduce costs of production. Accordingly, in the commodity firms, R&D emphasizes new or improved processes (synthesis), process engineering, and raw materials. The R&D facilities comprise synthesis laboratories engaged in research toward the discovery of new processes, and include many facilities for process development and pilot-plants. Although market research is still important, technical services and market testing are not.

At the opposite extreme, for firms manufacturing specialty chemicals ("specialty firms"), products are designed to solve specific customer problems and are sold to many different customers in small-volume. Producers can differentiate their products. Many products are made in one plant, in small volumes, and with simple and flexible equipment. Raw materials are purchased on the open markets as needed. Production is for short periods of time on flexible schedules. The focus of profit-maximizing "specialty firms" is on formulation, end-use knowledge, and the practical know-how of the customer's plant operations in applications and field-testing laboratories. Technical services and marketing testing are important to such companies. R&D facilities in specialty firms usually comprise applications laboratories and field-testing facilities.

There is little evidence that the amount of R&D investment differs between these two kinds of firms. However, the level of capital investment is different between them. Firms specializing in true commodities have a high capital investment, whereas the specialty firms have a low capital investment.[118]

In between these two extremes of the business spectrum, the companies that specialize in true chemicals and pseudocommodities have a mixture of the production and R&D characteristics of the end-point groups. Many large chemical firms are in all four types of business, usually centered in different divisions of the firm. Noted that, regardless the line of business, raw material (feedstocks) input is one of the key factors affecting the level of output, including not only the kind of material but also the possible combination of various materials. This unique characteristic of the input-output relationship in the process (chemical) industry creates some difficulties for the econometric study of R&D productivity using a production function. This problem will be discussed further in Chapter 5.

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[118] Emerson, 1983. p.225.

4.1.2 R&D in the Chemical Industry

The basic production process of the chemical industry is to transform simple, natural raw materials[119] into commercially useful products through chemical reactions. The major engineering considerations of this production process include increasing the yield of production (materials efficiency, energy efficiency and process efficiency), minimizing the formulation of an undesirable by-product, simplifying the engineering so that new capital investment can be reduced, and environmental concerns. The major economic considerations of the process include: (1) the producer's transfer (sale) price, which can be lowered with no reduction in profit; (2) the profitability resulting from the savings from new technology; and (3) raw material costs, which in many cases dictates the use of a new process.

The economic and financial impact of these considerations is shown in the following examples (Sherwin, 1974). First, for the manufacturing of vinyl chloride, a new process announced by the Lummus Company[120] offered a 16 percent reduction in the transfer price or a 100 percent increase in profitability. Second, in the production of Acrylonitrie, a new process used by Standard Oil Company (Ohio) offered a 16 percent reduction in the transfer price or a 63 percent increase in profitability. These improvements resulted from an increase in the process yield and cheaper new raw-material costs (proylene replacing acetylene). Another example of the reduction in raw-material cost (63 percent) which led to lower transfer price (12-16 percent) or increased profitability (47-94 percent) can be seen in the manufacturing process of ethylene glycol. Needless

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[119] The basic raw materials of industrial chemistry are very simple and relatively few in number--ores, inorganic, salts, coal, petroleum, air, and water.

[120] Those companies mentioned in this dissertation are not necessarily in the sample of this studies.

to say, engineering and economic considerations such as these are the objectives of industrial chemical research and development.

4.1.2.1 Industrial Chemical Research

As in other industries, industrial chemical research is directed toward the discovery of new scientific knowledge. The objective of industrial chemical research is "to learn how to make new reactions go with commercially attractive yields under conditions that can be established economically to make products for which there is a demand or a potential demand."[121] Research in the chemical industry has been conducted in many ways (Emerson, 1983). First, research has been directed to investigate a specific technical need. The most successful example of such an application has been those companies that synthesize components with expected biological activity and couple this synthesis with detailed observations in pharmacology, drug metabolism, biochemistry, and biology. Second, considerable research efforts have been made with raw materials. For example, the research efforts of Union Carbide Corporation on acetylene and ethylene have enabled the company to market more than 24 pure organic chemicals.[122] The third approach of industrial research is to focus on a specific use. Monsanto Company has successfully taken this approach in the discovery of nondiscoloring antiozonants (Emerson, 1983).

Industrial chemical research includes basic research that is idea seeking, and applied research that involves finding commercial uses of existing knowledge. Chemical basic research can be "performed" in the following ways. First, hiring new research scientists and engineers from research institutes and universities brings new, as well as state-of-the-art, knowledge to a company and

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[121] Franta, 1973. p.650.

[122] Union Carbide Corporation Catalogue, 1973-1974 edition.

enables the firm to update and enlarge its science and technology base. Second, the firm's science and technology base can be maintained/updated through interactions with research institutes, universities and Federal laboratories such as joint projects, personnel exchanges, etc. Third, the firm can contract its basic research to outside research institutes and universities. Finally, the firm can perform basic research by itself in its own laboratories. Usually, those firms that have basic research programs conduct it in some or all of these four ways. The CIMS R&D data base reveals that in the last decade, basic research was conducted differently in various project development phases. In the pre-commercial phases, basic research primarily was performed outside of the firm (Bean, 1989b, 1990).[123]

Applied research in the chemical industry is the first step of the industrial development process that reduces scientific findings to new products and new processes. Applied research also continues throughout the entire development process. Therefore, separating applied research from development in the chemical industry is relatively difficult.

Again note that research produces scientific knowledge, not products and processes. It is the use of research results through development and innovation that create new products/services and new processes. This indirect relationship between research–especially basic research–and end results is particularly important in the context of this study which attempts to link research input econometrically to an output measure (productivity). Such an indirect linkage seems to require different research methodology from studies linking development directly with output. Although basic research has been found to

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[123] The survey divided the stages of commercial development into pre-commercial, start-up, "niche" development, growth, mature, and harvest.

have a direct, positive impact on the productivity growth of the U.S. industries and negative impact on the Japanese industries' growth, (Mansfield, 1980, 1988), further investigation is needed because these linkages have not been clearly identified in past studies.

4.1.2.2 Industrial Chemical Development

Industrial chemical development is the use of known scientific knowledge to create new products and processes. Compared with industrial chemical research, it is objective and is measured by achievement rather than discovery. In most chemical companies, development constitutes the major portion of the R&D budget, often as much as 90 percent (Emerson, 1983). Johnson and Blair (1972) reported that for a specific case of pesticide development which cost a total of $7.8 billion, research costs were only $0.5 million.

Industrial chemical development may involve four phases: definitive development, laboratory development, design development, and final development (Emerson, 1983). In the definitive development phase, new products and processes are identified, the cost and availability of possible raw materials examined, and possible environmental problems noted. This phase also makes an initial economic evaluation in such areas as the size and type of market, economic scale of production, competition, and an initial patent search. The phase of laboratory development continues and extends the definitive phase, with establishment of tentative product specifications. A detailed evaluation of the chosen process is made, and costs are reviewed in more detail. The commercial development department begins to develop merchandizing concepts. With the product, process and market specified, the responsibility for the development project moves gradually from the R&D department to the commercial development department.

In the design phase, the results of the preliminary sampling conducted in the phase of laboratory development are summarized and carefully evaluated. Field trials are conducted by the commercial department, with backup from the R&D department. A pilot plant is designed, constructed and operated. Finally, in the phase of final development, the product and the process are commercialized. Usually, a plant technical-service group is also organized.

4.1.2.3 Facets of Chemical R&D

R&D has been an important economic tool for the chemical industry's growth.[124] Some chemical industrialists claimed many decades ago the same high rates of financial return from R&D that scholars have recently been suggesting.[125] As early as the 1920's, businessmen had believed in the value of R&D activities. A survey of 800 leading companies conducted in 1928 by the National Research Council (NRC) revealed that 68 percent of them operated research laboratories and that research had "practical utility in increasing profits and reducing costs."[126] Only three companies disagreed, and the other 797 manufacturing firms "seemed to be convinced that such research does pay. . . . Estimates of the ratio of profit to the amount expended for research ranged from 100 to 300 percent in many instances." This sort of appraisal, although rather crude in terms of data and analytical methods, is in line with the more recent studies of returns to R&D with better data and improved methodology (Mansfield, 1965 and 1980; Minasian, 1969).

In the 1920s, cost saving seems to have been a dominant objective for the firm's R&D program. Other major research objectives were to improve product

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[124] The chemical industry has been one of the R&D intensive industries in the U.S. private sector. R&D budgets vary in amount from about 1 to 4.5 percent of sales within the chemical industry itself (Aron, 1976). The major cost item in a R&D department is the time of the professionals involved.

[125] American Chemical Society (ACS), 1984.

[126] All results cited in this section are from ACS (1984), p.502.

or service, develop new fields of application, reduce by-products and discover new materials (ACS, 1984). These research emphases have changed over time. In another NRC survey of 256 firms in 1931, new products became the most important research objective of chemical and drug companies, while the emphases on new fields of application, by-products and new materials were of almost no importance. More current studies of 39 chemical firms in the CIMS[127] data base revealed that product development was the most important chemical R&D objective in the 1970s and 1980s.

In summary, R&D programs in the chemical industry have long emphasized product development. Chemical research has largely been oriented to applied research. It is relatively difficult to separate applied research from development in this industry.

4.2 Profile of the Sample

Given the focus of this study as the "chemical industry, except drugs,"[128] and as discussed in Chapter 3 (Section 3.2), data for the primary variables have come mainly from the following sources: the Standard and Poor's COMPUSTAT data base; company annual reports to stock-holders and FORM 10-K reports to the Security Exchange Commission (SEC); the Morgan Trust Company of New York; the CIMS data base of R&D Organization and Funding; and the U.S. government agencies–the Bureau of Labor Statistics (BLS); the Bureau of Economic Analysis (BEA) and the Bureau of the Census.

Annual consolidated company data on sales, materials, inventory, tangible capital expenditures, labor, total R&D expenditures were taken from the

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[127] Summary statistics of those survey variables relevant to this study are presented in table 4-4 in this Chapter.

[128] See page 98 for definition.

COMPUSTAT tapes covering a 20-year period, 1969-1988. The company reports enabled the disaggregation of the firm's businesses into segments at the SIC four-digit level and into geographical regions (domestic vs foreign) for the entire 20-year period. Relevant estimates from the BEA and BLS, along with the company FORM 10-K reports, made it possible to estimate capital stock for each firm in the sample. Producer price indices from the BLS, R&D price indices from Mansfield (1987) and the BLS,[129] the foreign exchange indices from the Morgan Trust Company and the Federal Reserve Board, and labor earning per hour index and capacity utilization index from the Census Bureau were used to make the appropriate adjustments to the company financial and R&D data. All of these indices, except the exchange index and R&D deflator, were obtained at the SIC four-digit level.

Annual data on the R&D components were estimated from the CIMS data base.[130] The annual data on technical services were estimated in the same fashion, but were computed based on the firm's actual reporting practice These estimates for each firm were then returned to the sample firm for verification. Fourteen chemical companies verified those estimates.[131] The final sample of 12 firms was chosen for this study from these 14 chemical firms. The other two firms were dropped because of either the problem of merger or the percent of chemical sales was less than 70 percent of the firm's total annual revenue.

The reporting practice of technical service expenditures has been quite different among firms. Some firms have classified such expenditures as part of

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[129] The Jeffe-Griliches R&D deflator. BLS. 1989. Bulletin 2331.

[130] See Section 3.2.5.5, page 88, Chapter 3.

[131] Verification requests were sent to 69 firms in 13 industries (at SIC two-digit level). Forty-nine firms verified and returned the requested estimates, of which 14 are chemical firms.

R&D, while others reported them as an addition to R&D. It appears that some firms even reported their total technical efforts as R&D activities, including non-R&D technical services. Obviously, such reporting practice makes it difficult to estimate accurately the returns to R&D.

4.2.1 Summary Statistics: Input & Output

Tables 4-2 and 4-3 provide summary statistics on the major variables of the current sample both for the 20-year period, 1969-1988, and for three separate sub-periods. Average growth rates of these variables for the chemical industry are also shown at the end of these two tables[132] for the purpose of comparison. These variables are the components of the TFP productivity index which are estimated in Chapter 5.

First, on the output side, deflated total output of the sample firms grew 6.2 percent per year (line 1 of table 4-2) and deflated net sales 5.8 percent per year (line 2) over the 20-year period. From table 4-3, sales of the sample firms grew the fastest among these three subperiods, averaging more than 10 percent per year, from 1970 to 1975, and the lowest between 1976 and 1982, following the business cycles. Compared with the chemical industry, the growth rate of sales of the current sample during the entire period is somewhat lower (5.80% vs 9.90% [line 37]). However, this difference is due to the difference in the calculation method. The sample statistics are all deflated and averaged over the sample firms, while the industry statistics are derived from the industry's undeflated aggregated data. By aggregating undeflated data across the sample firms the average rate of growth in net sales is 8.4 percent from 1970 to 1988 which is very compatible with the industry averages.

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[132] Notations in the tables are explained at the end of the tables.

Table 4-2: Sample Summary Profile, 1970-1988

Line	*Variable*	*Mean*	*Median*	*Std Dev*	*Mode*	*Kurtos.*	*SE Kurt*	*Skew.*	*SE Skew*	*Range*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
					Average Annual Growth Rates						
1	Output	**6.20%**	0.058	0.134	-0.270	9.732	0.337	1.921	0.169	1.184	206
2	Sales	**5.80%**	0.049	0.119	-0.236	9.487	0.337	1.766	0.169	1.036	206
3	Materials	**11.00%**	0.033	0.881	-0.752	185.772	0.337	13.307	0.169	13.133	206
4	Capital	**2.90%**	0.024	0.051	-0.067	1.122	0.333	0.733	0.167	0.305	212
5	Labor	**2.20%**	0.005	0.128	0.000	19.845	0.337	2.723	0.169	1.503	206
6	Cap Exp.	**10.20%**	0.027	0.469	-0.753	9.955	0.333	2.142	0.167	3.994	212
7	R&D/Sales	**1.50%**	0.001	0.357	-0.658	145.847	0.337	11.049	0.169	5.357	206
					Average Annual Ratios						
8	R&D/Sales	**3.20%**	0.027	0.018	0.004	1.140	0.328	1.092	0.165	0.100	218
9	R&D/Output	**3.00%**	0.026	0.017	0.003	1.559	0.328	1.163	0.165	0.099	218
10	BR/Output	**0.20%**	0.001	0.002	0.000	-0.487	0.328	0.929	0.165	0.007	218
11	AR/Output	**1.20%**	0.007	0.013	0.000	0.838	0.328	1.326	0.165	0.059	218
12	PDD/Output	**0.90%**	0.008	0.007	0.000	5.687	0.328	1.774	0.165	0.045	218
13	PCD/Output	**0.70%**	0.005	0.008	0.000	8.358	0.328	2.774	0.165	0.048	218
14	TS/Output	**0.70%**	0.005	0.006	0.001	2.787	0.328	1.769	0.165	0.033	218
15	RES/Output	**1.40%**	0.009	0.013	0.001	0.629	0.328	1.300	0.165	0.059	218
16	DEV/Output	**1.50%**	0.013	0.009	0.003	3.163	0.328	1.458	0.165	0.054	218
17	Fin/Output	**7.60%**	0.069	0.033	0.021	0.071	0.328	0.805	0.165	0.146	218
18	Fsales/Outp	**29.20%**	0.265	0.156	0.197	1.108	0.320	1.181	0.161	0.706	229

Line	*Variable*	*Mean*	*Median*	*Std Dev*	*Mode*	*Kurtosis*	*SE Kurt*	*Skew.*	*SE Skew*	*Range*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
19	C.E/Sales	**0.08**		.05		1.98	.31	1.41	.16	.27	240
20	D.C.E/Sales	**0.08**		.05		2.96	.33	1.55	.16	.30	218
					Annual Averages						
21	Def. R&D	**86.743**	44.088	111.116	0.232	4.322	0.328	2.059	0.165	566.724	218
22	DEF. BR	**7.861**	0.359	16.252	0.017	9.675	0.324	2.941	0.163	99.950	224
23	DEF. AR	**30.253**	12.348	54.612	0.032	11.751	0.324	3.215	0.163	321.396	224
24	DEF. PDD	**28.839**	8.173	47.279	0.042	9.976	0.324	2.930	0.163	300.111	224
25	DEF. PCD	**16.371**	10.574	25.275	0.296	11.825	0.324	3.190	0.163	166.457	224
26	DEF. TS	**25.473**	6.341	36.226	0.146	3.570	0.324	1.890	0.163	178.426	224
27	N of Empl	**22.262**	14.180	20.533	1.500	-0.577	0.328	0.843	0.165	76.760	218
28	Def.Output	**2925.938**	1802.745	3407.810	23.931	4.113	0.328	2.021	0.165	17763.256	218
29	Def. Sales	**2777.145**	1631.288	3279.038	24.027	3.712	0.328	1.959	0.165	16717.261	218
30	D.Frgn.Sale	**748.787**	367.973	1019.550	9.611	6.574	0.328	2.430	0.165	6305.601	218
31	D.Finished	**215.652**	107.632	225.581	0.934	1.407	0.328	1.329	0.165	1050.158	218
32	DEF. Cost	**1082.504**	768.386	1188.941	0.380	1.097	0.328	1.436	0.165	4552.781	218
33	Est.Stock	**2432.914**	1723.818	2540.668	38.188	0.732	0.324	1.245	0.163	9237.997	224
34	D.Net.Asset	**1114.359**	694.362	1239.978	5.108	1.498	0.324	1.393	0.163	5612.910	224
35	D.Grs.Asset	**1995.685**	1290.497	2148.067	7.436	0.366	0.324	1.160	0.163	8422.077	224
36	DCap.Exp.	**218.30**		246.50		1.50	.32	1.45	.16	1055.24	224
					Industry Average Rates and Ratios						
37	Sales %	**9.90%**	0.103	-0.054	0.076	1.700	1.038	0.247	0.536	0.342	18
38	Material %	**10.70%**	0.123	-0.095	0.118	4.337	1.038	1.189	0.536	0.556	18
39	Capital %	**2.50%**	0.092	-1.000	0.280	12.731	1.063	-3.360	0.550	1.268	17

Line	*Variable*	*Mean*	*Median*	*Std Dev*	*Mode*	*Kurtosis*	*SE Kurt*	*Skew.*	*SE Skew*	*Range*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
40	Labor %	**-0.30%**	-0.005	-0.036	0.022	-1.492	1.038	0.061	0.536	0.071	18
41	Cap Exp.%	**8.40%**	0.080	-0.221	0.174	3.623	1.038	1.273	0.536	0.812	18
42	D.C.E/Sales	**5.20%**	0.053	0.038	0.011	-1.036	1.038	0.314	0.536	0.033	18
43	Cap/Sales	**14.50%**	0.141	0.106	0.023	-0.751	1.091	0.327	0.564	0.079	16

Notations (all deflator, 1982=100)

- Many items listed in this table have multiple mode values. The mode value shown here is the minimum one for those items.

- Growth Rates (%) = Rates of growth from 1970-1988.
  Labor = total number of employees ; "Cap Exp." (line 6), "C.E" (19), "*D*.C.E" (20) = (*D*eflated) Capital Expenditures (Line 6).

- Ratios = Ratios of output or sales;
  BR = Basic Research; AR = Applied Research; PDD = Product Development; PCD = Process Development; TS = Technical Services; RES = RESearch (BR + AR); DEV = DEVelopment (PDD+PCD); R&D = RES + DEV;
  Fin = Finished Goods Inventory, Deflated; Fsales = International sales (= total sales - domestic sales), deflated.

- Averages = Mean values of the listed variables, all deflated.
  Est.Stock = total capital stock estimated in this study. It differs from those capital stock reported by the firms (D.Net.Asset = deflated net assets; D.Grs.Asset = Deflated gross Assets).

- Data for the chemical industry are from the Census of the Manufactures from 1970 to 1988, except data on capital stock which were estimated by BLS, unpublished.

- The measure of total output (line 28) is the sum of net sales (line 29) and the inventory of finished goods (line 31), all deflated. The inventory of finished goods on average is 7.6 percent of the total output.

Table 4-3: Sample Summary Profiles, By Sub-Periods

Variable	*1970–1975*			*1976–1982*			*1983–1988*		
Name	*Mean*	*Std.Dev*	*N*	*Mean*	*Std.Dev*	*N*	*Mean*	*Std.Dev*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
				Average Annual Rates of Growth					
Output	**10.32%**	0.1754	57	**3.40%**	0.0991	84	**6.24%**	0.1244	65
Sales	**9.33%**	0.1672	57	**3.68%**	0.0933	84	**5.45%**	0.0896	65
Materials	**32.26%**	1.6545	57	**2.22%**	0.1050	84	**3.63%**	0.1502	65
Capital	**5.41%**	0.0617	60	**2.58%**	0.0468	84	**0.95%**	0.0318	68
Labor	**6.62%**	0.1838	57	**1.78%**	0.0865	84	**-1.10%**	0.1031	65
Cap Exp	**17.73%**	0.6240	60	**9.10%**	0.4466	84	**5.02%**	0.3076	68
R&D/Sales	**3.85%**	0.6397	57	**-2.39%**	0.1647	84	**4.31%**	0.1092	65
				Average Annual Ratios					
R&D/Sales	**0.0361**	0.0190	69	**0.0257**	0.0152	84	**0.0345**	0.0191	65
R&D/Output	**0.0343**	0.0182	69	**0.0237**	0.0137	84	**0.0327**	0.0183	65
BR/Output	**0.0017**	0.0019	69	**0.0013**	0.0016	84	**0.0020**	0.0022	65
AR/Output	**0.0137**	0.0135	69	**0.0098**	0.0101	84	**0.0135**	0.0148	65
PDD/Output	**0.0105**	0.0086	69	**0.0065**	0.0041	84	**0.0092**	0.0061	65
PCD/Output	**0.0078**	0.0090	69	**0.0055**	0.0063	84	**0.0073**	0.0074	65
TS/Output	**0.0085**	0.0069	69	**0.0056**	0.0049	84	**0.0079**	0.0071	65
RES/Output	**0.0154**	0.0138	69	**0.0112**	0.0106	84	**0.0155**	0.0155	65
DEV/Output	**0.0183**	0.0109	69	**0.0119**	0.0062	84	**0.0165**	0.0078	65
Def.R&D	**71.2673**	77.2908	69	**71.0961**	82.1919	84	**123.3927**	157.5162	65

Variable	*1970–1975*			*1976–1982*			*1983–1988*		
Name	*Mean*	*Std.Dev*	*N*	*Mean*	*Std.Dev*	*N*	*Mean*	*Std.Dev*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
Industry Average Rates and Ratios									
Sales	**12.99%**	0.0940	5	**9.84%**	0.0712	7	**7.42%**	0.0684	6
Materials	**16.59%**	0.1697	5	**11.19%**	0.0954	7	**5.24%**	0.0798	6
Capital	**10.77%**	0.0226	5	**6.99%**	0.1313	7	**-12.04%**	0.4994	5
Labor	**-0.88%**	0.0250	5	**0.53%**	0.0207	7	**-0.81%**	0.0211	6
Cap Exp	**17.71%**	0.2709	5	**5.49%**	0.0770	7	**4.06%**	0.1563	6
C.E/Sales	**5.69%**	0.0094	5	**5.90%**	0.0074	7	**3.98%**	0.0016	6

- See notations at the end of the previous table.

