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A Review of the Literature on R&D and Productivity

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Abstract

This paper reviews the literature on R&D and productivity to provide a guideline to readers by combining all the findings in one title. According to the results, empirical studies analyse R&D spending from different angles by considering the characteristic of such spending. The results show that return to basic research is higher than return to applied R&D. Furthermore, in order to estimate the R&D elasticity in a more accurate way, double counting issues should be fixed. Evidence from earlier studies have shown that R&D input is double counted if labour and physical capital are not separated from labour and capital inputs. Empirical studies also show that returns to public funded R&D are lower than returns to firm financed R&D. There are two reasons behind this differentiation. First, government funded R&D might not be correlated with productivity because of its development nature. Second, the relation between public financed R&D and productivity might be indirect, such as it may increase the efficiency of private returns, leading productivity growth. Another point is the link between a reduction on R&D spending and the 1970s oil crisis. The correlation is most prominent for sectors such as chemical and petroleum refining due to the intensiveness of R&D operations in these sectors. Finally, empirical studies are consistent not only at the firm level but also at the industry level.

1 Introduction

Investment in research and development (R&D) is an indicator that clearly shows technological advancement. These advancements lead to higher productivity and consequently higher economic growth and higher living standards. Firms that invest in R&D also see a significant increase in sales. A multitude of studies have shown the positive relationship between R&D and productivity. In fact, R&D investments tend to provide a rate of return between 10 and 15 percent, sometimes even higher. Compared to capital investments, R&D investments are riskier, yet it has the potential to generate higher returns, increasing a firm's productivity and market value. For instance, a 1992 study (Evaluation of the BRITE/EURAM Programme, 1989-1992) of 196 EU-funded R&D projects found that companies as well as universities and research institutes that partnered with such firms had an additional return of approximately €650 million – €366 million in additional turnover; €278 million from increased efficiency, and about €6 million from technology transfers.

Given the importance of investment in research and development, it is important to investigate the relationship between R&D expenditures and productivity growth. The literature shows that there is a positive correlation between numerous proxies for innovation such as R&D employment and expenditure, and patents and productivity growth. These findings appear to hold at various levels of aggregation and econometric specifications (Link & Siegel, 2007, pp. 36-37). This paper, therefore, conducts a review of the literature on the relationship between R&D spending and productivity growth. It aims to identify the consistency of such literature and its drawbacks and significance. The questions guiding this research as well as its aims are discussed below in the following section.

1.1 Research Aim

The aim of this paper is to investigate the relationship between R&D and productivity growth. There is a vast literature on the relationship between R&D and productivity. This literature first appeared in the late 1940s and early 1950s. Yet, there are few studies that compile and review the existing literature, particularly on empirical studies. Thus, by reviewing and compiling the main body of work on the topic, it is possible to provide a solid foundation on the relationship between R&D spending and productivity growth and identify inconsistencies, weaknesses, and theoretical and methodological conflicts in the literature. This paper also serves as the foundation for my second-year master thesis, where I will carry out an empirical study based on the findings and gaps on the literature identified in this paper.

The few reviews of the literature found to date tend to focus mostly on the rate of return to research and development spending, either at the firm level or at the industry level. For this reason, this paper analyses studies at both firm and industry level in order to identify similarities as well as differences between them. The study also investigates the methodology and models used in empirical studies, paying particular attention to models using the Cobb-Douglas production function. It additionally identifies measurement and other data problems as well as possible solutions to obstacles encountered by scholars while carrying out these studies.

Therefore, the study will answer the following questions:

- Which statistical models have been used throughout the literature?

- What are the differences between time-series and cross-sectional studies and how do they affect the results?
- What kind of problems researchers have faced, and what are the possible solutions to these problems?
- Which variables are strongly correlated with productivity growth, and how do they affect the total rate of return to R&D? and
- How consistent are the findings?

Hence, by analysing the empirical literature, the paper will first identify whether these studies are consistent. The method used to carry out this study is discussed below in the method section.

1.2 Method

Since the main purpose of this paper is to examine studies related to R&D spending and its impact on productivity growth, the method used is research review. According to Hakim (2000), research reviews are a broad overview of the relevant literature. In other words, it is a thorough summary or a comprehensive survey of the existing academic literature on a specific topic. The rationale is to describe, summarize, clarify, and evaluate previous studies on the correlation between research and development investment and productivity growth. There are two kinds of research reviews, methodological research reviews and policy-oriented research review. According to Hakim (2000), methodological research reviews have a particular emphasis on describing the strengths and weaknesses of studies' research questions. Policy-oriented research reviews, on the other hand, summarize current knowledge based on their policy implications. It requires in depth knowledge of current policy debates and can be used by stakeholders in general as well as interest groups (Hakim, 2000). Literature review provides a means to identifies the weaknesses and strengths of existing research on a specific topic.

During the research phase for this paper, several studies have been analysed in order to select the most relevant ones for a comprehensive review and comparative analysis of the impact of R&D spending on productivity growth. Once the selection process was completed, the selected studies were divided into two group. One group encompasses empirical studies that are based on data at the industry level while the other includes studies that were based on data at the firm level. Each group was then analysed paying close attention to sample selection, methods used and relevant findings.

1.3 Outline of Thesis

The thesis is structured along five chapters. Chapter 2 presents the methodological and theoretical background. The chapter discusses the definition of R&D used in this paper as well as the different types of R&D activities, namely basic research, applied research and experimental development research. It also explores the forms of R&D funding – as public versus private funding – how they vary across sectors of the economy, and how different forms of funding affect productivity growth. In relation to the methodologies employed in previous empirical studies, the chapter explores the two main approaches used to estimate the effect of R&D spending on productivity growth – the production function and the cost function.