Second, on the input side, feedstocks grew far more than the output growth, at 11 percent annually (line 3), partly because of the oil shock in the early 1970s which resulted in the 32 percent growth in feedstock during the 1970-1975 sub-period as shown in the third line of table 4-3. Capital expenditures (line 6 of table 4-2) also increased considerably, relative to output growth, at about 10 percent annually during the period. However, the total number of employees increased only 2.2 percent and capital stock 2.9 percent annually during the period. Most of these increases occurred in the 1970-1975 sub-period. By comparison with the chemical industry's statistics, these ratios seem higher. However, results in line with the industry averages are obtained when appropriate adjustments are made. By aggregating undeflated data across the sample firms the average annual rates of growth from 1970 to 1988 in material is 9.0 percent and capital expenditures, 9.1 percent, which are also very comparable with the industry averages.

The difference in the growth rates of the input and output variables will have a direct impact on the overall total productivity growth of the sample because the productivity index of this study will be calculated essentially as the "weighted" difference between the growth rates of output and inputs. From table 4-3, it can be inferred that such an index will not be monotonically increasing. Furthermore, it is noted that there are also considerable variations in these statistics among firms. These variations are not only indicated by high standard deviations but also by the Kurtosis and Skewness statistics, particularly in the feedstock growth rates. If those variables are distributed normally, the statistic of Kurtosis and Skewness should be zero. The positive values of these two statistics indicate that the distribution is not symmetric and has more cases (or more of a "tail") toward the right end of the distribution (toward large values) and clustered more than those in the normal distribution (more peaked). The high Kurtosis and Skewness values, along with the high Range values in these statistics indicate that considerable variations in the estimated TFP indices among firms can be expected.

The ratio of total R&D to output averaged three percent per year (line 8, table 4-2 during the period, with mean value of about $87 million (1982 dollars, line 21) per firm. This ratio is very compatible with the industry average (1–4.5%).[133] Of these $87 million, less than 10 percent went to basic research ($7.9 million, lines 10, 22) while the majority went to applied research and product development (about $30 million each, line 23 and 24). This allocation pattern of total R&D among its components matches the patten at the national level.[134] However, the sample has more emphasis on applied research. But this emphasis seems to be in line with the chemical industry as described earlier.

The sample firm spent an average of $25.47 million each year on technical services per firm during the period (line 26). As a percent of total R&D (23.6%),[135] it is also compatible with the percentage of the entire CIMS data base of 139 firms (22.4%).[136] The amount of expenditures on technical services is very significant, close to product development and far more than process development ($16 million, line 25) and basic research ($8 million, line 22).

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[133] See Footnote [124] in this Chapter.

[134] In fact, this pattern also matches the pattern of 139 firms in the CIMS data base. In the national level, the portions of total R&D devoted to basic research have been between 9 and 14 percent since 1960; 21 and 24 percent for applied research; 63 and 69 percent for development (National Science Board, 1989). The CIMS data base of 139 firms also shows the similar patterns: basic research is 9.31%; applied research, 26.32%, product development 38.35%, and process development, 25.11%.

[135] This percentage is based on the CIMS data base for the purpose of comparison. In this study, since data on R&D and technical services are calculated based on the actual reporting practice of the sample firms, those expenditures on technical services reported as R&D are excluded from the total R&D expenditures reported to the SEC. Thus, the ratio of technical services to R&D is higher here since the denominator of the ratio, R&D, is smaller.

[136] No data on technical services has ever been published.

The changes in R&D investment over the three sub-periods are also shown in Table 4-3. The change patterns of R&D ratios over these three periods are similar to those of the other production factors, although the extent of changes is different. A strong relationship between R&D and growth of input and output can thus be expected.

4.2.2 Summary Statistics: R&D Programs

The CIMS data base provides further information about the R&D programs of the sample firms, including the focus of R&D programs, total technical effort allocations among various R&D activities, R&D program emphasis in the 1970s and the 1980s, business objectives of the R&D programs, and the expectation and realization of these business objectives by the R&D programs. Summary statistics of these variables are tabulated in table 4-4.[137] Also shown in this table are the same statistics for the other two samples: "all chemical firms" in the CIMS data base (24 firms, columns 7 - 10) and the "all firms in the CIMS data base " (127 firms, columns 11 - 14). Note that the "all chemical firms" excludes pharmaceutical firms and those 12 firms of this study. These 12 sample firms are also excluded from the "all firms in the CIMS data base."

A. The Scope of the R&D Programs

First, the overall scope of the R&D programs varies widely among these 12 firms. Four of them are highly diversified,[138] covering a broad spectrum of scientific and engineering (S&E) disciplines of current and potential interest to these companies. The R&D programs of another four firms are moderately

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[137] Notations used in this table are explained at the end of the table.

[138] The distribution table for each variable is not shown in this Chapter. They will be described in detail if necessary.

focused, covering core technologies plus some monitoring of technology outside these areas. For the remaining four firms, three of them are in between these two groups, and the last firm has its highly focused R&D programs covering only those technologies that are relevant to its current businesses. R&D programs of the sample firms are somewhat more diversified than those of "all chemical firms" and the entire CIMS survey (line 1 of table 4-4). Such widely diversified R&D programs may indicate the extent to which basic research is performed and the impact of these research programs on the firm's productivity growth. It can be hypothesized that such impacts on productivity growth for those seven firms with considerable interests in S&E potential may occur with a longer time lag and also may not be directly assessable. However, this analysis is subject to the examination of the firms' basic research programs below.

B. Basic and Applied Research Programs

As indicated in the earlier quantitative analysis, the sample firms maintained minimal basic research programs both in the 1970s and the 1980s. About one half of the 12 firms had none at all or extremely small basic research programs. Among the remaining firms, four of them had a minimal emphasis on basic research programs throughout the 1970s and the 1980s. The R&D budgets for the basic research were slightly reduced during the 1980s. Of this limited amount of basic research, about nine percent was performed by university scientists, engineers and graduate students, as shown in *italic* in Column 3 of table 4-4. The same emphasis on basic research can also be seen in the other two samples.

However, applied research is the second most important R&D effort of the sample firms. R&D budgets and program emphasis for applied research both were increased further in the 1980s (lines 8 and 15 of Table 4-4), and it can be inferred that the applied research programs have been more focused in the

1980s (lines 32 and 33). When compared with the other two samples, the current sample shows a greater emphasis[139] on applied research. There is little quantitative evidence on the impact of the strong applied research program relative to the basic research program. Intuitively, they both seem complementary to each other.[140]

B. The Development Programs

The main focus of the sample firms' R&D programs was in product design, development and engineering, followed by applied research. Such emphasis was further increased in the 1980s, as indicated by the underline numbers in the table. The most important focus of the R&D programs of the 12 firms shifted from "being a product leader" in the 1970s to "competing in existing markets areas" such as getting ahead of competitors, staying with competitors, etc. Related to this program focus, "increasing the sales volume or maintaining a certain level of sales" became one of the primary business goals associated with the R&D programs, according to the survey. This trend seems to be in response to increased international competitiveness in the 1980s. In the current context, such R&D programs may imply that product development will have a strong relationship with the firm's productivity growth since sales volume are taken as

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[139] From line 3, the current sample may conduct about 5-10 percent more applied research then other two samples.

[140] In the case of the Japanese industrial research, it has traditionally weak basic research programs and strong applied research programs. It has been estimated that the Japanese basic research has negative impacts on its industrial productivity growth. However, the strong applied research program of the Japanese industry is estimated to have higher productivity impact on productivity growth then the U.S. (Mansfield, 1988). However, such strong impact on productivity growth heavily relies on the international basic research programs, especially from the U.S.

the firm's output measure.[141]

The survey also indicates that these 12 firms believed that their R&D programs have paid off both in the areas of strengthening "competitive positions" and "reducing product costs and minimizing cost increases" (lines 42 and 54). As mentioned above, the program emphasis on product development may have contributed to the increases in the firm's market sales, while process development should be the most direct cause of the firm's cost reduction. Clearly, both product and process development can increase the firms' market competitiveness. In the context of this study, this implies that process development, along with product development, may have a strong relationship with the firm's productivity growth.[142]

In general, the summary statistics of the current sample indicate that the sample firms follow the economic conditions of the chemical industry. The current sample had high output growth rates in the 1970-1975 period and low growth rates in the 1976-1982 period. However, this high growth rate was offset by the higher growth rate of feedstock costs in that period. Investments in various R&D activities followed the same patterns. The CIMS data base further reveals that the sample firms, on average, have a small basic research programs relative to their applied research and development programs. Applied research and product development have been the main focus of the sample firms. Product and process development are strongly expected to be associated with output

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[141] "Complying with government regulations" has also been an important objective of the R&D programs across all three samples. The impact of this objective on the firm's productivity growth is not certain. The stricter the government regulations, the more company resources have to be devoted to comply with the regulations and the less to productions. Some studies have been argued that the slowdown of productivity in the 1970s may have resulted from the regulations came into effects at that decade.

[142] In equation (3.12), reducing material costs will increase the firm's π, TFP growth.

growth. However, the relationship between basic research and productivity growth is questionable. The R&D programs of the sample firms, on average, match those in the overall CIMS survey and the chemical industry.

Table 4-4: Summary Statistics of the CIMS Survey

		Current Sample Only				*Chem.Industry except Drugs*				*Survey "Population"*			
#	*Variable*	*Mean*	*StdDev*	*Skew.*	*N*	*Mean*	*StdDev*	*Skew.*	*N*	*Mean*	*StdDev*	*Skew.*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(14)*
		R&D Program Focus (Scale 1-4)											
1	R&D Focus	**2.583**	0.793	-0.325	12	**2.167**	1.007	0.753	24	**2.160**	0.902	0.616	125
		Allocations of Total Technical Efforts in 1987 (Scale 1-10: 1 = 10%)											
2	Basic Res %	*0.667*	0.707	0.606	9	**0.650**	0.587	0.212	20	**0.847**	0.761	1.473	107
3	App Res %	**3.300**	2.312	1.905	10	**2.636**	1.465	1.403	22	**2.512**	1.712	1.897	122
4	Prod Dev %	**3.800**	2.044	0.336	10	**3.619**	1.359	0.779	21	**3.781**	1.786	0.544	116
5	Proc Dev %	**2.000**	1.000	0.733	11	**2.409**	1.054	0.666	22	**2.492**	1.301	0.759	119
6	TS %	**2.364**	1.206	0.808	11	**2.227**	0.973	0.182	22	**2.148**	1.346	0.922	117
		Changes in the Allocations of Total Technical Efforts Over the 1980s (Scale 1-7, 4 = no change)											
7	Chg BR	*3.571*	1.618	-0.013	7	**3.533**	1.922	-0.059	15	**3.919**	1.702	-0.127	74
8	Chg AR	**4.636**	0.809	0.847	11	**4.316**	1.336	-0.026	19	**4.257**	1.214	-0.066	101
9	Chg PDD	**4.100**	0.876	1.018	10	**4.632**	1.165	1.059	19	**4.489**	1.114	0.265	94
10	Chg PCD	**4.091**	1.700	-0.768	11	**4.316**	1.293	1.059	19	**4.379**	1.178	0.097	95
11	Chg TS	**4.000**	1.000	-0.733	11	**3.947**	1.026	1.150	19	**4.183**	1.113	0.597	93

		Current Sample Only				*Chem.Industry except Drugs*				*Survey "Population"*			
#	*Variable*	*Mean*	*StdDev*	*Skew.*	*N*	*Mean*	*StdDev*	*Skew.*	*N*	*Mean*	*StdDev*	*Skew.*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(14)*
R&D Programs' Emphasis in the 1970s vs 1980s (Scale 1-7)													
12	BR: 70s	*1.700*	1.767	0.568	10	**1.800**	1.609	0.360	20	**1.694**	1.705	0.850	111
13	BR: 80s	*1.700*	1.703	0.753	10	**1.857**	1.824	0.779	21	**1.816**	1.727	0.731	114
14	AR: 70s	**3.833**	1.946	-0.697	12	**3.909**	1.571	-0.079	22	**3.756**	1.681	0.014	123
15	AR: 80s	**4.750**	1.288	-0.057	12	**4.130**	1.687	0.399	23	**4.325**	1.747	-0.347	126
16	Acq:70s	**2.083**	1.676	1.233	12	**2.409**	1.469	0.494	22	**2.463**	1.478	0.583	123
17	Acq:80s	**3.250**	1.485	0.487	12	**4.261**	1.764	-0.326	23	**3.928**	1.514	-0.089	125
18	Prod:70s	**4.750**	1.960	-0.625	12	**4.727**	1.695	-0.238	22	**4.542**	1.714	-0.245	120
19	Prod:80s	**5.500**	1.382	-0.372	12	**5.304**	1.396	-0.600	23	**5.325**	1.434	-0.590	123
20	Proc:70s	**3.583**	2.392	-0.028	12	**4.409**	1.736	-0.342	22	**3.934**	1.757	-0.010	122
21	Proc:80s	**4.417**	1.975	0.064	12	**4.696**	1.690	-0.216	23	**4.432**	1.720	-0.212	125
22	Trd: 70s	**3.300**	1.494	-0.639	10	**3.444**	1.464	-0.004	18	**3.680**	1.426	0.166	97
23	Trd: 80s	**3.500**	1.716	-0.330	10	**3.947**	1.747	-0.190	19	**3.980**	1.537	0.034	100
24	MkgN: 70s	**3.636**	1.433	0.786	11	**3.818**	1.763	0.131	22	**3.636**	1.673	0.095	121
25	MtgN: 80s	**4.727**	1.489	-1.651	11	**4.261**	1.630	-0.324	23	**4.202**	1.603	-0.311	124
26	MkgE:70s	**5.333**	1.435	-0.484	12	**5.455**	1.535	-0.775	22	**5.225**	1.399	-0.785	120
27	MkgE:80s	**5.917**	1.240	-1.188	12	**5.652**	1.301	-0.638	23	**5.626**	1.237	-0.836	123
28	GovA:70s	**3.727**	2.102	0.360	11	**3.474**	2.038	0.329	19	**3.718**	1.706	0.016	103
29	GovA:80s	**5.091**	1.375	-0.760	11	**3.950**	1.986	0.166	20	**4.377**	1.612	-0.386	106
30	GovC:70s	**4.833**	1.528	-0.034	12	**4.682**	2.147	-0.370	22	**5.091**	1.798	-0.838	121
31	GovC:80s	**5.833**	1.115	-0.560	12	**5.522**	1.855	-1.090	23	**5.595**	1.476	-1.077	126
32	FR: 70s	**4.250**	1.960	0.016	12	**4.727**	1.518	-0.389	22	**4.140**	1.655	-0.138	121
33	FR: 80s	**5.750**	1.138	-1.193	12	**6.217**	0.671	-0.280	23	**5.427**	1.460	-1.557	124

		Current Sample Only				Chem.Industry except Drugs				Survey "Population"			
#	Variable	Mean	StdDev	Skew.	N	Mean	StdDev	Skew.	N	Mean	StdDev	Skew.	N
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
34	DR: 70s	**2.250**	1.357	0.246	12	**2.429**	1.434	0.495	21	**2.717**	1.589	0.179	113
35	DR: 80s	**2.667**	1.155	0.362	12	**2.500**	1.766	1.312	22	**2.821**	1.720	0.666	117
Importance, Expectation, Realization & Pressure of Corp Bus.Goals on R&D Prog. (Scale 1-7)													
36	ImptSale	**6.000**	0.953	0.000	12	**5.000**	1.809	-0.807	23	**5.339**	1.385	-0.742	124
37	ExpSale	**4.750**	1.357	-0.508	12	**4.478**	1.729	0.098	23	**3.984**	1.547	0.230	123
38	RelzSale	**4.167**	1.267	-0.048	12	**4.435**	1.590	0.316	23	**4.033**	1.454	0.447	123
39	PrssSale	**5.667**	0.888	-1.075	12	**4.826**	1.029	0.104	23	**4.772**	1.093	-0.148	123
40	ImptCost	**4.917**	1.165	0.604	12	**5.348**	0.885	-0.355	23	**5.152**	1.350	-0.501	125
41	ExpCost	**4.667**	1.231	0.416	12	**4.913**	1.443	-0.530	23	**4.328**	1.491	-0.209	125
42	RelzCost	**4.500**	1.382	0.372	12	**4.913**	1.474	-0.210	23	**4.411**	1.562	-0.308	124
43	PrssCost	**4.333**	1.371	-0.725	12	**5.174**	1.072	-0.134	23	**5.097**	0.983	0.169	124
44	ImptPrft	**5.833**	1.193	-0.392	12	**5.870**	1.140	-0.730	23	**5.780**	1.184	-0.828	123
45	ExpPrft	**4.917**	1.165	-0.225	12	**4.826**	1.466	-0.429	23	**4.525**	1.386	-0.061	122
46	RelzPrft	**4.417**	1.311	0.507	12	**4.696**	1.460	0.007	23	**4.369**	1.306	0.100	122
47	PrssPrft	**5.167**	1.030	0.211	12	**5.391**	0.839	0.122	23	**5.361**	1.029	-0.034	122
48	ImptGovt	**3.750**	1.485	-0.287	12	**3.435**	1.727	0.120	23	**3.732**	1.784	-0.132	123
49	ExpGovt	**3.000**	1.706	0.396	12	**3.522**	1.855	-0.108	23	**3.180**	1.832	0.057	122
50	RelzGovt	**3.167**	1.697	0.092	12	**3.391**	1.948	-0.164	23	**3.221**	1.896	-0.043	122
51	PrssGovt	**4.667**	0.778	0.719	12	**4.870**	1.100	-0.394	23	**4.691**	1.001	0.606	123
52	ImptCmpt	**5.636**	1.286	-0.541	11	**5.783**	1.043	-0.315	23	**5.600**	1.129	-0.390	125
53	ExpCmpt	**5.273**	1.009	-0.661	11	**5.478**	1.201	-0.547	23	**5.187**	1.257	-0.134	123
54	RelzCmpt	**4.727**	1.191	0.205	11	**4.913**	1.411	-0.364	23	**4.756**	1.320	-0.256	123
55	PrssCmpt	**5.636**	0.924	-0.023	11	**5.217**	0.951	0.218	23	**5.317**	0.961	0.056	123
56	ImptMkt	**4.727**	1.489	-0.985	11	**4.783**	1.166	0.463	23	**4.760**	1.560	-0.516	121

		Current Sample Only				*Chem.Industry except Drugs*				*Survey "Population"*			
#	*Variable*	*Mean*	*StdDev*	*Skew.*	*N*	*Mean*	*StdDev*	*Skew.*	*N*	*Mean*	*StdDev*	*Skew.*	*N*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(14)*
57	ExpMkt	**4.455**	1.440	-0.504	11	**4.000**	1.314	0.658	23	**4.174**	1.600	-0.041	121
58	RelzMkt	**4.000**	1.549	-0.789	11	**4.087**	1.345	0.441	23	**3.875**	1.476	-0.052	120
59	PrssMkt	**5.273**	1.104	-0.108	11	**4.913**	0.949	0.884	23	**4.877**	0.941	0.552	122
		Percentage of Research Done By University (1= <10%)											
60	BR: Univ	*0.909*	0.539	-0.155	11	**1.118**	1.219	1.627	17	**1.239**	1.270	1.709	92
61	AR: Univ	**0.455**	0.522	0.213	11	**0.947**	0.405	-0.498	19	**1.030**	0.413	1.091	100
		Changes in the Percentage of Research Done By University (Scales 1-7, 4=no change)											
62	Chg: BR	*5.000*	1.000	0.000	11	**5.071**	1.141	-0.159	14	**4.438**	1.135	-0.188	80
63	Chg: AR	**4.375**	0.916	0.488	8	**5.118**	0.857	-0.245	17	**4.390**	1.136	-0.397	100

Notations

(also refer to the attached survey questionnaire in Appendix G):

- BR = Basic Research; AR = Applied Research; PDD = ProDuct Development; PCD = ProCess Development; TS = Technical Services;
- Acq = Aquisition of technical knowledge from outside the firm; Prod = Being a product leader; Proc = Being a process leader; Trd = Following trends; MkgN = Opening new market areas; MkgE = Competing in existing market areas; GovA = Anticipating government regulations; GovC = Complying with government regulations; FR = Focused Research; DR = Discretionary Research;
- Imptxxxx = Importance of business goal xxxx in R&D program; Expxxxx = Expected contribution to goal xxxx by R&D; Relzxxxx = Realized R&D contribution to goal xxxx; Prssxxxx = Business Pressure of goal xxxx on R&D; yyyyPrft = Profit as business goal; yyyyGovt = respond to government policy position as business goal; yyyyCmpt = Competitive position as business goal; yyyyMkt = Market positioning as business goals;
- Univ = University research.

Chapter 5
Methodology and Discussions of Results

Chapters 1 to 4 have provided the theoretical basis and defined the variables and the sample for this study. This chapter discusses the specification and estimation of the econometric model (Equation (3.12)). The first section of this chapter will present the TFP estimates as operational productivity measures. In section two, an appropriate estimator for equation (3.12) is selected. Section three provides discussions of the econometric results of R&D activities. Section four reports econometric estimates for technical services.

5.1 TFP Estimation

Based on previous R&D productivity studies, the TFP index was specified in Chapter 3:

$$TFP=\frac{d\Pi}{\Pi}=\frac{dQ}{Q}-[\alpha\frac{dL}{L}+\beta\frac{dM}{M}+\xi\frac{dK}{K}] \qquad (5.1)$$

$$\xi=(1-\alpha-\beta)$$

where $\frac{d\Pi}{\Pi}$ represents total factor productivity growth; α, β, and ξ are the respective prices of labor (L), materials (M), and capital (K). Under the assumption of perfect competition, α, β, and ξ are equal to their respective output shares of labor, materials, and capital. dQ, dL, dM, and dK are the time derivatives of Q, L, M, and K. From this equation, the TFP index is estimated for each firm in the sample and then used to derive an operational measure of TFP[143] for this dissertation.

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[143] In this chapter, the terms "estimated or original TFP" refer to the TFP index that estimated directly from equation (5.1), and "operational or frontier TFP index" refer to the TFP indices that are derived from the "original TFP index" based on various approaches described in this chapter.

Before linking the TFP measure to the R&D components, one important problem associated with it has to be addressed. As discussed in Chapters 1 and 3, the basic purpose of an R&D productivity study is to examine the impact of changes in a firm's technology stock on its production frontier. This analysis requires that the measure of TFP should reflect full capacity production levels. That is, the frontier can be correctly estimated only when the firm has fully utilized its production resources. Thus, an index of the firm's plant capacity utilization becomes an important component to be measured in R&D productivity studies.[144]

5.1.1 Problems of the Capacity Utilization Index

Although a capacity utilization index can be estimated at the SIC four-digit level from the Survey of Plant Capacity, the Bureau of the Census, U.S. Department of Commerce,[145] such a measure can be expected to deviate from the firms' capacity utilization because the concept of capacity is not precisely defined.[146] Rates of capacity utilization were estimated for each firm and returned to each firm for verification. Unfortunately, only one firm provided the requested verification or corrections. Many reasons have been given by the companies for their non-response, such as the proprietary nature of the data,

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[144] The causes of under-utilization of the firm's plant capacity include both economic and non-economic factors. Factors such as the business cycles, availability of critical feedstocks (materials), and the mix of materials are economic ones, while strikes, unexpected machine breakdowns, etc., are non-economic factors.

An additional problem with this estimated index may be that many companies have frequent divestiture and merger activities. Such problems may appear as outliers in the estimated index. In this study, these outliers have been excluded. Also, similar approaches used to deal with the capacity utilization problem have been used to remedy merger problem.

[145] There are other organizations such as the Wharton Econometric Forecast Associates (WEFA), McGraw Hill, and the Federal Reserve Board that estimate similar indices. However, the concept of capacity is defined differently among these organizations.

[146] See Section 3.2.1.4 of Chapter 3 for more discussion on this issue.

the disposal requirement for the data, and the high expense of re-constructing data series.

In addition to conceptual problems, a capacity utilization index for the chemical industry also presents another difficulty. Some corporate economists or financial officers of the sample firms have indicated that such an index is a very "soft" measure because the production output of a particular chemical plant not only depends on the capacity of the chemical facilities being used and the quantity of materials (feedstocks) consumed, but also depends critically on the combination (mix) of different kinds of materials. As discussed in Section 4.1.1 of Chapter 4, material efficiency is one of the important economic and engineering considerations in chemical production and R&D. Different mixtures of feedstocks have different levels of yield and cost. Thus, the chemical firms may change the feedstock mix from time to time based on economic (costs) and corporate managerial considerations. As a result, changes in the firm's output level, and thus productivity, are not only the result of such factors as business cycles, but also of those economic or corporate managerial considerations. Because of the difficulties inherent in definition and the lack of a firm-specific index of capacity utilization, the TFP index must be adjusted by alternative methods.

5.1.2 Alternative Measures of the TFP Index

In fact, no R&D study in the literature has been able to measure capacity utilization at the firm level. However, four alternative solutions have been suggested in the literature: (1) simply ignore the utilization issue based on lack of information on the sample (Griliches, 1980); (2) approximate the firm's utilization index by data at the SIC two-digit level (Clark and Griliches, 1984); (3) divide the study period into sub-periods and use the average TFP index in each sub-period (Griliches and Lichtenberg, 1984); and, (4) select those years when the firm is believed to have operated at full capacity and then estimate the growth trend of the TFP index with a regression line based on those selected data points. From the time trend, the regression coefficients are interpreted to represent the rates of growth of the firm's productivity during the study period (Mansfield, 1980).

Of these four alternative treatments, the fourth approach of Mansfield is certainly more appropriate from both a conceptual and statistical view point. In the second solution, an index at the two-digit SIC level can deviate significantly from the firm's actual capacity utilization because most chemical firms are multi-national and multi-segment corporations across different industries.[147] As for the third proposal, "averaging" approach, the correct basis for dividing subperiods should be the firm's performance through the business cycle which is unknown. Thus, an averaged index could not be evaluated for error or degree of precision. In addition, the selection of the breaking points of the study period could be arbitrary and become the "art of the possible."[148]

This dissertation follows Mansfield's approach with some modification. The first step taken is to follow the conceptual notion of an R&D study[149] by identifying from the estimated TFP index those years when the firm is believed to have operated at full capacity. In order to do this, the estimated TFP index is first plotted against time and those years when the TFP values are higher than some previous years are selected. Following Mansfield (1980), the trend of the

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[147] See Section 3.2 in Chapter 3 for more discussion on the problem of this approximation.

[148] See Section D.3 of Appendix D, page 190.

[149] That is, to analyze the impact of technological stock on the firm production frontier, as introduced in Chapter 1.

firm's TFP growth is estimated by fitting a regression line against time through these selected TFP data points for each firm. This "predicted" regression line represents the TFP trend that the firm could have achieved if all of the firm's production resources have been fully utilized and the firm has used the best combinations[150] of feedstock materials. Thus, this estimated trend is the frontier TFP index.

This frontier TFP index not only has a theoretical basis but also includes substantially more of the information available to this study than indices based on selected data points. Note that Mansfield (1980) used the regression coefficients to represent the TFP growth whereas, in this study, it is the entire regression line that is used to represent the TFP trend because of the limited number of firms (12 firms) in the sample. The TFP trend allows the analysis of the dynamic relationship between the "production frontier" and technology stock during the last two decades, as discussed in the following sections.[151]

5.2 Statistical Specification of the Model

The current sample consists of 12 firms and covers a 20-year period, 1969–1988, including both cross-sectional and time-series data. Model (3.12) can be estimated either for each firm separately or for all firms as panel data.[152] This section discusses two closely related statistical issues. The first is whether the data should be pooled as a panel, and after the this issue is resolved, the second is the appropriate estimator for the model.

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[150] The term "best" is referred to the combinations of materials that can produce the highest yields at a given cost level.

[151] Many other approaches have also been used to construct the operation TFP index. These approaches and their estimated results are described in Appendix D, page 185.

[152] Panel data are also referred to as longitudinal data.

5.2.1 Advantages of Panel Data

The research objective of this study is to estimate the R&D productivity of the entire sample and thus requires to pool the data of each firm. Furthermore, pooling cross-firm and time-series data offers more advantages which will be summarized in this section. There are problems associated with panel data as well. These problems will be discussed in next subsection.

(1) Pooling cross section and time series data enhances the external validity of the estimates. Time series data alone reveal the dynamics of the firm's behavior reflecting intra-firm differences, whereas cross sectional data alone reveal the inter-firm difference such as external managerial and business attributes. Through pooling, the combined data provide sequential observations for a number of firms and thus allow researchers to separate inter-firm differences from intra-firm differences. For example, through the use of dummy variables, researchers can measure the impact of such "quality" variables as size of the firm on the dependent variable (e.g., TFP) in question.

(2) Panel data can eliminate or reduce estimation biases which result from model specification problems. This advantage is particularly useful to the current study. As in any econometric study, omitted variable bias is often the ground for criticism of empirical results. However, in the panel data setting, if the effects of these omitted variables remain constant for a given firm over the entire study period,[153] omitted variable bias can be eliminated by simple statistical methods, e.g., first differences, dummy variables, or assumption of a

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[153] They are called the firm-specific effects. If the effects of those omitted variables vary with time but, at a given time period, stay constant for each firm, they are called the time effects. The treatment of these two effects are essentially the same.

conditional distribution of unobserved effects.[154] This advantage is especially true for linear models. In the current study, considerable variation in firm-specific factors such as managerial ability, institutional differences in production, marketing and R&D among firms can be expected. These factors are hard to model for an individual firms but, by pooling the data, the omitted variable bias can be eliminated from the estimates.

(3) Panel data provide "richer" information on both the intertemporal dynamics of each firm and the attributes of many firms. Statistically, panel data increase the degrees of freedom for estimation, lessen the problem of multicollinearity, and thus improve the efficiency of the econometric estimates. This particular advantage is important because the variables in equation (3.12) may be difficult to isolate and measure independently.

5.2.2 The Appropriate Estimator for the Panel Data Model

The general linear regression model for panel data is:

$$\pi_{it} = \lambda_i + \phi' \mathbf{y}_{it} + e_{it}, \tag{5.3}$$

where for $i = 1, \ldots, N$ individuals
and time $t = 1, \ldots, T$ periods,

where **y** is a vector of regressors and ϕ' is the vector of parameters, (for k regressors across i firms). λ_i is a scalar constant representing the effects of those

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[154] The results of the dummy variable methods can be seen from the following econometric model of panel data:

$$(\Pi_{it} - \overline{\Pi}_i) = \lambda + \phi_i (Y_{it} - \overline{Y}_i) + (e_{it} - \overline{e}_i) \tag{5.2}$$

where subscript i refers to the i^{th} firm and t is time. Therefore, if the value of Y is constant over time, it will become zero and be eliminated in the transformation process. The estimator will be discussed further in the following section.

variables peculiar to the i^{th} firm and e is the error term. Three estimators—Ordinary Least Square (OLS), Covariance (CV), and Generalized Least Square (GLS)—are most commonly used to estimate equation (5.3). The choice of an estimator for panel data is determined jointly by the assumptions on the parameters, λ, ϕ and e.[155]

First, assumptions about λ and ϕ determine whether OLS is the appropriate estimator for equation (5.3). If the overall homogeneity of λ and ϕ[156] cannot be simultaneously rejected and the error term satisfies the classical conditions, OLS will provide unbiased estimates. However, if the overall homogeneity hypothesis is rejected by the panel data, CV and GLS provide the BLUE.[157] Since the sample consists of 12 firms of various sizes with chemical and other diversified businesses, the individuality of the firms is expected to be different among these firms. Thus, a single homogeneous intercept is less likely than variable intercepts are for each firm.[158] Therefore, the choice of estimators is expected to be between CV and GLS. The hypotheses of homogeneity of intercepts and the slopes[159] can be tested statistically either by an analysis of covariance test or by the ordinary hypothesis test based on sums of squared residuals from linear regression outputs (the Chow test).

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[155] The estimator for panel data is discussed within the context of the current study only. A brief survey on panel data estimation is given in End-Note 1 of this chapter, page 152. This survey also provides references to the panel data literature.

[156] The overall homogeneity hypothesis is:
$H_0: \lambda_1 = \lambda_2 = \dots = \lambda_n$ and
$H_0: \phi_1 = \phi_2 = \dots = \phi_n$.

[157] "BLUE" = Best Linear Unbiased Estimator.

[158] Tables 4-2 and 4-4 have documented statistically the high deviations of the key inputs, output and R&D variables.

[159] H_0: $\lambda_1 = \lambda_2 = \dots = \lambda_n$ and/or
H_0: $\phi_1 = \phi_2 = \dots = \phi_n$

The choice between the CV and GLS estimators depend on another set of assumptions about the variable intercept term.[160] The existence of variable intercepts means that omitted variable effects are present in equation (5.3), which include firm-specific effects, time-specific effects, and the combination of these two effects. In the case of variable intercepts due to the presence of the firm-specific effects,[161] the firm-specific effects can be assumed to be fixed or random over time. Models which assume fixed firm-specific effects are called "fixed effects models" (FEM) and those assuming varying effects are "random effects models" (REM). The BLUE for the fixed effects models is CV, and for the random effects models, it is GLS.[162]

Unfortunately, estimates of ϕ from FEM and REM may be quite different. Whether to treat the effects as fixed or random depends both on research objectives and statistical problems of the panel data in question. The advantage of the REM specification is that a number of degrees of freedom can be preserved because the only unknown parameter involved is the variance of the cross-sectional characteristics. Thus, estimates from the REM are more efficient. However, this advantage depends critically on the assumption that the effects of omitted variables are not correlated with those independent variables in the model. If this assumption is violated, GLS no longer possesses the BLUE properties, and the BLUE is CV. On the other hand, FEM does not make such an assumption about the omitted variable effects and the

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[160] It is obviously meaningless to assume that equation (5.3) has homogeneous intercepts but heterogeneous slopes.

[161] For simplicity, the current discussion is limited to the firm-variant but time-invariant effect. The statistical treatment of other two effects are the same although more complicated analysis is involved.

[162] It can be shown that when the sample size, T, tends to infinity, GLS estimator for ϕ converges to the CV estimator (Hsiao, 1989).

disadvantage of the REM becomes exactly the major advantage of the FEM. However, the trade-off for such an advantage of the FEM is the loss of efficiency because of the increased number of parameters to be estimated. Therefore, the crucial statistical factor in selecting FEM vs. REM is the possibility of a correlation between the firm-specific effects and those explanatory variables.[163]

A statistical hypothesis test has been developed by Hausman[164] to aid in such a model selection. Hausman's Chi-square statistic has been used to test whether the GLS estimator of ϕ differs significantly from the CV estimator. If the Chi-square statistic is large, the CV estimator (FEM)[165] is the appropriate choice.

This study has adopted the FEM for the following reasons:

1. Firm-specific effects are expected in the current sample which is composed of firms of various sizes, as shown in Table 4-2. These firms have multiple product lines and are multinational corporations operating primarily in the chemical industry but in other industries as well. Each firm has its own unique competitive business environment such as the availability of key materials,

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[163] If the firm-specific effects are randomly distributed, the REM can be viewed as one in which inferences are made unconditionally or marginally with respect to the population of all effects. In other words, inferences are made about the population characteristics from samples which are considered to be random. In contrast, the FEM is then viewed as one in which inferences are made conditional on the effects that are in the sample; that is, inferences are going to be confined to the effects in the model. Note that, in the FEM, the firm-specific effects and time-effects are parameters to be estimated in the model.

[164] Hausman, J.A. 1978. "Specification Tests in Econometrics," Econometrica, 46 (November), pp. 1251-1271.

[165] For the REM, Breusch and Pagan have also developed a Lagrange multiplier statistic to test the presence of cross-sectional and time-related effects. Large values of this statistic will lead to reject the FEM in favor of the REM. Breusch, T.S. and Pagan, A.R. 1980. "The Lagrange Multiplier Test and Its Applications To Model Specification In Econometrics." Review of Economic Studies, 47, pp. 239-254. Also see Greene, W. H. 1991. LIMDEP version 5.1. Econometric Software, Inc. New York: New York. January 1991. pp. 173-174.

government regulations and legal issues regarding its products and services, market positions, and R&D programs. Variables capturing the effects of these factors should be included in the current study and failure to do so might lead to biased estimates. Therefore, the variable-intercept model is more appropriate.

2. The current sample covers the period of 20 years, 1969 to 1988, in which there were two economic recessions. This suggests that time-related effects should be modeled explicitly.

3. There is no reason to believe that the firm-effects are randomly distributed in the current sample and have no correlation with the regressors, because it is the same management that made decisions on production and R&D programs. The corporate business strategies are mostly likely to determine the R&D strategies. The CIMS data base reveals that the integration of these two strategies has been strong, especially in the 1980s (Bean, *et al.* 1984; Bean, 1989c).

This discussion has only concentrated on the intercept term and has assumed that the estimates of the regression coefficients, ϕ, are the same for each firm. Because the current sample is intentionally limited to a single industry in which competition has been assumed, the coefficient vector, ϕ, is assumed to be homogeneous. Statistical tests (covariance or the Chow test) are also available to assess this assumption.

5.3 Econometric Results: R&D Components

The primary objectives of this dissertation are: (1) to estimate the productivity effects of these four R&D components, basic research, applied research, product development, and process development; and (2) to assess the impact of technical services on the firm's productivity growth. This section presents estimates and analysis of the R&D components. The productivity impact of technical services will be examined in next section.[166]

The analysis of model (3.12) begins with the following model specification:

$$\pi = \lambda + \phi_1 \cdot BR + \phi_2 \cdot AR + \phi_3 \cdot PDD + \phi_4 \cdot PCD + e. \tag{5.4}$$

where π is the frontier TFP index measuring the annual changes of the firm's productivity growth and ϕ is the rate of marginal return. The independent variables, BR, AR, PDD, PCD, are the R&D investment intensity ratios on basic research, applied research, product development, and process development, as defined in sections[167] 3.1 and 3.2.5 of Chapter 3. Note that those variables discussed in Section 3.2.6 are implicitly included in this equation. They are not specified here because these variables are eliminated from the transformation process when the Covariance (CV) estimator is used.[168]

First, results of several statistical tests described in the previous section are reported.[169] The F-statistic rejects the hypothesis that there is no firm effect

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[166] The computer program, LIMDEP (version 5.1, May 1990. By William H. Greene, Econometric Software, Inc. New York), is the primary computer package used in this study. Among other computer programs for panel data (e.g. SAS/TSCSREG, RATS), LIMDEP provides more test statistics.

[167] That is, these independent variables are the specifications of y in page 60.

[168] See equation (5.2), footnote [154].

[169] For the description of these tests, see the LIMDEP manual.

on the mean of π (F = 100.13) and indicates the presence of strong firm effects. However, the hypotheses of no time-related effects cannot be rejected based on the incremental R^2 statistic[170] ($\Delta R^2 < 0.01$). Also, the Hausman's Chi-Square statistic rejects the use of REM specification ($\chi^2 = 2.77$).

The CV estimates of equation (5.4) are as follows:

$$\begin{array}{l} \pi = 0.09 - 4.14BR - 0.630AR + 1.76PDD + 3.38PCD \\ (p)\ (.01)\ \ (0.58)\ \ (0.45)\qquad (0.05)\qquad (0.08) \\ R^2 = 0.86 \quad \overline{R}^2 = 0.83 \end{array} \tag{5.5}$$

where the estimated statistic in parentheses is the p-value for each t-ratio (which is not shown).[171] Equation (5.5) can be interpreted literally as: given the rate of technology advance[172] of the firm, if the firm conducts no development projects, the research efforts (BR and AR) will have no impact on the firm's productivity growth.[173] Whereas the firm's development efforts (PDD and PCD) will contribute strongly and positively to productivity growth without the presence of basic and applied research efforts. Furthermore, the rate of return to process development is higher than that to product development. These interpretations seem correct in the sense that, in manufacturing firms, the research activities themselves do not produce products, processes and services, whereas the development activities do. In addition, the higher rate of return to

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[170] The incremental R^2 is obtained by first calculating an R^2 of a model with firm-specific variables but no time-specific variable. Then, the time-specific variables are entered into the model and another R^2 is computed. The difference between these two R^2 statistic is the incremental value. The small incremental value indicates that the time-specific variables do not have explanatory power over the dependent variable, as described in the LIMDEP manual.

[171] The estimated firm and time effects for each firm and year are not shown because they are lengthy and will not be used in the following analysis.

[172] The firm's technology advance is represented by the R&D intensity ratio as derived in Chapter 3.

[173] The regression coefficients for BR and AR are negative and not statistically significant.

process development than to product development is expected for two reasons. First, new processes can be kept secret and are difficult for other firms to imitate (Nelson, Peck, and Kalachek, 1967). Second, new processes are easier to install and can immediately benefit the firm once they are installed whereas new products may take longer to develop and, in the early commercialization stage of the products' life cycles, the firm may not benefit from them at all.

However, in this multiple regression model, the regression coefficient, ϕ_i, measures the effect of R&D activity i on $E(\pi)$ while the values of the other three regressors are held constant. Each regression coefficient is therefore the partial regression coefficient. This feature of the multiple regression model requires that all regression coefficients be analyzed simultaneously. This requirement indicates that negative and statistically insignificant returns to the research activities, especially to applied research, in equation (5.5) *may* be questionable and suggests further analysis because, as described in Section 4.1.2 of Chapter 4, applied research plays an important part in product and process development.

In a multiple regression model, a common source of statistical difficulty is multicollinearity, which is often not of its existence but of its degree.[174] Although panel data lessens the problem of multicollinearity, it might still be present to some degree, since the investment in each R&D activity may not be independent of the others.

Remedies for the multicollinearity problem are limited. Suggestions include: (1) increasing the sample size; (2) trading some bias for a reduction in variance by the "ridge regression" method (Kmenta, 1986); and, (3) to re-specify the regression model. Unfortunately, the first remedy is not applicable to this

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[174] Theoretically, the condition of the regressors is assumed nonstochastic in the regression analysis but, in the empirical research, this assumption is often violated, and some degrees of correlation among these regressors will usually occur.

study because of the lack of firm-specific R&D data. The second suggestion requires some arbitrary "guess" of an adjusting factor (*k*). Because more than one model specification is included in this investigation and the estimation of each specification may require a different value of *k*, the arbitrary nature of the adjusting factor will prevent econometric comparison across equations. However, the third possibility is applicable because of the empirical relationship among R&D activities. Thus, Model (5.4) has been re-specified and the estimated results are below.

First, R&D activities are combined on a theoretical basis as research (RES) and development (DEV), where research is the sum of basic and applied research (RES = BR + AR), and development is the sum of product and process development (DEV = PDD + PCD). These two combinations also have an empirical basis because the distinction between research activities and between development activities is often hazy (Mansfield, 1968; 1980). With these combinations, equation (5.4) is modified so that the frontier TFP is specified as a linear function of research (RES) and development (DEV). The CV estimates are:[175]

$$\begin{aligned} &\pi = 0.10 - .60RES + 2.0DEV. \qquad (5.6) \\ &(p)\ (.01)\ \ (0.38)\quad\ (0.01) \\ &R^2 = 0.86 \quad \overline{R}^2 = 0.83 \end{aligned}$$

These estimates do not change the fundamental results of equation (5.5) in that research efforts (RES) have no impact, and development efforts (DEV) have positive and strong effects, on the firm's productivity growth. This outcome

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[175] The F statistic and the Hausman's Chi-Square statistic of this equation lead to the same conclusions as for equation (5.5). That is, The F-statistic rejects the hypothesis that there is no firm effect on the mean of π (F = 100.00), and indicates the presence of strong firm effects. However, the hypotheses of no time-related effects cannot be rejected based on the incremental R^2 statistic ($\Delta R^2 < 0.01$). Also, the Hausman's Chi-Square statistic rejects the use of REM specification ($\chi^2 = 1.57$).

indicates that the multicollinearity problem, if any, does not appear to originate from the correlation within either the research activities or the development activities. Moreover, note that the magnitude of the estimated regression coefficient of RES in equation (5.6) is reduced to a comparable level to AR in equation (5.5), and the estimated regression coefficient of DEV is also reduced. These results should not be surprising because, as profiled in Table 4-2, the majority of R&D investment has been devoted to applied research and product development. Nevertheless, equation (5.6) provides results for the aggregated impact of research and development on π.[176]

In order to search further for the cause of multicollinearity, the relationship between research and development is examined next. From the analysis in Section 4.1.2 of Chapter 4, the strong relationship between applied research and development activities suggests that, for the chemical industry, it could be relatively difficulty to disentangle these two activities. This evidence suggests that R&D investment in applied research be added to that in development. Thus, Equation (5.4) is modified so that π is the function of basic research (BR) and the sum of applied research and development (ARDEV). The Covariance estimates of this modified function are:[177]

$$\begin{array}{llll} \pi = & 0.11 & -5.83BR & +.67ARDEV. \\ (p) & (.01) & (0.36) & (0.10) \end{array} \tag{5.7}$$

$$R^2 = 0.85 \quad \bar{R}^2 = 0.83$$

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[176] When RES and DEV are further aggregated as total R&D expenditures, its regression coefficient is 0.62, significant at 0.10 level.

[177] The F statistic and the Hausman's Chi-Square statistic of this equation lead to the same conclusions as for equation (5.6). That is, The F-statistic rejects the hypothesis that there is no firm effect on the mean of π ($F = 100.13$), and indicates the presence of strong firm effects. However, the hypotheses of no time-related effects cannot be rejected based on the incremental R^2 statistic ($\Delta R^2 < 0.01$). Also, the Hausman's Chi-Square statistic rejects the use of REM specification ($\chi^2 = 1.26$).

Results of this equation reveal that when applied research is combined with development, it has a positive contribution to the firm's productivity growth. The positive sign of ARDEV in the equation may indicate some degree of multicollinearity in previous equations. However, in this Equation (5.7), the p-value for ARDEV is reasonably low so that the problem of multicollinearity does not seem to be a serious problem, at least in part because of the use of panel data, implying that the effectiveness of the applied research program itself is in question. Note that combining AR with DEV in such an analysis was proposed by Link (1981) and the regression coefficient of the combined variable in his study also had a weak p-value.[178] Also note that a weak coefficient of applied research has been found by Mansfield (1980). Nevertheless, the estimated equation (5.7) does indicate that applied research efforts, together with development efforts, have contributed to productivity growth of the sample firms. The weak p value may be the result of mis-specification of applied research in the model.

5.3.1 Discussion of Model Specification for Basic Research

Thus far, the analysis has concentrated only on applied research and development activities. As for basic research, its regression coefficient has been consistently negative but not statistically significant. However, before committing to interpret this result as an indication of the ineffectiveness of basic research,[179] two model specification issues should be discussed. First, a

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[178] In Link's study, the t-statistic for the combined variable was reported as 1.83.

[179] The interpretation of an ineffective basic research program is also plausible. Responding to the strong positive effects of research activities estimated in the literature, Pakes and Schankerman (1984) have questioned why private firms did not increase the share of their resources to such activities if their previous research efforts were so highly profitable. Some evidence from this study seems to support this reasoning, i.e., little basic research has been done and no positive return is found.

time lag occurs between the basic research activities and the final commercialized output. Mansfield (1980) suggested that the lags in the effects of basic research may be relatively longer than other R&D activities. He proposed that the research intensity be modified to include this lag factor as follows:

$$\pi = \lambda + \phi_B \cdot \frac{B_{t-\tau_1}}{Q_{t-\tau_1}} + \phi_A \cdot \frac{A_{t-\tau_2}}{Q_{t-\tau_2}} + \sum_{i=3}^{I} \phi_i \cdot y_i + e \tag{5.8}$$

where B and A are R&D investment in basic research and applied research, respectively; Q is output; and y_i's are development activities. Time is t and τ is the time lag.

In order to examine the lag effect on the regression coefficient of basic research, experiments with various τ values were conducted in equation (5.8). However, this experiment is not intended to study the lag structure itself but its effect on the signs of the coefficients of basic research as well as applied research. The results are as follows. First, τ_1 was assigned values of 1 to 7 and all other regressors were measured in the current period (no lag). The estimated results indicate that the sign of ϕ_B changes from negative to positive when $\tau = 3$ and 5, and negative otherwise. Second, lag values were also assigned to τ_2, the lag of applied research, from 1 to 7 as well as various combinations of τ_1 and τ_2. No clear relationship was established between the values of τ_1 or τ_2 and the sign of ϕ_B. Finally, the development activities were also lagged from 1 to 4. Again, combinations of the various lags of basic research, applied research, product development, and process development were tested. No clear pattern between the lag values and the sign of basic research was evident. However, the p-value of the basic research coefficient remained high indicating insignificant coefficients throughout this experiment. This was not surprising because the amount of basic research expenditures was small and the sample firms have not emphasized basic research during the last two decades. The major implication of this extensive experiment is that the estimated effects of basic research have been relatively stable over time. Statistically, this outcome means that the research intensity variable is stable over time. The correlation coefficients among basic research intensity ratios over time are all over 0.90 as shown in Appendix A. Mansfield (1980) has suggested that, in such cases, the current R&D to output ratio is a good proxy of the actual lagged ratio.

The second issue concerning the negative and insignificant coefficient of basic research is the problem of the single equation model. As discussed in Section 4.1.2.1 of Chapter 4, basic research is the search for fundamental knowledge that is not motivated by any commercial purpose. In the chemical industry, basic research has been conducted in four different ways: interactions with universities, cooperation with Federal laboratories, contracting out, and in-house research. However, the measure of productivity in the equations above is due to the firm's tangible and marketed products and services.

The linkage between the effects of basic research and marketed products and services is obviously not a direct one. Link and Bozeman (1987) have further argued that the concept of basic research is "elusive" and that the correlation between productivity growth and basic research is "spurious." They suggested that basic research be linked to the production process through the interactions among three technologies: (1) "intratechnologies" which are technologies that support applied R&D, production and marketing; (2) "generic technology" which represents the organization of knowledge that has the conceptual form of an eventual application and the laboratory testing of concept; and (3) "proprietary technologies" which are fully appropriable by the firm as long as they are secret.

In the current context, two model specifications for this linkage can be proposed, depending on the firm's business and R&D strategies. First, the impact of basic research on productivity is initially through interactions with outside research institutions and laboratories, then through internal applied research, development, and finally to commercialized output measured by π. Second, the impact on productivity π is through applied research and then development, without the external interaction path. A preliminary analysis of the second model has been made as reported in Appendix C, which established the indirect and statistically significant relationship between basic research and the firm's productivity growth.

This indirect relationship between research and productivity growth may also explain the statistically weak regression coefficients of applied research both in the literature and in this study. The search for new specifications of an indirect model of the more complex relationship within research and development should be the direction of future studies of R&D productivity.

5.4 Econometric Results: Technical Services

The second primary objective of this dissertation is to assess the impact of technical services on the firm's productivity growth. No study has been made on this subject and this section initiates a first attempt in this area.

The productivity impact of technical services will be analysed together with R&D components because the technical service activities studied in this dissertation are limited to those performed by R&D personnel. It is possible to distinguish physically the personnel involved in research from those in technical services. However, when the total R&D efforts are translated into monetary terms as R&D expenditures, the distinction vanishes.

Based on the final model specification of R&D components in the previous section, the analysis of technical services begins with the following model specification:

$$\pi = \lambda + \phi_1 \cdot BR + \phi_5 \cdot ARDEV + \phi_6 \cdot TS + e. \tag{5.9}$$

where *TS* is ratio of technical service expenditures to output and other notations are the same as those in equation (5.7).

Two statistics indicate strong firm effects ($F = 100.13$) but weak time effects ($\Delta R^2 < 0.01$). The Hausman's Chi-square statistic rejects the use of the random effect model in favor of the covariance estimator ($\chi^2 = 1.27$). The CV estimated results of equation (5.9) are:

$$\begin{array}{lllll} \pi = 0.10 & -\ 1.04BR & +\ 1.48ARDEV & -\ 3.159TS & \quad (5.10) \\ (p)\ (.01) & (0.89) & (0.02) & (0.08) & \end{array}$$

$$R^2 = 0.86 \quad \bar{R}^2 = 0.83$$

The negative sign of technical services[180] was expected because the time length that this study covered is a long term (20 years). Unlike R&D activities which are aimed to move the firm's production frontier outward, technical services theoretically are performed as a maintenance function.

Technical services are particularly important to chemical firms, especially to specialty product firms, as described in Section 4.1.1 of Chapter 4. However, like many other marketing activities in manufacturing firms, the positive impact of technical services on sales is expected only for a shorter time span, e.g., certain quarters, or a certain year but not in the mid- and long term. Because of this short-term impact on sales, and thus on profitability, companies

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[180] Following the same analytical process described in the previous section, many other model specifications have been estimated but the negative sign persists throughout (see equation (D.5), page 187). That is, the inverse relationship between TS and long term productivity growth appears very robust.

can be misled to devote more technical effort to technical services in response to the increased competitiveness. However, given an R&D budget constraint, the more technical services which are performed in the R&D departments, the less technical resources will be available to research and development activities. Hence, such practices may increase the probability of achieving short-term profit gains while missing key technology breakthroughs and thus the long term competitive edge (Bean, 1990). Note that technical services make up a substantial portion of the technical effort of the firm, as shown in table 4-2, and the current estimates of technical services indicate the need for the firm to review its technical services programs frequently.[181]

This study constitutes a first attempt to evaluate the impact of technical services on the firm's long-term productivity growth. Any final conclusion about this impact for all the U.S. manufacturing industries will require more extensive theoretical and empirical research. First, this study is limited to the chemical industry. Second, the term "technical service" is not well defined. No clear guideline or definition of technical services is given by the National Science Foundation, despite the magnitude of this activity. In practice, the organization and scope of this activity differs from firm to firm, as well as the accounting/reporting practices for technical service expenditures. These issues certainly add complexities to the research on technical services.[182]

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[181] An statistical issue concerning the model specification for technical services is discussed in End-Note 2, page 156.

[182] In addition, there is some evidence indicating that data on technical services used in this study may have been contaminated by inclusion of technical services performed outside of the R&D departments of some sample firms.

5.5 Limitations and Alternatives of the Current Analysis

The current study has followed Mansfield's approach of estimating the frontier TFP index by excluding those years when the firms were believed to have operated below full capacity. The operational measure of TFP is represented by a regression line fitted through the selected data points for each firm. This operational TFP measure (trend) allows this study to utilize all 20 years of data of each firm and, by pooling the data of all firms, to form a panel data set. Because of the advantages of panel data, the estimated results above avoid the common statistical problems of omitted variable bias and lessen the problem of multicollinearity.

A fitted regression line has been used commonly in many studies across fields of knowledge and areas of use to represent a "growth trend." However, in the current context, the use of this regression line as the operational TFP index has its disadvantages. First, the operational TFP measure can be criticized as "hypothetical" because it was derived from the original TFP index using a statistical method — regression. Second, the estimated results may be sensitive to the data selection criteria which eliminated data of those years when the firm was believed to have operated well below its full capacity.[183]

Attempts have been made in this dissertation to provide alternative methods to the regression line approach. These alternative methods and their results have been documented in Appendix D. The following sections selectively report some of the results directly related to the problems listed above.

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[183] Another limitation of the current analysis is obviously the small sample size. However, the bootstrap results in Appendix F indicated that as long as the current sample can represent the chemical industry (except drugs), the results of this study can be extended to the industry as well. Chapter 4 has discussed the relationship between the current sample and the chemical industry.

5.5.1 The Use of the Selected Original TFP Index

The direct solution to the "hypothetical" problem above is to use the selected TFP data points (TFP1), from which the regression line was derived. By regressing TFP1 on the R&D intensity ratios in models specified in sections 5.3 and 5.4, the corresponding OLS estimates are as follows:

$$\begin{array}{llllll} \pi = 0.01 & -\,19.57BR & +\,0.720AR & +\,8.02PDD & +\,7.16PCD & (5.11) \\ (p)\ (.50) & (0.01) & (0.42) & (0.01) & (0.01) & \end{array}$$

$$R^2 = 0.48 \quad \bar{R}^2 = 0.44 \quad F = 11.53$$

$$\begin{array}{llll} \pi = 0.02 & -\,0.36RES & +\,5.82DEV. & (5.12) \\ (p)\ (.30) & (0.66) & (0.01) & \end{array}$$

$$R^2 = 0.35 \quad \bar{R}^2 = 0.32 \quad F = 13.42$$

$$\begin{array}{llll} \pi = 0.05 & -\,12.43BR & +\,2.87ARDEV. & (5.13) \\ (p)\ (.02) & (0.06) & (0.01) & \end{array}$$

$$R^2 = 0.21 \quad \bar{R}^2 = 0.18 \quad F = 6.71$$

$$\begin{array}{lllll} \pi = 0.06 & -\ 12.81BR & +\ 3.05ARDEV & -\ 2.11TS & (5.14) \\ (p)\ (.01) & (0.06) & (0.01) & (0.25) & \end{array}$$

$$R^2 = 0.23 \quad \bar{R}^2 = 0.18 \quad F = 5.00$$

These estimated results do not change the basic conclusions about the productivity impact of various R&D activities. Note that the magnitudes of the estimates here are higher than their counterparts in sections 5.3 and 5.4. This is because the regression line is fitted through the middle of the data points, minimizing the sum of differences (residuals) from the data points to the fitted line. Also note that the p-values for the estimates of BR are below 0.10. However, as has been argued throughout this dissertation and shown in Appendix C, these negative estimates of BR may be the result of model mis-specification.

One of the disadvantages of using the selected TFP index is that the sample is no longer a balanced one because each firm may have a different number of data points and may have data on different time periods. This disadvantage creates difficulties in making inferences from these estimates.

5.5.2 Alternative Data Selection Criteria and Line Fitting Methods

In order to test the sensitivity of the data selection criterion, two alternative criteria also have been used to select data points and to construct alternative operational TFP measures. The first alternative criterion is to relax the previous one, which selected only the peak years in a series of troughs and peaks in the original index, and included those years of data that are positive but may be lower than some previous years. The resulted operational TFP index is TFP2. The third criterion is to include those years of data that are negative but exclude those years when the firm was in deep recessions such as in 1973–1974, and 1981–1982. The resulted operational TFP measure is TFP3.

The alternative line fitting method is the smoothing technique. Estimated results of these alternatives (criteria and line fitting method) have been shown in Section D.1 of Appendix D. These estimates indicate that so long as the negative values of the original TFP are excluded, the alternative criteria and line fitting method do not change the fundamental conclusions on the productivity impact of each R&D activity.

Sections D.2 to D.8 also discuss seven other methods of estimating the operational TFP measure and their results.

5.6 Conclusions

The current analysis indicates a strong positive relationship between development activities and the firm's productivity growth. Evidence of direct effects of basic research programs on productivity growth of this sample have not been found. Neither have the direct effects of applied research and the technical services programs.

The estimates obtained in this chapter appear to be free of omitted variable bias either specific to firm or specific in time. These advantages have resulted from the use of panel data and have increased the confidence placed in the estimated results.[184]

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[184] The results obtained in this section are very robust too. As described in Appendix D, different dependent variable (alternative TFP measures) have been regressed and the patterns of negative and insignificant basic research coefficients and positive, strong coefficients for development can be found in most of the estimates.

End-Notes to Chapter 5

1. Literature Survey on Panel Data Analysis

Various approaches to the specification of the behavior of "disturbances" in panel data have been used in the literature.

The model of a pooled cross-sectional and time series data set (CSTS) can be expressed as:

$$Y_{it} = b_i X_{it} + e_{it} \tag{1}$$

where i is the number of cross-sectional units (1 = 1, 2, ..., I); t, the number of time period within each cross-sectional unit (t = 1, 2, ..., T); Y_{it} is a vector of observations on a dependent variable; X_{it} is a matrix of observations on independent variables; b_i a vector of unknown regression coefficients; and e_{it} a vector of unknown and unobservable random disturbances. The purpose of the study is to estimate the b_i vector for the i^{th} individual unit (firm) and to summarize the effect of the X_i's on Y_i for all firms.

In order for the estimator of b_i to have the BLUE properties, the following assumptions must hold:[185]

$$E(e_i)=0; \tag{2}$$

$$E(e_i'e_i)=\sigma_i^2 I_T; \tag{3}$$

$$E(e_i'e_j)=0, \quad for \quad i \neq j; \tag{4}$$

X_i is a fixed matrix (in repeated samples) (5)

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[185] The detail description of these assumptions is given in Kmenta (1986).

In empirical research, these assumptions are often violated; solutions or remedies to these violations constitute a series of studies in the econometric literature.

When the performance of one individual firm is of interest, a separate regression equations can be estimated for each individual firm. Another approach is to pool the data set for multiple firms and to replace OLS by GLS estimators. The GLS estimator has been shown to be more efficient than OLS if assumption (3) is violated and the disturbances are either serially correlated or heteroscedastic.[186] The Seemingly Unrelated Regressions (SUR) technique is used when assumption (4) is violated and contemporaneous correlation is present. However, if the X_i matrices involve exactly the same elements, e.g., the independent variable for each firm takes exactly the same values, or if no cross - equation correlation of the disturbance exists, it has been shown that OLS is as efficient as GLS and SUR; OLS can then be applied equation by equation.

When it is necessary to summarize individual relationships and, from the summary statistics, to draw inferences about certain population parameters, estimators proposed in the literature are assumption–dependent. Several models in this framework are important to this dissertation. First, the classical pooling approach ignores differences among individual firms, or if the coefficient vectors are assumed to be different, these differences

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[186] Pindyck, R. and Rubinfeld, D. 1976. Econometric Models and Economic Forecasts, New York, McGraw Hill.

are at least random. With these restrictions, OLS or GLS applied to the aggregate data may yield an unbiased estimator with respect to the mean or expected value of the coefficient to be estimated.[187]

The second model is the analysis of covariance model (ANCOVA) which attempts to relax some of the stringent assumptions. ANCOVA allows the equation intercept to vary as a means of representing individual firm or time effects. The introduction of a set of dummy variable is the central part of this model (Pindyck and Rubinfeld, 1976). However, ANCOVA still assumes that the slope coefficients are identical for all firms. It also involves many parameters to be estimated.

Because the ANCOVA technique uses dummy variables to measure the shifts in the regression line and the variable that might cause the shifts is treated as exogenous, a third model, an error components model, approaches the problem differently by incorporating the unknown variances into the disturbance term. This overall disturbance term is decomposed into three components: one associated with time, another associated with the cross-sectional firms, and the last one varying in both dimensions. Within this approach, various model specifications have been proposed depending on assumptions such as the independence among the three components. Estimators for error component

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[187] Kuh, E. 1974. "An Essay on Aggregation Theory and Practice" in Econometric and Economic Theory, Willy Sellekaerts edited. White Plains, N. Y.: International Arts and Science Press.

models have been studied under various conditions such as sample size, number of independent variables, time span, and the assumption about the independence among components. OLS, ANCOVA, two stage GLS and MLE are appropriate under *certain assumptions.*

Several points about this model are worth noting. (1) With appropriate data transformations, OLS can be applied to this model under most of the conditions. (2) The use of the error components model does not change the assumption that the slope coefficients are equal across firms. (3) Due to the complexity of the error components model involving three components, models with two components have been widely used - dropping the component associated with time.[188] However, the error components model depends critically on the assumption that the unknown variances are normally distributed.

The fourth group of models are those that not only allow the intercept to vary across firms, but also the slope coefficients of regressors to differ, using the aggregated database. One specification introduces dummy variables for the differences in the coefficients across firms and is similar to and shares the same problems as ANCOVA.[189] Another generalizes further the error

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[188] This time component can be approximately modeled by a time trend variable in the equation.

[189] Maddala, E. 1977. Econometrics. New York: McGraw Hill.

components model, treating all the coefficients, as random.[190] The most general of all random coefficients models has been proposed by Hsiao, C. (1974), Rosenberg (1973) and others.[191] However, the generality of this model adds complexity of the methodology and the tradeoff between flexibility and complexity of a model has to be weighed by the individual researcher.

2. Alternative Model Specification for Technical Services

A statistical issue which may be important here is the model specification for technical services. Although the term "technical services" is confined to that in an R&D department, it may have to be modeled differently from R&D activities because the fundamental functions of technical services differ from those of R&D. One attempt was made to transform the TS variable as percentage changes rather than as the ratio of investment intensity of the R&D components. Another approach was to regress TS on the original TFP index rather on the frontier TFP index, either with or without R&D activities in the model, because the function of TS is not to influence the production frontier.

Various specifications were tested using the annual change rates of TS and various dependent variables. However, the only result was

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[190] Swamy, P. 1970. "Efficient Inference in a Random Coefficient Regression Model." Econometrics. 38, pp.311-323.
Rao, R. 1965. "The Theory of Least Squares When the Parameters Are Stochastic And Its Application to the Analysis of Growth Curves." Biometrika, 52, pp.447-458.

[191] Hsiao, C. 1974. "Statistical Influence for A Model With Both Random Cross-sectional and Time Effects." International Economics Review 15, pp.12-30.
Rosenberg, B. 1973. "The Analysis of a Cross-Section of Time Series by Stochastically Convergent Parameter Regression", Annals of Economic and Social Measurement, 2, pp.399-428.

that regardless of the specification of the model — with or without R&D activities, and regressing on the original TFP indices or on the frontier TFP indices — a positive and statistical significant relationship between technical services and long-term productivity growth could not be established, as demonstrated in Equation (D.5) of Appendix D.

Chapter 6
Conclusions and Suggestions for Future Research

This dissertation has made considerable efforts in deriving appropriate price deflators at the SIC four-digit level and in estimating the productivity impacts of various R&D activities and technical services. This chapter summarizes observations from the data estimation process, makes suggestions for future research, and draws conclusions from the estimation of R&D activities.

6.1 Observations on Data Estimation

The current data estimation process has brought about the following observations:

1. The reliability of the estimated total factor productivity index rests mainly on the accuracy of the price deflator for output, material, and capital expenditures. This study suggests that such price indices derived from public sources at the SIC four-digit level are very close to the firm-specific indices. However, this is not true for the index of plant capacity utilization in a process (chemical) industry because of its conceptual problem and a unique characteristic of the industry that the output levels of the chemical facilities also depend on the mixture of feedstock inputs.
2. Econometric studies of R&D productivity at the firm level should examine each firm in the sample for the following key factors: divestiture history, product mix, and international markets.

Failure to consider these factors could produce misleading estimates because the TFP index, in essence, is the weighted difference of output and inputs, both of which are strongly influenced by these factors.

3. While the Standard & Poor's COMPUSTAT data base is one of the most used public data sources in empirical research, care must be exercised in its use. In particular, the assignment of standard industry classification code(s) (SIC) to each firm requires close attention. In addition to the issue of appropriateness, the SIC code assigned may change over time because it is assigned based on one primary business segment of the firm. Whenever possible, data from COMPUSTAT should be cross-checked against company reports. Some data items such as net sales and the total number of employees have been modified by Standard & Poor's to ensure the compatibility of accounting and reporting methods across firms. These modifications improve the quality of data for any analysis across firms, but they may also raise potential problems.

4. For most sample firms, the estimated capital stock closely follows the patterns of the firm's net capital stocks and gross capital stock published in company reports. It has a higher value of, but is close to, the firm's gross capital stock. The difference in magnitude is the result of using a longer depreciation scheme in the BLS and BEA estimates. This means that, if data on the firm's past investment are not available, the firm's gross capital stock may be a more appropriate measure of capital stock in productivity studies.

5. Data on total annual R&D expenditures that companies reported

to the SEC and collected in the COMPUSTAT data base appear to be inflated by technical services expenses. Firms that report technical service expenses as part of R&D would inflate, on average, their R&D expenditures by about 20 percent.

6.2 Suggestions for Future Research

As has been cautioned throughout this dissertation, there are still many problems unresolved in econometric studies of R&D productivity using production functions. Thus, suggestions for future research derived from the current investigation are:

1. The assumption of disembodied technological changes has been the prevalent one underlying the majority of R&D productivity studies in the literature. However, research results from other fields have indicated that the impact of most technological advances in the private sector has been embodied in tangible capital and labor. Also, the econometric results under the assumption of embodied technological change have been shown to be very different from those using the disembodied assumption. This evidence suggests that more research effort should be directed towards R&D productivity assuming embodied technological changes at the firm level.

2. Related to the previous suggestion about the technological embodiment assumption, the annual tangible capital expenditures should be decomposed into those of replacement and those of new investment. Also, a measure of the "quality" improvement of labor inputs should be further developed at the firm level. With such

disaggregated data, the productivity impact of technology advance can be more thoroughly and accurately assessed.

3. Although the theoretical relationships among R&D activities have been well documented, very little has been done empirically on their interrelations. This study has shown that the productivity impact of various R&D activities is quite different and has demonstrated the need to promote studies at the individual R&D activity level. Only when the inter-relationships among these activities are theoretically and empirically established can further understanding in R&D productivity become possible.

4. When various R&D activities were examined simultaneously, results from this study clearly indicated that new models are needed to assess the productivity impact of research activities. The LISREL framework appears to be a more appropriate analytical tool in the study of individual R&D activities because of its capacity and flexibility for modeling both the direct and indirect effects of each of the R&D activities on productivity as well as among themselves.

5. The operational measure of capacity utilization at the firm level still is a challenge to any R&D productivity study. Cooperation from the firm is essential in estimating such an index. If that is possible, the following approach seems plausible. First, estimate the firm's physical plant capacity and the change of plant capacity from the firm's new capital investment. Second, calculate the change in the firm's labor stock. Third, compute the real output growth. Finally, in the process industries, it is essential to

estimate changes in the mixture of feedstocks used by the firm and their prices. It is also important to obtain a measure of changes in the "quality" of these feedstocks that result from technology advance. With all this information, a proper formula can be constructed to estimate the rates of capacity utilization of the firm.

6. The total factor productivity index is calculated basically as the "weighted" difference between output and inputs, with the factor shares in real output as the weights based on the assumption of perfect competition. This assumption and the subsequent way of assigning those factor weights seem to be problematic. For example, if the markets are perfectly competitive, R&D activities may not be performed in an organized way and there will be no incentive for the firm to innovate. Hence, this competitive assumption contradicts the theories on which most R&D studies are based. Also, if technology is recognized as one of the key factors in the production process, there should be a factor share for technology (R&D) too. The relationship between the factor share of technology (R&D) and those of other factors has not been clearly specified in the theories. Before a new theoretical basis emerges, an alternative basis of assigning weights may be the "factor loadings" of capital, labor, materials, and technology. These weights could be derived using the method of Factor Analysis on these four input components. This alternative approach implicitly treats the combination of those production inputs as a latent variable and assigns the weights based on the "importance" of each production factor each year. The theoretical underpinning and

feasibility of this approach remain to be developed.

7. Theoretically, the purposes of any study of R&D productivity is to analyze the impact of technology advance on the firm's production frontier which is measured by some productivity indices. Because of the difficulties in deriving these indices due to either under-developed theories or the lack of firm-specific data on such important variables as capacity utilization, one should consider alternative cross validation methods. One feasible alternative is to use Linear Programming (LP) to derive the production frontier and subsequently estimate the efficiency of production over time. Examining the relationship between this efficiency index and R&D activities should be equivalent to studying the relationship between the productivity indices and R&D, although the interpretation of the estimated results may differ.
8. This study has demonstrated the need to examine the productivity impact of technical services. Because so little has been known about this activity, future investigation should focus on more generalized definitions and on the improvement in measuring the technical service expenditures. In addition, the total technical efforts devoted to technical services should be disaggregated into appropriate elements (R&D vs non-R&D — marketing, manufacturing — quality control, etc.) and studied separately.

6.3 Major Conclusions

The theoretical and empirical analyses throughout this study have led to the following major conclusions:

1. Increasing competitiveness in existing markets was the most important business goal of the sample firms during the last two decades. Accordingly, the focus of most R&D programs has been on product and process development programs. This study estimated that product and process development efforts have contributed more strongly to the firms' productivity growth during the last two decades than basic and applied research and technical services.
2. Applied research programs in the chemical industry actively supported development activities. These two programs were closely related statistically and the applied research efforts have, together with the development activities, promoted the firms' productivity growth. In some sense, it might be inferred that applied research provided the "infra-structure" for effective product and process development.
3. The basic research programs in the sample have been very weak in the last 20 years. Basic research efforts did not positively and directly contribute to the firm's productivity growth, but it appears to have a strong positive impact on applied research.
4. Technical service activities performed by the R&D departments of the sample firms made up a substantial part of their R&D effort. However, this study did not find any contribution from technical

service activities to the firm's long-term productivity growth. It should be noted that there has been an increasing emphasis since 1988 on greater contact between the technical staff and customers. It would seem important to collect new panel data in the near future to see whether such an emphasis results in greater efforts deployed to technical services, and to re-examine possible productivity effects.

5. The estimate of returns to *total* R&D is comparable to the results of previous R&D productivity studies. However, when total R&D is decomposed into appropriate elements, this study suggests strong developmental effects on the firm's productivity growth and weak research effects. It might be conjectured from the results of this study that the effects of total R&D on the firm's productivity growth remain within a comparable range (marginal private rates of returns to R&D: 30% to 60%) since the 1950s but the effects of specific R&D activities have changed during the last two decades. In the 1950s and 1960s, a strong productivity impact of basic research was found. However, during the 1970s and 1980s, the strong productivity effects may have shifted to development activities.

   This conjecture about a shift of strong productivity effects from research to development activities is based on a comparison of the current analysis with several previous ones (e.g. Mansfield, 1980; Link, 1981; and Griliches, 1986). First, it is important to note that there is a difference in the time periods of these studies. This dissertation extended from the 1970s and into the late 1980s, whereas the previous ones covered from the 1950s to the mid-1970s. Second, there may have been differences in the focus and priorities of research programs after the 1970s. It is possible that, in the 1950s and 1960s, research programs were more oriented toward exploring new markets and new products and processes, and businesses may have been more diversified, than in the 1970s and 1980s. In the chemical industry in the last two decades, basic research may have been financed more through sources outside of the firms, i.e. government, and performed mostly by outside research institutions and universities, especially in the precommercial phases of product development.

It should be noted that this study used the same analytical framework as the previous ones but measured the R&D and productivity variables in greater detail, especially by accounting for changes in product mix over time. However, this dissertation concentrated on the chemical industry only, whereas the previous studies examined other industries as well. Replications of such R&D productivity studies in the 1980s in other industries are needed to provide more conclusive evidence on the shift of the productivity effects of these R&D activities.

Appendix A
Correlation Coefficients of R&D Activities

(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
	BR71	BR72	BR73	BR74	BR75	BR76
BR71	1.0000					
BR72	.9958	1.0000				
BR73	.9723	.9889	1.0000			
BR74	.9475	.9689	.9928	1.0000		
BR75	.9802	.9873	.9830	.9713	1.0000	
BR76	.9943	.9886	.9684	.9533	.9819	1.0000
BR77	.9933	.9845	.9582	.9379	.9739	.9975
BR78	.9894	.9797	.9522	.9343	.9666	.9957
BR79	.9879	.9794	.9543	.9398	.9707	.9964
BR80	.9760	.9683	.9449	.9342	.9767	.9898
BR81	.9767	.9676	.9432	.9326	.9745	.9904
BR82	.9811	.9719	.9429	.9254	.9740	.9895
BR83	.9826	.9756	.9464	.9233	.9665	.9869
BR84	.9793	.9787	.9545	.9283	.9692	.9769
BR85	.9746	.9753	.9521	.9251	.9735	.9710
BR86	.9490	.9576	.9418	.9204	.9635	.9488
BR87	.9399	.9581	.9576	.9449	.9650	.9401
BR88	.9477	.9685	.9697	.9467	.9770	.9339
Coeff.	BR77	BR78	BR79	BR80	BR81	BR82
BR77	1.0000					
BR78	.9986	1.0000				
BR79	.9975	.9992	1.0000			
BR80	.9885	.9895	.9937	1.0000		
BR81	.9889	.9902	.9944	.9997	1.0000	
BR82	.9914	.9923	.9946	.9978	.9972	1.0000
BR83	.9930	.9935	.9920	.9859	.9839	.9926
BR84	.9832	.9819	.9800	.9743	.9707	.9839
BR85	.9765	.9737	.9731	.9733	.9690	.9827
BR86	.9532	.9502	.9511	.9558	.9485	.9631
BR87	.9374	.9341	.9369	.9409	.9327	.9446
BR88	.9287	.9223	.9253	.9274	.9197	.9345

(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
Coeff.	BR83	BR84	BR85	BR86	BR87	BR88
BR83	1.0000					
BR84	.9954	1.0000				
BR85	.9904	.9979	1.0000			
BR86	.9761	.9882	.9916	1.0000		
BR87	.9585	.9751	.9784	.9942	1.0000	
BR88	.9459	.9707	.9771	.9850	.9935	1.0000

Notation:

BRxx: BR = Basic Research, xx = year.

All correlation coefficients are statistically significant at 0.01 level (one-tailed)

Appendix B
Estimation of the Tangible Capital Stock

Based on economic theories, the tangible capital stock can be estimated from the *deflated* and *depreciated* annual capital expenditures. Components of annual capital expenditures include land and natural resources, machinery and equipment, and industrial structures (buildings). Annual capital expenditures initially are charged to the "construction in progress" account and subsequently transferred to these asset classifications when placed in services. However, no information on the vintage of the transferred asset is available.

Two adjustments are needed before the annual capital expenditures can be used to estimate the capital stock: deflation and depreciation. It has also been generally agreed that both the deflator (price movement) and depreciation scheme for structure investment are different from those for equipment and machinery investment, and that land should be excluded from any adjustment, i.e, it should *not* be depreciated and deflated. These adjustment processes will be described separately below.

B.1 Deflated Annual Capital Expenditures

Raw data on the company's annual capital expenditures are obtained from "Schedule V" (plant and equipment) of the firm's Form 10-K reports, which contains capital expenditures on each component of plant and equipment—land, building, and equipment from 1969 to 1988. Data prior to 1969 are obtained from the company's annual reports in which total annual capital expenditures were compiled. In an effort to apply a more appropriate price deflator for such data, a weighted price index is computed based on the composition of the company's expenditures on natural resources (land), industrial buildings, and equipment from 1969 to 1988. For the sample firms, the average proportions of capital additions on natural resources (land) and industrial structures are both small, relative to that of equipment and machinery. Based on the depreciation scheme which will be explained next, data on annual capital expenditures are obtained from 1953 to 1988.

The price deflator for annual capital expenditures is computed from three individual price indices, all from 1953 to 1988: the Engineering News Record index on building construction (ENR), producer price indices for SIC 3559, and a constant value of one. In the literature of productivity studies, ENR has been used to deflate the annual expenditures for buildings. It is published by the Department of Commerce (Construction Review) and estimated on the basis of hypothetical unit of construction requiring 6 bbl. of Portland cement, 1,088 M bd. ft. of 2" × 4" lumber, 2500 lb. of structural steel, and 68.38 hours of skilled labor. BLS's PPI on chemical machinery and equipment (SIC 3559) can be used to deflate the annual expenditures on equipment. The constant value of one represents the "price index" of natural resources (land). The price deflator is computed for each firm as a weighted composite index of these three price indices, weighted by the percentage of each capital component in total annual capital expenditures. This composite index is then converted to the base year of 1982 and used to deflate the annual capital expenditures from 1953 to 1988.

B.2 Depreciated Annual Capital Expenditures

This deflated annual capital expenditures series is then depreciated before it is used to form the total capital stock for this study.

In the context of this study, the depreciation function should reflect the decline in the ability of capital to produce goods and services. Thus, depreciation is defined here as the decline in potential productivity or efficiency of capital. Depreciation expenses reported by the company for accounting and tax purposes are not directly applicable to this study. Thus, the capital stock of the company has to be estimated based on methods of similar studies made by the Bureau of Labor Statistics (BLS), U.S. Department of Labor, and the Bureau of Economic Analysis (BEA), U.S. Department of Commerce.

B.2.1 Estimated Replacement Function

The estimation of a replacement function on the formation of capital stock involves the estimations of the asset service lives, discard pattern, and depreciation function. Given the asset service lives, the combination of both the discard and depreciation functions can be used to estimate the replacement function. The estimation procedure of such a function is described as follows:

1. Determining the assets' service lives The source of service lives used in this supplement is the BEA capital stocks study.[192] The lives of "special industry equipment" including chemical equipment have been estimated to be 16 years and industrial structures to be 27 years.
2. Selecting a discard function The discard function used in this supplement is the Winfrey S-3 curve modified by BEA. Retirement begins at 45 percent and ends at 155 percent of the average service life for non-residential private capital. This modified S-3 curve is bell-shaped distributions centered on the average service life of the asset.

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[192] The origin sources of asset lives are from the U.S. Internal Revenue Services' Bulletin F and data from the Agriculture Department on the lives of farm assets. The BEA modified and aggregated these data sources to 20 different equipment categories and 11 structure categories.

3. Choosing a depreciation function As mentioned earlier, depreciation is defined in this study as the decline in potential productivity or efficiency of capital. Although there is no general consensus on the exact time path of efficiency depreciation, both technological and economic arguments tend to support the theory that efficiency declines more in the later years than in the early year. One form of the depreciation function is:

$$R_L = \frac{L-\lambda}{L-\beta\lambda} \qquad (B.1)$$

where L is the service life of the asset; λ the actual age of the asset; and β is the curvature parameter. From the argument above, β is less than one but greater than zero. Based on the BLS studies of capital stock estimates,[193] the final β values are 0.9 for structures and 0.75 for equipment. Equation (B.1) and the β values will be applied in this study too.

4. Estimating the replacement function The replacement function is developed by mapping both the discard and depreciation of an investment over time. Statistically stated, given the mean service life of L years, the actual service lives of assets will range between 45 percent and 155 percent of the mean life. For *each* of these service lives, there exists a depreciation function which describes the change in the relative efficiency of assets. The efficiency of each depreciation function will be weighted by the relative frequency of

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[193] BLS. 1979. Capital Stock Estimates for Input-Output Industries: Methods and Data, Bulletin 2034.

the discard pattern. These weighted efficiency values then are summed across all depreciation functions to yield the replacement function.

The discard pattern (function) can be thought of as a probability distribution function of various depreciation functions of those asset service lives within the discard range (45 percent to 155 percent of the mean life), and the replacement function so derived is the weighted average of those depreciation functions, weighted by the discard "probability function." For example, given the service life of chemical equipment (L) of 16 years and β of 0.75, and the discard range from year seven to year 25, 19 depreciation schemes (R_L) will thus be computed according to equation *(B.1)* above (L = 7, 8, ... 25, λ = 1, 2, ... 25). For any year λ, the replacement function is computed as the weighted average of those 19 depreciation schemes, weighted by the discard pattern.

The discard pattern and the estimated replacement functions for chemical equipment and industrial structures are shown in table B-1.

Note that in this table,

1. Columns (1) and (2) are the modified Winfrey retirement patterns (nonresidential S-3 curve). Column (1) is the percent of average service life; column (2) is the cumulative percent of original expenditures discarded.
2. Columns (7) to (10) are the continuation of columns (3) to (6). Columns (3) and (7) are the actual age of the asset service life. Columns (6) and (10) are the "replacement function" for land, which takes a constant value of one indicating that no depreciation is made for land when a weighted depreciation index is derived.

Table B-1: The Modified Winfrey Curve and Replacement functions

Winfrey Curve		*Replacement functions for both Equipment and Structures*							
%SL	*Cum%*	*Age*	*Equip*	*Bldg*	*Land*	*Age*	*Equip*	*Bldg*	*Land*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
<0.45	0.00	1	0.980	0.996	1	26	0.000	0.330	1
0.45	1.20	2	0.960	0.990	1	27	0.000	0.284	1
0.50	2.40	3	0.940	0.986	1	28	0.000	0.240	1
0.55	4.10	4	0.914	0.980	1	29	0.000	0.200	1
0.60	6.50	5	0.880	0.975	1	30	0.000	0.165	1
0.65	9.70	6	0.850	0.970	1	31	0.000	0.132	1
0.70	13.70	7	0.800	0.960	1	32	0.000	0.100	1
0.75	18.70	8	0.750	0.952	1	33	0.000	0.080	1
0.80	24.60	9	0.690	0.940	1	34	0.000	0.060	1
0.85	31.20	10	0.625	0.930	1	35	0.000	0.045	1
0.90	38.40	11	0.550	0.920	1	36	0.000	0.030	1
0.95	46.10	12	0.475	0.900	1	37	0.000	0.020	1
1.00	53.90	13	0.400	0.880	1	38	0.000	0.015	1
1.05	61.60	14	0.325	0.855	1	39	0.000	0.010	1
1.10	68.80	15	0.250	0.823	1	40	0.000	0.005	1
1.15	75.40	16	0.192	0.793	1	41	0.000	0.003	1
1.20	81.30	17	0.140	0.760	1	42	0.000	0.000	1
1.25	86.30	18	0.100	0.719	1				
1.30	90.30	19	0.065	0.670	1				
1.35	93.50	20	0.040	0.630	1				
1.40	95.90	21	0.025	0.575	1				
1.45	97.60	22	0.020	0.530	1				
1.50	98.80	23	0.010	0.480	1				
1.55	100.00	24	0.001	0.432	1				
>1.55	100.00	25	0.000	0.375	1				

B.2.2 The Perpetual Inventory Method and Estimated Capital Stock

With these estimated replacement functions for chemical equipment and industrial structures, D, the remaining productive portion of a capital expenditure in industrial structure and chemical equipment on year λ can be computed, respectively, for any year between the year of investment, t, and year 1988 as follows:

$$PCE_{\lambda} = A_t \times (1 - D)^{(\lambda - 1)} \qquad (B.2)$$

where PCE_{λ} is the productive portion of an capital investment of year λ ($\lambda = 1, 2, \ldots L$, the number of year(s) from year t). A_t is the amount of annual capital expenditures in year t. Equation (B.2) represents the perpetual inventory method (PIM), which has been widely used in the capital stock estimation.[194]

Summing up horizontally the productive portions at year T ($T = 1969, 1970, \ldots 1988$) of *all* capital expenditures invested since 1953 will provide an estimate of the capital stock for year T, both deflated and depreciated.

Note that the average service lives for chemical equipment have been estimated to be 16 years and the capital stock of equipment in 1969 is formed by capital expenditures of the last 16 years, 1953 to 1969. The average service lives for industrial structures have been estimated to be 27 years and the capital stock of structure in 1969 should consist of the remaining productive portions of capital expenditures since 1942. Due to the lack of such data in the early years, this stock of 1969 is formed by capital expenditures of the last 16 years. No significant bias in the estimated structure stock is expected from such data deficiency because of the following three factors: First, the annual expenditures

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[194] Alternatively, this method can be expressed as $K_t = K_{t-1} + I_t - D_t$ where K_t and K_{t-1} are the value of capital stocks in years t and t-1, respectively; I_t investment in year t; D_t depreciation and discards in year t.

in years from 1942 to 1952 are expected to be very *small*, compared with those from 1953 to 1968. Second, the portion of investment in structures was very *small*; and third, one dollar investment in structure in 1942 will have only a *small* percent left in 1969 after it has been depreciated over those years. The compounded impact of these three *small* values and portions will result in a statistically insignificant impact on the estimated capital stock.

By comparing the estimated capital stock with the net assets and total gross assets reported by the company to SEC, deflated by the same price deflator estimated above, the estimated capital stock has greater values but these three stock measures share the same patterns of changes over time.

Appendix C
The LISREL Estimates

The purpose of this Appendix is to use the LISREL technique to estimate the productivity impact of basic and applied research. A brief introduction of this technique is given below but is limited to the model specified in this study. No attempt is made to compare thoroughly this technique with the simultaneous equation systems (SES).

LISREL (LInear Structure RELationships) is a structural equation system.[195] It emphasizes covariances rather than cases as a regression technique, and thus, it minimizes the difference between the sample covariance and covariances predicted by the model, whereas the regression technique minimizes functions of observed and predicted individual values. The regression model and SES can be considered as a special case of the LISREL model.

The general LISREL model consists of two parts: the measurement model and the structural equation model. The former specifies how latent variables or hypothetical constructs depend on or indicated by the observed variables, while the latter specifies the causal relationships among the latent variables, describes the causal effects, and assigns the explained and unexplained variance. When the latent variables are represented by the observed variables, the LISREL model reduces to the structural equation model as follows:

$$\mathbf{y} = \mathrm{B}\mathbf{y} + \Gamma\mathbf{x} + \zeta \qquad (C.1)$$

$$\|I - \mathrm{B}\| \neq 0$$

---

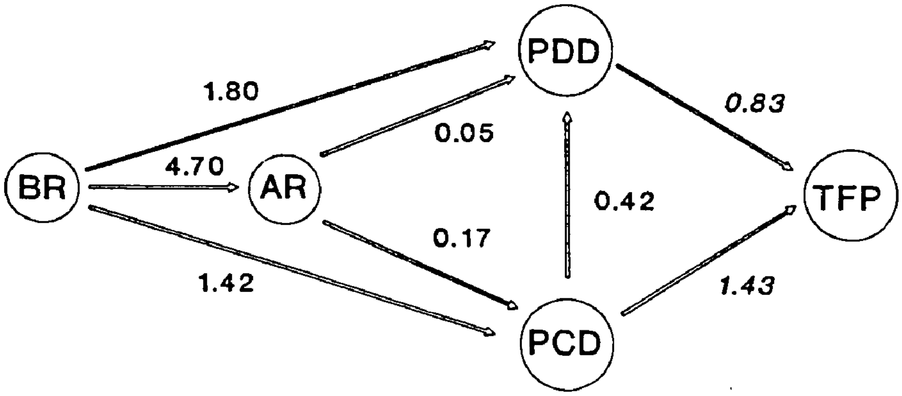
[195] For a comprehensive review of the LISREL model, see Bollen, K.A. 1989. Structural Equations With Latent Variables. John Wiley & Son, Inc.
Joreskog, K.G. and Sorbom, D. LISREL 7 A Guide to the Program and Applications, 2nd Edition. SPSS Inc. 444 N. Michigan Avenue, Chicago, Il. 60611.

where B is the structural coefficient matrix of y, the dependent variables; Γ the structural matrix of x, the independent variables; ζ the vector of structural residuals. This model assumes that ζ is not correlated with x and y and shares many statistical problems as the SES such as model identification and an BLUE. However, this model allows one to specify and estimate the covariance matrix of ζ, Ψ. "Fixing" the off-diagonal elements of this matrix to zero means that the structural equations are independent each other. In fact, Equation (C.1) with such specifications is the model specification of this Appendix.

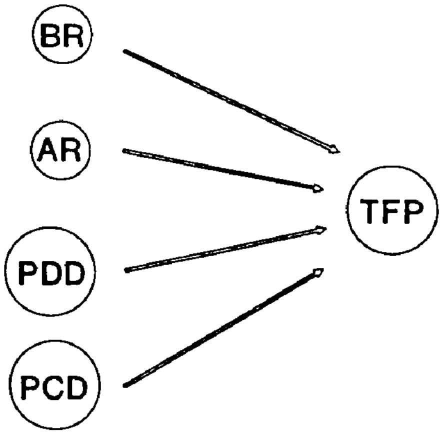
Unlike the SES, LISREL incorporates the features of the Path Analysis framework and distinguishes three types of effects (x on y): direct, indirect, and total effects. The direct effect is that influence of one variable on another that is unmediated by other variables. The indirect effects of a variable are mediated by at least one intervening variable. The sum of the direct and indirect effects is the total effects. Examining each type of effect allows one to understand more completely the relations between variables. This is the reason that the LISREL model is used here to analyze the indirect and total impact of basic and applied research on productivity growth.

Because of the lack of data on the interactions between the sample firms and outside research institutes, the model proposed in Chapter 5 that the impact of basic research on the firm's productivity growth is through its internal research and development efforts is estimated here. The final model specification is shown below as path diagram 1. Note that path diagram 2 is the regression model used in Chapter 5 which specified the direct relation between all R&D activities and productivity growth.

Path Diagram 1



Path Diagram 2



From path diagram 1 above, the total effect of basic research is positive and statistically significant, as shown below.

LISREL output

```
TOTAL AND INDIRECT EFFECTS

 TOTAL EFFECTS OF X ON Y

                BR
           --------
  PTFP1      5.648
     AR      4.708
    PDD      2.976
    PCD      2.225

STANDARD ERRORS FOR TOTAL EFFECTS OF X ON Y

                BR
           --------
  PTFP1      2.935
     AR       .455
    PDD       .430
    PCD       .208

 INDIRECT EFFECTS OF X ON Y

                BR
           --------
  PTFP1      5.648
     AR       .000
    PDD      1.175
    PCD       .804

 STANDARD ERRORS FOR INDIRECT EFFECTS OF X ON Y

                BR
           --------
  PTFP1      2.935
     AR       .000
    PDD       .384
    PCD       .160
```

This model is a recursive system and thus, is identified. The p-value for the χ^2 is .269, and the "hypothesis" that the estimated covariance matrix is different from the true one can be rejected. The "Goodness of Fit" indices are close to one and the "Root Mean Residual" is small. These statistics shown below appear to signify the model is well fitted.

```
CHI-SQUARE WITH 2 DEGREES OF FREEDOM =     2.63 (P = .269)
                GOODNESS OF FIT INDEX =      .995
       ADJUSTED GOODNESS OF FIT INDEX =      .962
           ROOT MEAN SQUARE RESIDUAL =     2.394
```

The goodness of fit of this model can also be seen from other statistics. First, estimates of these effects shown above are almost identical for three common estimators: Two Stage Least Squares, Maximum Likelihood, and Generalized Least Square. Second, the standard errors of those estimates and the modification indices below directly or indirectly indicate that the model is well fitted. The absolute value of any standard error greater than 1.9 is considered problematic; any modification index greater than four suggests that the model be analyzed further.

STANDARD ERRORS

```
       BETA

              PTFP1        AR        PDD        PCD
            --------  --------  --------  --------
 PTFP1        .000      .000      .738     1.356
    AR        .000      .000      .000      .000
   PDD        .000      .069      .000      .151
   PCD        .000      .030      .000      .000

       GAMMA
                 BR
            --------
 PTFP1        .000
    AR        .455
   PDD        .560
   PCD        .239
```

MODIFICATION INDICES

```
 MODIFICATION INDICES FOR BETA

              PTFP1        AR        PDD        PCD
            --------  --------  --------  --------
 PTFP1        .000     1.915      .000      .000
    AR        .477      .000      .000      .000
   PDD       2.056      .000      .000      .000
   PCD       2.599      .000      .000      .000
```

```
MODIFICATION INDICES FOR GAMMA

                  BR
              --------
PTFP1          1.574
   AR           .000
  PDD           .000
  PCD           .000
```

Note that the model specification above is a preliminary one for panel data. Corresponding to the estimation method (covariance) in Chapter 5, data were transformed as deviations from means for each firm and used to form the covariance matrix to be analyzed by the LISREL program. However, further analysis should incorporate the mean structures into this LISREL model, either by specifying multiple groups or by creating dummy variables. The LISREL estimates above thus should be interpreted with care. The overall conclusion of this Appendix is that the indirect, positive, and statistically significant effects of basic and applied research on the firm's productivity growth can be established.

It is too early to compare the total effects of research activities with those of development activities because of the simple model specification above. In addition, because the differences in measurement units, such a comparison of the total effects is meaningless. In the path diagram above, the research activities were specified as "functions" of development activities, all measured as ratios (intensity) of R&D expenditures to output, whereas the development activities were specified as "functions" of TFP which measured the rates of growth. However, one can standardize all these variables in the LISREL analysis so that all measurement units are between zero and one, and thus compare the estimates of research activities with the development efforts after the model is specified more adequately.

The LISREL program is also appended here for reference.

```
                         DOS - L I S R E L  7.16
                                   BY
                       KARL G JORESKOG AND DAG SORBOM

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 THE FOLLOWING LISREL CONTROL LINES HAVE BEEN READ :

  DA NI=6 NO=207 MA=CM
  LA
  'ptfp1' 'br' 'ar' 'pdd' 'pcd' 'ts'
  CM FU FO
  (6F10.7)
  SE
  1 3 4 5 2/
  MO NY=4 NX=1 BE=FU FI GA=FI PS=DI
  FR BE 1 3 BE 1 4 be 3 2 be 4 2 BE 3 4
  FR GA 2 GA 4 GA 3
  OU ALL

                              NUMBER OF INPUT VARIABLES  6
                              NUMBER OF Y - VARIABLES    4
                              NUMBER OF X - VARIABLES    1
                              NUMBER OF ETA - VARIABLES  4
                              NUMBER OF KSI - VARIABLES  1
                              NUMBER OF OBSERVATIONS   207

      COVARIANCE MATRIX TO BE ANALYZED
            PTFP1        AR         PDD         PCD         BR
          --------    --------    --------    --------    --------
  PTFP1    996.870
     AR       .165      14.676
    PDD     12.318       4.371      10.650
    PCD      6.525       4.027       2.439       3.150
     BR       .274       1.071        .677        .506        .227
```

[Note that the values of each variable were multiplied by 1,000.]

```
PARAMETER SPECIFICATIONS
        BETA
             PTFP1        AR         PDD        PCD

           --------   --------   --------   --------
  PTFP1           0          0          1          2
     AR           0          0          0          0
    PDD           0          3          0          4
    PCD           0          5          0          0
        GAMMA
                 BR

           --------
  PTFP1           0
     AR           6
    PDD           7
    PCD           8
        PSI
             PTFP1        AR         PDD        PCD

           --------   --------   --------   --------
                  9         10         11         12
```

[Note that parameter 13 is for the covariance "matrix" of X.]

Appendix D
Alternative TFP Measures

In addition to the frontier TFP index used in Chapter 5, eight alternative approaches have also been used to estimate an operational TFP index and the coefficients of the model.

D.1 Data Elimination and Alternative Line Fitting Method

This approach selected data points as described in Section 5.1.2 but employed multiple selection criteria and multiple fitting methods in order to assess the sensitivity and robustness of the frontier TFP index. A total of 12 alternative dependent variables were thus created using the following methods of data elimination and line fitting techniques:

First, from those TFP data points selected in Chapter 5 (as variable TFP1), another method of estimating the frontier TFP is to link these data points using straight lines. This line-connected TFP line (CTFP1) represents the rates of TFP growth that the firm could had achieved if it had operated at full capacity and used an optimal material mix.

Second, the selection criterion is relaxed to include all those years when the TFP index is positive (TFP2). Finally, the selection criterion is further relaxed to include the negative growth rates but outlier points are excluded (TFP3).

Then, the growth trends of these variables are estimated by fitting a regression line against time through each of these two selected TFP data series, TFP2 and TFP3, for each firm. Data on each regression line represent another set of TFP indices (PTFP2 and PTFP3). However, these fitted variables represent the TFP growth trend of the firm, not necessarily on the firm's production frontier. They thus provide a set of indices which can be compared with the frontier TFP used in Chapter 5.

As an alternative to the line-fitting method, a curve smoothing technique is also used. A smoothed curve can be fitted though each of these two series with relaxed selection criterion (TFP2 and TFP3), and, as a result, two smoothed TFP indices are derived (SMTFP2 and SMTFP3).

This smoothing technique (Gardner, 1985)[196] can be developed mathematically:

$$\begin{aligned} Y_t &= Y_{t-1} + T_t + \alpha \cdot e \qquad (D.1) \\ T_t &= T_{t-1} + \alpha \cdot \gamma \cdot e \end{aligned}$$

where Y is the smoothed series; T is the trend rate, α and γ are two smoothing parameters, and e is forecast error. For most firms, α and γ were either estimated by the software RATS or set at $\alpha = 0.10$ and $\gamma = 0.5$. When α is greater than 0.10, the smoothed series follows closely the original series. The γ is less sensitive to changes in its values.

The inter-relationship among these alternative TFP indices can be examined by using the conceptual framework of the Multiple-trait, Multiple-method Matrix (MMM) developed by Campbell and Fiske (1959). The introduction and analyses of MMM are documented in Appendix E. Results from MMM suggest that as long as no negative TFP value is selected, the estimated operational TFP indices will be highly correlated regardless of line-fitting methods, and highly compatible regression results using any of these indices can be expected.

---

[196] Gardner, E.S. 1985. "Exponential Smoothing: The State of the Art." Journal of Forecasting, 4, pp.1-28.

These alternative dependent variables (TFP1, CTFP1, TFP2, PTFP2, and SMTFP2) are then regressed, separately, on the the various combinations of the following explanatory variables: BR, AR, PDD, PCD, RES, DEV, ARPCD (= AR + PCD), ARPDD (= AR + PDD), ARDEV (= AR + DEV), and TS. In addition to the CV estimator, the GLS estimator was also used to estimate these regression equations. For purposes of comparison and tests of sensitivity and robustness of those regression estimates in Section 5.3, the mean estimates from these alternative dependent variables are shown below (the constant term is omitted), corresponding to the model specifications in sections 5.3 and 5.4.

$$\begin{array}{ll} \pi = & -5.38BR - 0.73AR + 3.51PDD + 3.28PCD \\ (p) & \quad(>.1)\quad(>.1)\qquad(<.1)\qquad(<.1) \end{array} \tag{D.2}$$

$$\begin{array}{ll} \pi = & -.99RES + 3.0DEV. \\ (p) & \quad(>.1)\quad(<.1) \end{array} \tag{D.3}$$

$$\begin{array}{ll} \pi = & -3.74BR + 1.04ARDEV. \\ (p) & \quad(>.1)\quad(<.1) \end{array} \tag{D.4}$$

$$\begin{array}{ll} \pi = & -6.20BR + 2.30ARDEV - 2.76TS \\ (p) & \quad(>.1)\quad(<.1)\qquad(>.1) \end{array} \tag{D.5}$$

In general, these "alternative estimates" are very comparable with those in Chapter 5. The estimates for the research variables (BR, AR, and RES) have been consistently negative and not statistically significant. The development variables (PDD, PCD, and DEV) have positive and strong coefficients. However, the magnitude of the PDD estimates has increased and even surpassed that of PCD's. This outcome indicates that care must be exercised in interpreting the development estimates in equation (5.5), but does not change the fundamental conclusions about the positive and strong relationship between development and the firm's productivity growth.

No positive sign was found for the estimates of technical services. They were statistically significant with the frontier TFPs (TFP1 and CTFP1) as with the TFP measure used in Chapter 5. However, these estimates became statistically insignificant when TFP2, PTFP2 and SMTFP2 were regressed. This result appears to indicate further that, given the substantial amount of technical services performed during the last two decades, this activity has not contributed to the firm's long-term productivity growth regardless of whether or not the firm had operated at full capacity. In fact, the OLS, CV and GLS estimates of TS have never been both statistically significant and positive when it was regressed on TFP3, PTFP3 and SMTFP3 under all possible model specifications, either with R&D activities or by itself. Note that TFP3, PTFP3 and SMTFP3 include those years when the firms have operated below their plant capacity.

This additional evidence on the productivity impact of TS also may have practical importance. As described in Section 4.2 of Chapter 4, the sample firms have emphasized competition in their existing markets, and a substantial amount of technical services has been performed at the same time. This finding appears to indicate that the sample firms have over-emphasized the existing markets and the amount of technical services that has been performed was beyond the "optimal level." This indication in turn questions the corporate business and R&D strategies as those that have fostered the long-term productivity growth and have gained global competitiveness during the last two decades.

In summary, alternative estimates in equations (D.2) to (D.5) indicate that the selection criteria and line-fitting methods have not resulted in significantly different estimates from those in Chapter 5 as long as the negative TFP values are *not* selected.

D.2 Output Adjustments

The approaches of deriving a final TFP index described so far have been based on the original estimated TFP index. Alternatively, adjustments for capacity utilization can be made on the deflated output measure before it is used to derive the TFP index. One way to adjust the output measure for capacity utilization is to plot the real output series against time and then link two end-points of any trough. Thus, the real output is monotonically increasing. The corresponding adjustments can also be made on all inputs during those trough periods.

A second adjustment method is to "guess" the "best" production years for each firm based on the national business cycles–1972, 1979, and 1984 and so on. A straight line is then used to link the output levels of 1972 and 1979 and another line to link the production levels of 1979 and 1984. These two linked segments along with the original series between 1971 and 1972 and between 1984 and 1988 represent the "potential output levels" of the firm. A series of ratios are then calculated by dividing the actual output levels into those potential ones (as a capacity utilization index) and then used to adjust the input factors. This potential output measure and the adjusted input factors are then used to derive the TFP index.

The results of these two output adjusting methods are equivalent to drawing a straight line through those trough periods in the TFP derived without such adjustments because both input and output measures are adjusted upward by the same ratios. However, the linked points at both ends of the "trough" are not the highest points of the trough periods but are the mid-points. The advantage of these two methods is that only the deep trough periods in the TFP index are adjusted; the original TFP can be preserved in the analysis instead of the regression line. In many ways these methods are preferred when the estimation of the production frontier is not an issue. In the context of this study, however, these two methods may leave many negative TFP growth rates unadjusted. Those negative growth rates clearly indicate that the firm has operated below full capacity during those periods, and thus they should not be included in the analysis. Another disadvantage of such methods is that the potential output line may not be monotonically increasing when the firm divests its businesses. From the output measure, it is sometimes very difficult to distinguish the effects of "under utilization" from those of "divestiture."

The TFP indices adjusted by these two methods were used as the dependent variables in the estimation and analysis of model (3.12). The results were very disappointing. Despite the use of various specifications of the model, almost none of the estimates for the R&D components were statistically different from zero.

D.3 Averaging TFP Over Some Sub-periods

This approach first divides the 20-year period into some sub-periods and then averages the original TFP index and all R&D and technical services intensity ratios over each sub-period. These averaged variables are then entered into model (3.12) in various combinations.

In order to test the sensitivity of the regression estimates corresponding to different years that divide the sub-periods, various breaking points (years) have been tested with both a two-subperiod model and a three-subperiod model. In the two-subperiod regression runs, nine subperiod breaking years from 1974 to 1982 were tested. In the three-subperiod regression runs, there are two breaking points that divide the 20-year period into three subperiods. The first breaking point was tested from 1974 to 1979 and the second from 1980 to 1984. These breaking points produce a total of 25 (5×5) combinations of three-subperiods. Thus, the averaging approach yielded a total of 34 combinations of sub-periods (nine two-subperiods and 25 three-subperiods).

The specification of model (3.12) in some combinations of BR, AR, PDD, PCD, PDD, TS, RES, DEV, ARPCD, ARPDD, and ARDEV was estimated for each of the 34 subperiods. Of the large number of OLS estimates made, most were statistically insignificant. Of those significant estimates, most were from the two-subperiod models. The signs for basic research and technical services were negative but positive for the development and the sum of applied research and development efforts in most of these regressions. The statistical significance and the magnitude of these estimates were very sensitive to the subperiod breaking points. National business cycle years were not necessarily the best breaking points. Because this method includes the TFP in those years when the firm was operating at under-capacity utilization, it was not the appropriate approach to be used for frontier estimation.

D.4 Moving Average

The second method of deriving an average operational TFP measure is the moving average technique. Three moving-averaged TFP measures of two-period, three-period, and four-period have been constructed from the original TFP index. Each of them was then regressed on various combinations of BR, AR, PDD, PCD, TS, RES, DEV, and ARDEV. Almost all the regression coefficients (OLS, CV, GLS) of these R&D intensity variables were statistically insignificant.

D.5 Averaged TFP and R&D Variables

The third method of obtaining mean TFP measure is to average the original TFP index and all R&D intensity ratios over the entire 20 year period for each firm. Based on the suggestion from Section D.1 above, only those positive values of the index are included. Because the original TFP index represents the annual rates of productivity growth, the average TFP for each firm is the mean annual rate of TFP changes. This approach is another preferred one because it avoids both the problems of determining a sub-period dividing point and the criticism of using a secondary estimation method to derive the operational TFP measure. However, this method limits the total number of observations for the entire sample to 12, one for each firm.

The OLS estimates of equation (5.5) to (5.10) in Chapter 5 are:

$$\pi = 0.01 - 14.12BR + 0.43AR + 4.87PDD + 5.15PCD \tag{D.6}$$
$$(p)\ (0.60)\,(0.05)\quad (0.60)\quad (0.03)\quad (0.02)$$
$$R^2 = 0.66 \quad \bar{R}^2 = 0.46 \quad F = 3.38 \ (p=0.08)$$

$$\pi = 0.03 - 0.14RES + 2.98DEV. \tag{D.7}$$
$$(p)\ (0.26)\,(0.85)\quad (0.05)$$
$$R^2 = 0.37 \quad \bar{R}^2 = 0.21 \quad F = 2.50 \ (p=0.14)$$

$$\pi = 0.05 - 6.16BR + 1.22ARDEV. \tag{D.8}$$
$$(p)\ (0.06)\,(0.38)\quad (0.19)$$
$$R^2 = 0.19 \quad \bar{R}^2 = 0.01 \quad F = 1.05 \ (p=0.39)$$

$$\pi = 0.06 - 6.18BR + 1.23ARDEV - 1.38TS \tag{D.9}$$
$$(p)\ (0.06)\quad (0.40)\quad (0.19)\quad (0.45)$$
$$R^2 = 0.25 \quad \bar{R}^2 = -0.04 \quad F = 0.08 \ (p=0.50)$$

Despite the limited number of observations, these estimates are very consistent with those obtained in Chapter 5. Equations (D.7) and (D.8) are actually not necessary but listed here for reference. Equation (D.9) indicates the poor fit of the model. By comparing the R and F statistics with those of Equation

(D.7), the inclusion of the average TS variable does not improve the fit of the model at all. In fact, the *F* value decreases. This result further indicates that technical services have not contributed to the firm's productivity growth.

D.6 Deriving TFP Based on Both the Output Measure and Capacity Utilization Index

Those approaches above are based on either TFP or output alone. The sixth alternative would be to eliminate data points of the TFP index based on the growth rates of a estimated capacity utilization index. First, a series of growth rates of the real output of each firm was calculated. Second, the growth rates were compared with the growth rates of capacity utilization estimated for the chemical industry from the Wharton Econometric Forecast Associates. Finally, those data points of the TFP index were selected when the growth rates of the real output were both positive and greater than the growth rates of the capacity utilization index. However, the use of this operational TFP index as the dependent variable did not result in any meaningful and statistically significant estimates.

D.7 The Use of Capacity Utilization Indices

In this approach, the estimated capacity utilization for the chemical industry (SIC 28), obtained from the Wharton Econometric Forecast Associates, and the capacity utilization index estimated by the current study were used separately to either adjust the output, or to adjust the estimated tangible capital stock. All efforts of such adjustments were in vain, resulting in very disappointing estimated parameters. These outcomes were not surprising because of the problems associated with the capacity utilization measure. This analysis also raises questions about the accuracy of the capacity utilization indices estimated for the chemical industry and published by various organizations.

D.8 The Use of Selected Time Period

The seven approaches above were based on the entire 20-year period. Based on the overall national economic growth trend, the period from 1983 to 1988 can be regarded as a prospective one. Thus, the current study is limited to this six-year period and no adjustment was made to the TFP. Again, no statistically significant estimate was obtained despite various model specifications and the use of OLS and GLS estimators in addition to the CV estimator. To search for the cause of these disappointing results, the original TFP index of each firm was plotted against time. By comparing the TFP during and prior to this selected period, the TFP did not appear to have deep troughs as those prior to this period but it was not monotonically increasing either for most sample firms. This observation is also true for the TFP of the chemical industry estimated by the BLS from 1949 to 1986, and indicates that the economic prospective at the national level does not necessarily mean that an individual firm has operated at full capacity and followed the similar growth trend of the entire economy.

Appendix E
Correlation Analysis of the Selected Dependent Variables

Three selection criteria and two line fitting methods produce a total of eight dependent variables for this study. The relationship among these eight indices can be examined using the concept of Multi-trait Multi-methods Matrix (M-M Matrix) developed by Campbell and Fiske (1959). This preliminary analysis will help interpret the estimated results using these variables and provide useful information in assessing the sensitivity of these results because correlation analysis uses the same underlying statistical technique as regression. This appendix will briefly describe the M-M Matrix and present the M-M Matrix of these eight dependent variables.

Note that the purpose of this appendix is to examine the linear relationship among the eight variables due to difference in the selection criteria and fitting methods, using *some* of the features of the Matrix. No attempt is made to build a full M-M Matrix, and to use the matrix to examine validity issue of the eight variables.

E.1 The Multitrait Multimethod Matrix

The multitrait-multimethod matrix was designed by Campbell and Fiske[197] as a means to test the convergent validity across different methods of the same trait and divergent validity between methods of related but *conceptually distinct* traits. This method can be applied when two or more traits are being measured by two or more methods.

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[197] T. D. Campbell and D. W. Fiske: Convergent and Discriminant Validation by the MultiTrait-MultiMethod Matrix. *Psychological Bulletin*, Vol. 56, No. 2, 3/1959.

The Matrix is a correlation matrix with the main diagonal of 1.00 replaced by estimated reliability. Table E-1 maps the multitrait multimethod matrix structure of three traits by three methods. It consists of a mono-method block and a hetero-method block. The mono-method block contains the reliability diagonal (*R*), i.e. the mono-trait-mono-method values, and the hetero-trait-mono-method triangles (*M*) which are the correlation values of the same method for different traits. The hetero-method block has two parts: the validity diagonals (*V*) which are correlations of the same trait measured by different methods, and the heterotrait-heteromethod triangles ***(h)*** which are the correlations of different traits measured by different methods.

The *convergent validity* requires that the validity diagonals should be significantly different from zero and sufficiently larger. The *divergent validity* requires:

1. The values in the validity diagonals should be higher than values in it's row and column in the heterotrait-heteromethod triangle.
2. The values in the validity diagonals should be higher than corresponding values in the monomethod-heterotrait triangle.
3. Same pattern of trait interrelationship should be shown in all of the heterotrait triangles of both the monomethod and heteromethod blocks.

E.2 Correlation Analysis of the Selected Variables

Table E-2 is the Matrix calculated from those eight dependent variables. Three line-fitting techniques (original series, predicted [P], and smoothed [SM]) are treated as methods labelled vertically, and three selection criteria (the most restrictive [TFP1], the moderate [TFP2], and the most loose [TFP3]) as "traits"

Table E-1: Maps of the Multi-Trait Multi-Method Matrix

	Criterion 1			*Criterion 2*			*Criterion 3*		
Variables	*TFP1*	*PTFP1*	*SMTFP1*	*TPF2*	*PTFP2*	*SMTFP2*	*TFP3*	*PTFP3*	*SMTFP3*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
TFP1	**R**								
PTFP1	**M**	**R**							
SMTFP1	**M**	**M**	**R**						
TFP2	**V**	**h**	**h**	**R**					
PTFP2	**h**	**V**	**h**	**M**	**R**				
SMTFP2	**h**	**h**	**V**	**M**	**M**	**R**			
TFP3	**V**	**h**	**h**	**V**	**h**	**h**	**R**		
PTFP3	**h**	**V**	**h**	**h**	**V**	**h**	**M**	**R**	
SMTFP3	**h**	**h**	**V**	**h**	**h**	**V**	**M**	**M**	**R**

labelled horizontally in the table. Note that the smoothing method is not applied to TFP1 because it should be equivalent to PTFP1 which is used in Chapter 5.

From the Matrix E-2, the following observations can be made:

1. The three selected original TFP indices are perfectly correlated. This is because they are selected from the same index and the correlation coefficients in this Matrix are computed by the list-wise deletion of missing values, i.e, the sample size is limited to those observations that all these eight variables have valid values.

2. The correlation coefficients in the matrix are all statistically different from zero and are correlated fairly strong, particularly between selection 1 and 2, regardless of the line-fitting methods. This can be seen from the strong correlations in two mono-trait hetero-method triangles. This appears to indicate that the regression estimates will not be sensitive to the methods of line-fitting for a given TFP index.

3. No dominant correlation coefficients appear on the validity diagonals. Also, the values in the hetero-method hetero-trait blocks do not seem different significantly, especially for the first such block between the first selection criterion and the second. This analysis seems to signify that for the neighbor two set of variables, the regression estimates will not only be insensitive to method of fitting, but also insensitive to the selection criteria.

4. However, as the selection criteria relaxed, the correlations between pairs of these variables decrease. For example, the correlation coefficient between PTFP1 and PTFP2 is 0.9298 but it reduces to 0.7508 between PTFP1 and PTFP3. Especially, the smoothing technique has the most significant difference. For example, the correlation difference between PTFP1 and PTFP2 vs PTFP3 is 0.18 while it is 0.39 between TFP1 and SMTFP3 vs SMTFP3. The coefficients in the last line (correlation of SMTFP3 with others) are relatively

low. Therefore, if there is a difference in regression estimates, one can expect these differences most likely will be those regression estimates between the first selection criterion and the last one.

In summary, the MM Matrix is used both to investigate the relationship among the eight variables and to aid the sensitive analysis of regression estimates. It appears that (1) there is no significant difference between selection criteria one and two; (2) the line-fitting methods do not create much difference; (3) selection criterion three can be expected to have some difference in the final estimated results from those of criteria one and two. The MM Matrix analysis thus seems to suggest that selection criteria three be dropped from the final regression analysis. This analysis seems particularly useful here because it provides statistically the lower limit of the data selection criteria when actually many criteria and methods can be used to select various sets of dependent variables.

Table E-2: The Multi-Trait Multi-Method Matrix for This Study

		Criterion 1			*Criterion 2*			*Criterion 3*	
Variables	*TFP1*	*PTFP1*	*SMTFP1*	*TPF2*	*PTFP2*	*SMTFP2*	*TFP3*	*PTFP3*	*SMTFP3*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
TFP1	(1.0000)								
PTFP1	.9447	(1.0000)							
SMTFP1	(N/A)	(N/A)	(1.0000)						
TFP2	1.0000	.9447	(N/A)	(1.0000)					
PTFP2	.8673	.9298	(N/A)	.8673	(1.0000)				
SMTFP2	.8295	.986	(N/A)	.8295	.8512	(1.0000)			
TFP3	1.0000	.9447	(N/A)	1.0000	.8673	.8295	(1.0000)		
PTFP3	.6820	.7508	(N/A)	.6819	.7225	.7017	.6819	(1.0000)	
SMTFP3	.4429	.5127	(N/A)	.4429	.5206	.4948	.4429	.6515	(1.0000)

Appendix F
Statistical Inference

This appendix discusses the problems of statistical inference of the CV estimates, obtained in Chapter 5, beyond the current sample. Because these estimates are based on the basic assumptions of the classical normal linear regression model (normality of distribution, homogeneity of variance, and independence of observations), it is important to assess the bias and sampling error of the estimates computed from the current sample so that more accurate statistical inference can be made from these estimates. Such an assessment is also of importance because, as reviewed in Chapter 2, estimated results in the literature seem to be sample dependent.

F.1 The Classical Sampling Distribution

The basic task in statistical inference is to assess how close the estimated results ($\hat{\phi}$) are to the true parameters (ϕ). This assessment is usually made by a means of sampling distribution of the estimates ($F(\phi)$) which shows what the distribution of estimates would look like if one were to go on and on drawing samples from the same population and deriving from yet another estimate.

The main characteristics of the sampling distribution of the estimate (F) are location, spread and shape. First, the location of a distribution is the value of its mean (its expected value, $E[\hat{\phi}]$). An estimate of a parameter ($\hat{\phi}$) is said to be unbiased if $E[\hat{\phi}]$ is equal to ϕ. Second, the standard deviation of a sampling distribution is usually used to summarize its spread. By custom this is referred to as the standard error of the sampling distribution and symbolized as $SE(\hat{\phi})$. if $E(\hat{\phi}) = \phi$, $SE(\hat{\phi})$ also provides a measure of how closely the estimates are distributed about the "true" parameter value, ϕ. Finally, the shapes of some sampling distributions are described by relating them to other known distributions such as the normal, χ^2, or Binomial distributions. Skewness, Kurtosis and other properties can also be used to describe a sampling distribution.

The goodness of $\hat{\phi}$ as an estimate of ϕ can be inferred from these three main characteristics of the sampling distribution of the estimate. For example, if $F(\hat{\phi})$ is normal in shape, with $E(\hat{\phi}) = 0$ and $SE(\hat{\phi}) = 1.5$, it can be shown that 95% of the sample estimates, $\hat{\phi}_i$, will miss ϕ by no more than $\pm(1.96\times1.5)$. Typically, this argument can be inverted to establish a confidence interval for ϕ: one can have 95% confidence that ϕ lies in the interval $[\hat{\phi}\pm 1.96\times SE(\hat{\phi})]$.

Note that one's confidence about the characteristics of an estimate's sampling distribution is by making assumptions about the population from which the sample is drawn and about the way of sampling. Such assumptions may lead to an unknown magnitude of bias and sampling error in the estimates. The obvious way to avoid making these assumptions would be actually to create the sampling distribution by computing a series of $\hat{\phi}_i$'s. However, because of the limitations in time, efforts and financial support for re-sampling, such a practice is usually impossible. Therefore, there is a need of substituting computation for theoretical assumptions. The recent statistical technique, bootstrap, provides such an alternative.

F.2 The Bootstrap Sampling Distribution

Bootstrap is a recent development of statistical method. It was introduced by Bradley Efron[198] in 1979 and provides a new basis for making statistical

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[198] For references on the bootstrap method, see:
Efron, B. 1979. "Bootstrap Method: Another Look at the Jackknife." Journal of Statistics, 7.
Efron, B. 1986. "On Bootstrap Inference." American Education Research Association Annual Meeting, San Francisco.
Efron, B. 1987. "Better Bootstrap Confidence Intervals." Journal of American Statistical Association, 82, pp. 171-185.

inference from data which have been sampled from some larger population. Bootstrap method offers an alternative to classical and parametric inference. In particular, bootstrap can be used to assess the bias and sampling error of a statistic or of an estimate of a population parameter derived from a sample; to establish a confidence interval for an estimated parameter; and to compose and evaluate statistical test of hypotheses about one or more population parameters.[199]

The idea basic to the bootstrap is the bootstrap sample. Such a sample differs from an ordinary one in that the bootstrap sample is drawn from a known "population" (an ordinary sample), while the ordinary sample is drawn from an unknown population. A statistic or parameter estimate from the bootstrap sample is computed exactly the same way as that from a "real" sample (the classical sampling distribution). The resulting statistics are bootstrap statistics (ϕ^*) and their distributions are bootstrap sampling distributions ($\boldsymbol{F}^*(\phi^*)$). It has been shown statistically that for a wide range of (1) populations subject to random sampling, (2) parameters of those populations, (3) plans for obtaining samples, and (4) estimates derived from samples, at lease certain of the characteristics of the bootstrap sampling distribution, $\boldsymbol{F}^*$, will be close enough to those of the classical sampling distribution, $\boldsymbol{F}$, that the first may be used in place of the second (Efron, 1979, 1986, 1987).

The bootstrap sampling distribution, $\boldsymbol{F}^*$, may be similar to the classical sampling distribution, $\boldsymbol{F}$, in that both distributions are centered about their population parameters: $\boldsymbol{F}^*$ about $\hat{\phi}$ and $\boldsymbol{F}$ about ϕ. Conventionally, it is the bootstrap distribution $\boldsymbol{F}^*(\phi^* - \hat{\phi})$ that is compared to the sampling distribution

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[199] Lunneborg, C. E. 1987. Bootstrap Applications for the Behavior Science. WA: University of Washington.

$F(\hat{\phi} - \phi)$. In effect, the knowledge of F^* can be substituted for those of F when one or more aspects of the bootstrap conjecture above are correct. There is good evidence[200] that the standard error of the bootstrap sampling distribution (SE^*) provides a good estimate of the standard error of the classical sampling distribution, $SE(\hat{\phi})$, in nearly every setting and does so on the basis of about 100 bootstrap samples. The bootstrap statistics thus can be used to assess and adjust the confidence intervals of the estimates based on the classical sampling distribution.

The bootstrap method establishes three bootstrap confidence intervals (CI) according to different sampling distributions. First is the symmetric CI. If the bootstrap sampling distribution is unbiased and normal in shape, the CI can be developed based on the standard deviation of the sampling distribution. If the bootstrap sampling distribution is median unbiased, the percentile method CI can be used. Note that this CI method does not require the assumption of normality. The third CI adjusts for bias in the bootstrap sampling distribution when the bootstrap median is different from $\hat{\phi}$.

F.3 Bootstrap Estimates of the Current Sample

The bootstrap principle is applied in this study to provide an alternative basis for inference. Because of the constraints in the current computer program, bootstrap still maintains other assumptions of a classical normal linear regression model but makes no assumption about the shape of the error distribution of the parameter estimates for basic research (BR), applied research (AR), product development (PDD), process development (PCD) and technical

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[200] Efron, B. and Tibshirani, R. 1986. "Bootstrap Methods for Standard Errors, Confidence Intervals, and Other Measures of Statistical Accuracy." Statistical Science, 1, pp. 54-75.

services (TS). As shown above, the bootstrap sampling distribution can be considered to have the same characteristics as the classical sampling distribution.

Because of the limited features of the current version of the bootstrap computer program, only 15 variables and the maximum likelihood estimation technique are available. The panel data set used in Chapter 5 are thus modified so that the current bootstrap program can be used. Specifically, each variable was transformed as deviations from each firm's mean. This data transformation avoids the use of dummy variables so that the total number of variables does not excess 15. Because of the differences in the input data and the estimator, the estimated results here are different from those in Chapter 5. However, the fundamental conclusions about the productivity impact of each R&D activity are the same. Therefore, the analysis in this appendix can be extended to the estimates of Chapter 5.

The estimates of BR, AR, PDD, and PCD are obtained based on the model specification of Equation (5.5), and TS on Equation (5.10). For each estimate, $\hat{\phi}$, 1,000 bootstrap runs were made and 1,000 bootstrap estimates, ϕ^*s, were computed. From these bootstrap estimates, the letter-spreads[201] were calculated and reported, for each variable (R&D activity), in tables F-1 to F-5. The technical descriptions of these bootstrap processes can be found in Lunneborg (1987) in which both descriptive technical detail and program codes are given.

In these tables, letter-value spreads (LVS) are central ranges of values in a distribution obtained by trimming specific proportions from the upper and lower tails of the distribution. The advantage of LVS is that two statistical

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[201] Velleman, P.F., and Hoaglin, D. C. 1981. Applications, Basics, and Computing of Exploratory Data Analysis. Boston: Duxbury.

indices can be derived and used to indicate the shape of the distribution (skewness and kurtosis). The first LVS, "H," is that between the "hinges" of the distribution which are the first and third quartiles. They separate the middle 50% of the distribution from the lower and upper 25%. LVSs beyond that separating the hinges are defined successively halving the amount trimming from each tail of the distribution. Hence, LVS "E" contains the middle 75% of the distribution. The third "D" contains the middle 87.5%, and so on. The last LVS excludes only the one or two largest and smallest observations from the distribution. Finally, the largest and the smallest values in the distribution are reported.

From these LVSs, the sequence of mid-points and gauss estimates can be derived and used to assess the characteristics of the distribution. If the sampling distribution were symmetric, the mid-points of the several LVSs should all fall at about the same value. Otherwise, if the values of the mid-points become progressively smaller (or larger) as the LVSs widen out, this is evidence of a non-symmetric distribution. Increasing mid-points suggests positive skewness and decreasing mid-points are consistent with a negative skewness. The gauss measure, on the other hand, provides some evidence of the normality of the shape of the bootstrap distribution, at least where the distribution is symmetric. If the gauss values remain constant from one LVS to another, it indicates a normal distribution. if the estimates increases as the spreads become wider that is evidence of a platykurtic distribution, one flatter than normal. A decreasing gauss, by comparison, suggests a leptokurtic distribution, one more peaked than normal.

The first set of LVSs in each table is for the bootstrap sampling distribution of ϕ^* that is centering at $\hat{\phi}$. As indicated above, conventionally, one is interested in comparing the bootstrap distribution $F^*(\phi^* - \hat{\phi})$ with the sampling distribution $F(\hat{\phi} - \phi)$. The LVSs for such a bootstrap distribution centering at $F^*(\phi^* - \hat{\phi})$ are provided at the bottom of each table. The depth, spread, and gauss values are identical for the two sets of LVSs. Only the lower and upper values of the spreads and their mid-points are affected by the centering. If the bootstrap distribution were truly symmetric about $\hat{\phi}$, the mid-points of all the spreads would be zero and the lower and upper limits of each spread would equal but opposite in sign.

The gauss estimate, mid-points, and lower/upper limit values thus provide statistical evidence for evaluating those estimates obtained from the classical regression models and for selecting an appropriate method to construct confidence intervals for the estimates. The confidence intervals for the current estimates are shown in table F-6.

By examining the LVSs at the lower part of each table, one can see that all of the mid-points in all tables are slightly away from zero and the lower limits of the spreads are not exactly equal to the upper limits. These both are signs of a bootstrap distribution not centered exactly at the sample estimate. However, the magnitudes of differences are rather small, especially for the estimates of the development activities (PDD and PCD). These findings suggest that one can be reasonably well confident on the estimates obtained in this appendix and in Chapter 5. Nevertheless, these findings indicate that the classical confidence intervals for these estimates would be biased and require some statistical adjustment. As indicated earlier in this appendix, when the bootstrap sampling distribution is biased and not normal in shape, bias corrected percentile method should be used to construct the confidence intervals for the estimates. Table F-6 shows four confidence intervals, each at 90% and 95% confidence, for the estimate of each R&D activity.

Table F-1: Letter Value Spreads: Basic Research

```
BOOTLV: Letter Value Spreads From Bootstrap Trials: BR

Number of Trials to Be Read:  1,000

Estimator = -5.2265
Mean      = -5.3929
S.D.      =  6.1250
Median    =  5.5475

   DEPTH        LOWER         UPPER    WIDTH        MID          SPREAD       GAUSS
H 250.50    -.9818E+01   -.1311E+01  50.00    -.5565E+01   .8506E+01   .6306E+01
E 125.50    -.1223E+02    .1874E+01  75.00    -.5176E+01   .1410E+02   .6128E+01
D  63.00    -.1442E+02    .4113E+01  87.50    -.5154E+01   .1854E+02   .6041E+01
C  32.00    -.1639E+02    .6323E+01  93.70    -.5031E+01   .2271E+02   .6094E+01
B  16.50    -.1873E+02    .8850E+01  96.80    -.4938E+01   .2758E+02   .6401E+01
A   8.50    -.2019E+02    .9976E+01  98.40    -.5108E+01   .3017E+02   .6239E+01
Z   4.50    -.2185E+02    .1173E+02  99.20    -.5061E+01   .3357E+02   .6311E+01
Y   2.50    -.2360E+02    .1219E+02  99.60    -.5705E+01   .3578E+02   .0000E+00
X   1.50    -.2450E+02    .1302E+02  99.80    -.5740E+01   .3753E+02   .0000E+00
    1       -.2453E+02    .1383E+02           -.5349E+01   .3836E+02


   DEPTH        LOWER         UPPER    WIDTH        MID          SPREAD       GAUSS
H 250.50    -.4591E+01    .3915E+01  50.00    -.3380E+00   .8506E+01   .6306E+01
E 125.50    -.7000E+01    .7101E+01  75.00     .5010E-01   .1410E+02   .6128E+01
D  63.00    -.9195E+01    .9340E+01  87.50     .7205E-01   .1854E+02   .6041E+01
C  32.00    -.1116E+02    .1155E+02  93.70     .1952E+00   .2271E+02   .6094E+01
B  16.50    -.1350E+02    .1408E+02  96.80     .2881E+00   .2758E+02   .6401E+01
A   8.50    -.1497E+02    .1520E+02  98.40     .1182E+00   .3017E+02   .6239E+01
Z   4.50    -.1662E+02    .1695E+02  99.20     .1650E+00   .3357E+02   .6311E+01
Y   2.50    -.1837E+02    .1741E+02  99.60    -.4780E+00   .3578E+02   .0000E+00
X   1.50    -.1928E+02    .1825E+02  99.80    -.5138E+00   .3753E+02   .0000E+00
    1       -.2453E+02    .1383E+02           -.5349E+01   .3836E+02
```

Technical Notes:

1. Computer program (BOOTLV) was written by Prof. C.E. Lunneborg, University of Washington, Seattle.

2. In the 1000 Bootstrap runs (REGBOOT), raw residuals were used and the option of "no evidence of singular matrix" was selected.

Table F-2: Letter Value Spreads: Applied Research

```
BOOTLV: Letter Value Spreads From Bootstrap Trials: AR

Number of Trials to Be Read:  1,000

Estimator = -0.7718
Mean      = -0.7688
S.D.      =  0.7536
Median    =  0.7706

   DEPTH        LOWER          UPPER     WIDTH        MID           SPREAD          GAUSS
H 250.50    -.1271E+01    -.2487E+00 50.00    -.7599E+00     .1022E+01      .7579E+00
E 125.50    -.1631E+01     .1106E+00 75.00    -.7602E+00     .1742E+01      .7569E+00
D   63.00   -.1979E+01     .3437E+00 87.50    -.8176E+00     .2323E+01      .7570E+00
C   32.00   -.2193E+01     .6989E+00 93.70    -.7469E+00     .2891E+01      .7760E+00
B   16.50   -.2376E+01     .8590E+00 96.80    -.7584E+00     .3235E+01      .7509E+00
A    8.50   -.2501E+01     .1060E+01 98.40    -.7207E+00     .3561E+01      .7364E+00
Z    4.50   -.2586E+01     .1229E+01 99.20    -.6783E+00     .3815E+01      .7171E+00
Y    2.50   -.2729E+01     .1499E+01 99.60    -.6150E+00     .4228E+01      .0000E+00
X    1.50   -.2871E+01     .1540E+01 99.80    -.6655E+00     .4411E+01      .0000E+00
     1      -.2951E+01     .1579E+01          -.6857E+00     .4530E+01


   DEPTH        LOWER          UPPER     WIDTH        MID           SPREAD          GAUSS
H 250.50    -.4993E+00     .5231E+00 50.00      .1190E-01     .1022E+01      .7579E+00
E 125.50    -.8593E+00     .8824E+00 75.00      .1156E-01     .1742E+01      .7569E+00
D   63.00   -.1207E+01     .1115E+01 87.50    -.4583E-01     .2323E+01      .7570E+00
C   32.00   -.1421E+01     .1471E+01 93.70      .2490E-01     .2891E+01      .7760E+00
B   16.50   -.1604E+01     .1631E+01 96.80      .1336E-01     .3235E+01      .7509E+00
A    8.50   -.1730E+01     .1832E+01 98.40      .5102E-01     .3561E+01      .7364E+00
Z    4.50   -.1814E+01     .2001E+01 99.20      .9345E-01     .3815E+01      .7171E+00
Y    2.50   -.1957E+01     .2271E+01 99.60      .1568E+00     .4228E+01      .0000E+00
X    1.50   -.2099E+01     .2312E+01 99.80      .1062E+00     .4411E+01      .0000E+00
```

Table F-3: Letter Value Spreads: Product Development

```
BOOTLV: Letter Value Spreads From Bootstrap Trials: PDD

Number of Trials to Be Read:  1,000

Estimator = 1.1100
Mean      = 1.1120
S.D.      = 0.7753
Median    = 1.1225

    DEPTH        LOWER          UPPER    WIDTH        MID          SPREAD        GAUSS
H 250.50      .5957E+00     .1612E+01  50.00     .1104E+01     .1017E+01     .7536E+00
E 125.50      .2445E+00     .2005E+01  75.00     .1125E+01     .1760E+01     .7651E+00
D   63.00    -.8476E-01     .2302E+01  87.50     .1109E+01     .2387E+01     .7779E+00
C   32.00    -.3331E+00     .2546E+01  93.70     .1107E+01     .2879E+01     .7727E+00
B   16.50    -.5760E+00     .2788E+01  96.80     .1106E+01     .3364E+01     .7808E+00
A    8.50    -.8228E+00     .2974E+01  98.40     .1076E+01     .3797E+01     .7852E+00
Z    4.50    -.1016E+01     .3212E+01  99.20     .1098E+01     .4227E+01     .7946E+00
Y    2.50    -.1225E+01     .3475E+01  99.60     .1125E+01     .4700E+01     .0000E+00
X    1.50    -.1548E+01     .3794E+01  99.80     .1123E+01     .5342E+01     .0000E+00
     1       -.1704E+01     .3989E+01            .1142E+01     .5693E+01

    DEPTH        LOWER          UPPER    WIDTH        MID          SPREAD        GAUSS
H 250.50     -.5138E+00     .5028E+00  50.00    -.5523E-02     .1017E+01     .7536E+00
E 125.50     -.8650E+00     .8954E+00  75.00     .1524E-01     .1760E+01     .7651E+00
D   63.00    -.1194E+01     .1192E+01  87.50    -.9820E-03     .2387E+01     .7779E+00
C   32.00    -.1443E+01     .1437E+01  93.70    -.2930E-02     .2879E+01     .7727E+00
B   16.50    -.1686E+01     .1678E+01  96.80    -.3710E-02     .3364E+01     .7808E+00
A    8.50    -.1932E+01     .1865E+01  98.40    -.3371E-01     .3797E+01     .7852E+00
Z    4.50    -.2125E+01     .2102E+01  99.20    -.1151E-01     .4227E+01     .7946E+00
Y    2.50    -.2335E+01     .2365E+01  99.60     .1537E-01     .4700E+01     .0000E+00
X    1.50    -.2658E+01     .2685E+01  99.80     .1350E-01     .5342E+01     .0000E+00
     1       -.1704E+01     .3989E+01            .1142E+01     .5693E+01
```

Table F-4: Letter Value Spreads: Process Development

```
BOOTLV: Letter Value Spreads From Bootstrap Trials: PCD

Number of Trials to Be Read:  1,000

Estimator = 3.0388
Mean      = 3.0618
S.D.      = 1.6296
Median    = 3.0849

   DEPTH      LOWER        UPPER     WIDTH       MID         SPREAD       GAUSS
H 250.50    .1989E+01    .4117E+01  50.00    .3053E+01    .2128E+01    .1578E+01
E 125.50    .1264E+01    .4897E+01  75.00    .3080E+01    .3633E+01    .1579E+01
D   63.00   .7061E+00    .5578E+01  87.50    .3142E+01    .4872E+01    .1588E+01
C   32.00   .9430E-01    .5996E+01  93.70    .3045E+01    .5902E+01    .1584E+01
B   16.50  -.6211E+00    .6666E+01  96.80    .3022E+01    .7287E+01    .1692E+01
A    8.50  -.1113E+01    .7234E+01  98.40    .3061E+01    .8348E+01    .1726E+01
Z    4.50  -.1749E+01    .7643E+01  99.20    .2947E+01    .9392E+01    .1765E+01
Y    2.50  -.2262E+01    .7834E+01  99.60    .2786E+01    .1010E+02    .0000E+00
X    1.50  -.3382E+01    .8533E+01  99.80    .2575E+01    .1192E+02    .0000E+00
     1     -.4421E+01    .9138E+01           .2358E+01    .1356E+02

   DEPTH      LOWER        UPPER     WIDTH       MID         SPREAD       GAUSS
H 250.50   -.1050E+01    .1078E+01  50.00    .1425E-01    .2128E+01    .1578E+01
E 125.50   -.1775E+01    .1858E+01  75.00    .4168E-01    .3633E+01    .1579E+01
D   63.00  -.2333E+01    .2539E+01  87.50    .1033E+00    .4872E+01    .1588E+01
C   32.00  -.2945E+01    .2957E+01  93.70    .6248E-02    .5902E+01    .1584E+01
B   16.50  -.3660E+01    .3627E+01  96.80   -.1637E-01    .7287E+01    .1692E+01
A    8.50  -.4152E+01    .4196E+01  98.40    .2187E-01    .8348E+01    .1726E+01
Z    4.50  -.4788E+01    .4604E+01  99.20   -.9192E-01    .9392E+01    .1765E+01
Y    2.50  -.5301E+01    .4795E+01  99.60   -.2531E+00    .1010E+02    .0000E+00
X    1.50  -.6421E+01    .5494E+01  99.80   -.4634E+00    .1192E+02    .0000E+00
     1     -.4421E+01    .9138E+01           .2358E+01    .1356E+02
```

Table F-5: Letter Value Spreads: Technical Services

```
BOOTLV: Letter Value Spreads From Bootstrap Trials: TS

Number of Trials to Be Read:  1,000

Estimator = -3.3608
Mean      = -3.4476
S.D.      =  1.5728
Median    = -3.4408

   DEPTH       LOWER         UPPER     WIDTH       MID          SPREAD       GAUSS
H 250.50   -.4475E+01   -.2484E+01 50.00   -.3479E+01    .1991E+01    .1476E+01
E 125.50   -.5175E+01   -.1783E+01 75.00   -.3479E+01    .3392E+01    .1474E+01
D   63.00  -.5844E+01   -.9789E+00 87.50   -.3411E+01    .4865E+01    .1586E+01
C   32.00  -.6410E+01   -.3401E+00 93.70   -.3375E+01    .6070E+01    .1629E+01
B   16.50  -.6951E+01    .8859E-01 96.80   -.3431E+01    .7040E+01    .1634E+01
A    8.50  -.7351E+01    .5176E+00 98.40   -.3417E+01    .7869E+01    .1627E+01
Z    4.50  -.7701E+01    .7865E+00 99.20   -.3457E+01    .8487E+01    .1595E+01
Y    2.50  -.8576E+01    .1464E+01 99.60   -.3556E+01    .1004E+02    .0000E+00
X    1.50  -.9225E+01    .2243E+01 99.80   -.3491E+01    .1147E+02    .0000E+00
     1     -.9640E+01    .2700E+01         -.3470E+01    .1234E+02


   DEPTH       LOWER         UPPER     WIDTH       MID          SPREAD       GAUSS
H 250.50   -.1114E+01    .8770E+00 50.00   -.1184E+00    .1991E+01    .1476E+01
E 125.50   -.1814E+01    .1578E+01 75.00   -.1180E+00    .3392E+01    .1474E+01
D   63.00  -.2483E+01    .2382E+01 87.50   -.5062E-01    .4865E+01    .1586E+01
C   32.00  -.3049E+01    .3021E+01 93.70   -.1422E-01    .6070E+01    .1629E+01
B   16.50  -.3591E+01    .3449E+01 96.80   -.7058E-01    .7040E+01    .1634E+01
A    8.50  -.3990E+01    .3878E+01 98.40   -.5589E-01    .7869E+01    .1627E+01
Z    4.50  -.4340E+01    .4147E+01 99.20   -.9623E-01    .8487E+01    .1595E+01
Y    2.50  -.5215E+01    .4825E+01 99.60   -.1952E+00    .1004E+02    .0000E+00
X    1.50  -.5864E+01    .5604E+01 99.80   -.1302E+00    .1147E+02    .0000E+00
     1     -.9640E+01    .2700E+01         -.3470E+01    .1234E+02
```

Table F-6: Confidence Intervals From Bootstrap Trials

Limits	*Basic Research*		*Applied Research*		*Product Develop.*		*Process Develop.*		*Technical Services*	
	90%	*95%*	*90%*	*95%*	*90%*	*95%*	*90%*	*95%*	*90%*	*95%*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*
Symmetric (Normal Theory) C. I.										
Lower Bound	-15.3200	-17.2520	-2.0137	-2.2514	-.1681	-.4127	.3534	-.1607	-5.9526	-6.4487
Estimator	-5.2265	-5.2265	-.7718	-.7718	1.1110	1.1110	3.0388	3.0388	-3.3608	-3.3608
Upper Bound	4.867	6.7989	.4702	.7079	2.3871	2.6317	5.7242	6.2383	-.7690	-.2729
Percentile Method C. I.										
Lower Bound	-14.9610	-17.5190	-2.036	-2.2232	-.1755	-.4028	.4899	-.2546	6.0354	-6.5815
Estimator	-5.2265	-5.2265	-.7718	-.7718	1.1110	1.1110	3.0388	3.0388	-3.3608	-3.3608
Upper Bound	4.9556	7.1722	.4288	.7371	2.3866	2.6152	5.6946	6.2342	-.7350	-.1829
Bias Corrected Percentile C. I.										
Lower Bound	-14.710	-16.9190	-2.042	-2.2322	-.2122	-.4926	.3643	-.3829	-5.9164	-6.414
Estimator	-5.2265	-5.2265	-.7718	-.7718	1.1110	1.1110	3.0388	3.0388	-3.3608	-3.3608
Upper Bound	4.9556	7.7042	.4235	.7371	2.3455	2.5734	5.6400	6.0649	-.5413	-.3575

Note

- Number of Bootstrap trials = 1,000
- Computer program (BOOTCI) was written by Prof. C. E. Lunneborg, University of Washington, Seattle.

Appendix G
The NSF/IRI/CIMS Survey

This appendix is extracted from the questionnaire of the 1988 NSF/IRI/CIMS Survey of R&D Organization and Funding, covering those topics that have been discussed in Chapter 3 and Chapter 4. The entire copy of this survey questionnaire is available from the Center for Innovation Management Studies, Lehigh University, Bethlehem, Pennsylvania.

Questionnaire A

R&D Organization and Funding:
Interactions of Industrial and University Laboratories

Introduction

The Industrial Research Institute (IRI) is working with the National Science Foundation to develop a perspective on emerging patterns of industrial R&D activity that may carry into the 1990s. The Research-on-Research Committee of the IRI and the Center for Innovation Management Studies at Lehigh University have developed the questionnaires for the study. They are based, in part, on previous studies initiated by the ROR Committee and supplemented by new questions drawn up by the National Science Foundation. The project has been reviewed and approved by the Executive Committee of the IRI Board of Directors. To maximize its value to the NSF, the questionnaires must be returned to Lehigh by May 18, 1988. We look forward to your full and timely participation.

Definitions

The questionnaires frequently refer to a spectrum of industrial R&D activities ranging from basic research to technical service. The official National Science Foundation definitions of these activities are intended to apply throughout the questionnaire. These definitions are:

> *Research and Development:* Basic and applied research in the sciences and engineering, and the design and development of prototypes and processes. This definition excludes quality control, routine product testing, market research, sales promotion, sales service, research in the social sciences or psychology, and other nontechnological activities or technical services.
>
> *Basic Research:* Original investigations for the advancement of scientific knowledge not having specific commercial objectives, although such investigations may be in fields of present or potential interest to the reporting company.
>
> *Applied Research:* Investigations directed to the discovery of new scientific knowledge having specific commercial objectives with respect to products or processes. This definition differs from that of basic research chiefly in terms of the objectives of the reporting company.
>
> *Development:* Technical activities of a nonroutine nature concerned with translating research findings or other scientific knowledge into products or processes. Does not include routine technical service to customers or other activities excluded from the above definition of research and development.

Definitions of other terms are introduced throughout the questionnaire as appropriate. Please read the questionnaire carefully before proceeding. Refer any questions about procedures or terminology to the Center for Innovation Management Studies, (215) 758-3427.

2. In general, how would you characterize the overall scope of the R&D programs and activities of your firm?

This firm's R&D activities can be best described as:

_______ 1. Highly focused, covering only those technologies that are relevant to our current businesses.

_______ 2. Moderately focused, covering our core technologies plus some monitoring of technology outside these areas.

_______ 3. Moderately diversified, covering our core technologies, with solid competence in other selected areas.

_______ 4. Highly diversified, covering a broad spectrum of scientific and engineering disciplines of current and potential interest to the company.

R&D Emphasis and Trends

This section deals with the types of research and business issues addressed by the firm's R&D activities. The NSF definition of R&D includes basic research, applied research, and product and process design, development, and engineering. The term "total technical effort" includes these NSF-defined R&D activities plus any additional technical support work that you consider to be part of the firm's R&D function.

1. Approximately what percentage of your firm's total technical effort last year was allocated to the following activities?

	N/A	0%	1–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80	81–90	91–100%
·Basic research	___	___	___	___	___	___	___	___	___	___	___	___
Applied research	___	___	___	___	___	___	___	___	___	___	___	___
Product design, development and engrg.	___	___	___	___	___	___	___	___	___	___	___	___
Process design, development and engrg.	___	___	___	___	___	___	___	___	___	___	___	___
Technical service	___	___	___	___	___	___	___	___	___	___	___	___

2. During the 1980s, has the percentage of your firm's total technical effort allocated to these activities changed significantly?

	N/A	Significantly Reduced			No Change			Significantly Increased
Basic research	___	___	___	___	___	___	___	___
Applied research	___	___	___	___	___	___	___	___
Product design, development and engrg.	___	___	___	___	___	___	___	___
Process design, development and engrg.	___	___	___	___	___	___	___	___
Technical service	___	___	___	___	___	___	___	___

4. During the 1970s and 1980s, to what extent did the corporation emphasize:

	N/A	Nil	Minimal		Moderate		Strong		Very Strong
a. Basic research									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
b. Applied research									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
c. Acquisition of technical knowledge from outside the firm									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7

	N/A	Nil	Minimal		Moderate		Strong		Very Strong
d. Being a product leader									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
e. Being a process leader									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
f. Following trends									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
g. Opening new market areas									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
h. Competing in existing market areas									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
i. Anticipating government regulations									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
j. Complying with government regulations									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
k. Focused research									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7
l. Discretionary research									
in the 1970s	N/A	0	1	2	3	4	5	6	7
in the 1980s	N/A	0	1	2	3	4	5	6	7

Business Goals

This question deals with a number of representative business goals associated with your R&D programs and projects. The relevant definitions are:

Contribution: the firm wide contribution to a specific business goal that was expected and realized from R&D performed in the firm during the 1980–87 period.
Project initiation: the time at which resources are first allocated to the project.

1. *Sales volume:* increasing the sales volume, maintaining a certain level of sales, etc.

		Nil	Minimal		Moderate		High		Very High
a.	The importance of sales volume as a corporate goal during the 1980–87 period was:	0	1	2	3	4	5	6	7
b.	The expected contribution to sales volume by R&D during 1980–87 was:	0	1	2	3	4	5	6	7
c.	The realized contribution was:	0	1	2	3	4	5	6	7

d. Over the 1980–87 period, the importance of sales volume as a factor in decisions to initiate R&D projects:

Decreased Significantly			Did not Change			Increased Significantly
–3	–2	–1	0	+1	+2	+3

2. *Product cost:* reducing product costs, minimizing cost increases, etc.

		Nil	Minimal		Moderate		High		Very High
a.	The importance of product cost as a corporate goal during the 1980–87 period was:	0	1	2	3	4	5	6	7
b.	The expected contribution to product cost by R&D during 1980–87 was:	0	1	2	3	4	5	6	7
c.	The realized contribution was:	0	1	2	3	4	5	6	7

d. Over the 1980–87 period, the importance of product cost as a factor in decisions to initiate R&D projects:

Decreased Significantly			Did not Change			Increased Significantly
–3	–2	–1	0	+1	+2	+3

3. *Profitability:* increased profit, protection of a threatened profit position, etc.

	Nil	Minimal		Moderate		High		Very High
a. The importance of profitability as a goal during the 1980–87 period was:	0	1	2	3	4	5	6	7
b. The expected contribution to profitability by R&D during 1980–87 was:	0	1	2	3	4	5	6	7
c. The realized contribution was:	0	1	2	3	4	5	6	7

d. Over the 1980–87 period, the importance of profitability as a factor in decisions to initiate R&D projects:

Decreased Significantly			Did not Change			Increased Significantly
−3	−2	−1	0	+1	+2	+3

4. *Government policy position:* respond to or anticipate a regulation, standard, or legal ruling, seek federal funding, etc.

	Nil	Minimal		Moderate		High		Very High
a. The importance of government policy position as a goal during the 1980–87 period was:	0	1	2	3	4	5	6	7
b. The expected contribution to government policy position by R&D during 1980–87 was:	0	1	2	3	4	5	6	7
c. The realized contribution was:	0	1	2	3	4	5	6	7

d. Over the 1980–87 period, the importance of government policy position as a factor in decisions to initiate R&D projects:

Decreased Significantly			Did not Change			Increased Significantly
−3	−2	−1	0	+1	+2	+3

5. *Competitive position:* get ahead of competitors, stay even with competitors, catch up with competitors, etc.

	Nil	Minimal		Moderate		High		Very High
a. The importance of competitive position as a goal during the 1980–87 period was:	0	1	2	3	4	5	6	7
b. The expected contribution to competitive position by R&D during 1980–87 was:	0	1	2	3	4	5	6	7
c. The realized contribution was:	0	1	2	3	4	5	6	7

d. Over the 1980–87 period, the importance of competitive position as a factor in decisions to initiate R&D projects:

Decreased Significantly			Did not Change			Increased Significantly
−3	−2	−1	0	+1	+2	+3

6. *Market positioning:* establish a new market area, increase an existing market area or share, consolidate a fragmented market, etc.

	Nil	Minimal		Moderate		High		Very High
a. The importance of market positioning as a goal during the 1980–87 period was:	0	1	2	3	4	5	6	7
b. The expected contribution to market positioning by R&D during 1980–87 was:	0	1	2	3	4	5	6	7
c. The realized contribution was:	0	1	2	3	4	5	6	7

d. Over the 1980–87 period, the importance of market positioning as a factor in decisions to initiate R&D projects:

Decreased Significantly			Did not Change			Increased Significantly
−3	−2	−1	0	+1	+2	+3

II. Funding of University Research

This section seeks information about your firm's support of university research. The National Science Foundation's research definitions apply, as referenced in the introduction to this questionnaire.

1. Approximately what percentage of your firm's basic or applied research is now performed by university scientists, engineers and graduate students?

	None	<10%	11–25	26–50	51–75	>75%
Basic research	___	___	___	___	___	___
Applied research	___	___	___	___	___	___

2. To what extent has this percentage changed in the 1980s?

	N/A	Reduced Significantly			No Change			Increased Significantly
Basic research	___	___	___	___	___	___	___	___
Applied research	___	___	___	___	___	___	___	___

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Technical Notes on Processing This Dissertation:
This dissertation was formated in Scribe System 7(1700), a documentation production software by UNILOGIC, Ltd. and printed in PrintServer 40, a mainframe printer at the Lehigh University Computing Center, using the font family of "New-Century-School-Book" (11-point for the normal text).

There are about 57,900 words (8,764 EMACS-lines) in this dissertation.