Chapter 3, in turn, reviews the measurement issues encountered by scholars when estimating the relationship between R&D spending and productivity growth. The chapter is divided into three parts; part one examines the statistical models used in the literature. This is followed by a discussion of the issues associated with measuring output, and finally, by a discussion of the problems associated with measuring R&D capital. After examining the various issues researchers have come across during their studies, the paper focuses on the Cobb-Douglas function, mainly because there are several studies whose models are based on the Cobb-Douglas production function or on a variation of it.

Chapter 4 examines a number of empirical studies, both at firm level and at the industry level. Attention is paid to a set of characteristics, such as sample selection and sample size, and whether studies are based on firm or industry level data; it also looks at the main findings and conclusions of such studies. The chapter further examines R&D elasticities at both industry and firm level and discusses the differences between estimation based on time-series and cross-sectional models. Finally, chapter 5 reviews and summarizes the main conclusions of the thesis and offers insights on the implications for future research on R&D spending and productivity growth.

2 Review of the Literature

This chapter is divided into two sections. The first section presents the definition of R&D used in this thesis. It also provides an overview of the different types of activities in which we can classify research and development spending. This is followed by a discussion of the two main approaches – production function and cost function – used throughout the literature to estimate the relationship between R&D spending and productivity growth.

2.1 Theoretical Background

Research and development (R&D) have an important place in a product’s life cycle. Science, especially basic science, must exist to support a product’s utility; if the science is missing, it must be discovered. The process of discovery is called research phase. On the other hand, if the science exists, it should be turned into a useful product or process. This process is called development phase. Research and development should be considered an investment in a firm’s or country’s future. If firms do not spend efficiently in R&D, their current product lines will become obsolete and they will, most likely, be overtaken by competitors. Therefore, spending sufficiently on research and development is essential to the continued growth of a company as well as of a country.

While research and development can be broadly defined as an activity that companies and public and private institutions undertake to create new products, introduce new services, or advance new knowledge, the definition used in this paper follows the Organisation for Economic Co-operation and Development’s (OECD) Frascati Manual (2015). As put by the Frascati Manual (2015, p. 44), “research and experimental development (R&D) comprise creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge.” Such definition was chosen due to its longevity and consistency. According to the Frascati Manual (2015, p. 44), their definition of R&D has been virtually unchanged over the past five decades, proving its constancy over time.
R&D can be further classified according to three types of activities. According to the OECD Frascati Manual (2015, p. 29) and the Code Section 41 of the Internal Revenue Service (Research and Experimentation Tax Credit), research and development activities are classified in three categories: basic research, applied research, and experimental development research.

The main objective of basic research is to create a comprehensive understanding of a subject, in other words, its primary goal is to acquire new knowledge. It is often theoretical and not geared towards any particular application or commercial objective. Basic research often takes place at universities or at public or private research institutes. It is one of the most important types of R&D activities. As argued by Griliches (1985), when compared to other types of R&D activities, basic research seems to be the most relevant for productivity growth, since in the long-run, basic research is often the starting point for any form of applied research.

Applied research, on the other hand, is primarily directed towards a specific objective. It seeks knowledge in order to cope with a specific need, or to create new products or processes. Contrary to basic research, it often has commercial objectives (Frascati Manual, 2015, p. 51). Experimental development research, in turn, can be defined as "systematic work, drawing on existing knowledge," and aimed at producing new products or improving existing ones (Link & Siegel, 2007, pp. 42-43; see also Frascati Manual 7.0, Chapter 2, pp. 43-45). It is mainly funded by public funds; its aim is to produce practical materials, devices, systems, or new processes.

In the applied research and experimental development phase either the new idea behind new processes or products or the process or product itself tend to spillover to other agents in society. In some sectors, however, research is usually kept secret. For instance, R&D applied to the defence sector are often kept secret by governments and firms due to national security concerns. Besides the defence sector, governments also conduct or fund their own development programs in other sectors, such as in space exploration and in the health and medical sector.

Furthermore, according to Smith (2005), in addition to classifying R&D according to types of activities, it can also be categorized according to sector, such as businesses, government, and academia. Another classification is based on the sources of funding (Fagerberg, Mowery, & Nelson, 2005). Sources of R&D funding can basically be divided into two groups: privately financed R&D investments and publicly financed R&D investments. These funding methods are distinct; privately financed R&D investments refer to funding provided mostly by individual firm's liquid assets. Publicly (or government) financed R&D investments, instead, refer to funding that individual governments are responsible for or choose to promote; most often than not these include, R&D related to defence, space exploration and research, and health sciences.

Yet, it is complicated to measure R&D output in the aforementioned fields. Griliches (1979, pp. 96-97) argues that output measurements are based on inputs. Inputs, in turn, are difficult to measure because they do not necessarily reflect an increase in productivity. For example, in space exploration and research, output is usually measured by man-hours and in the quality of equipment. Output, however, is irrelevant to the success of the venture. Similarly, in the defence sector, companies sell equipment to the government. There are no price indices on military aircraft that take into account an equipment's improved performance nor are there price indices that reflect, for instance, the improved resolution and range of radar equipment. Defence purchases are deflated by cost indices and as a result do not show on measures of productivity growth. Further, in the health sector, output of hospitals is measured by patient days while the output of physicians is measured by the number of patient visits. Any improvement in the rate of patients that are cured would not show up as an increase in the productivity of the sector. The difficulty in measuring R&D output is a problem in econometric studies, which use the production function, particularly among studies that investigate the link between R&D spending and economic growth. This, as well as other measurement issues, will be thoroughly discussed in chapter 3.

The effects of publicly and privately funded R&D investment on productivity growth have been studied by several authors both at the industry and at the firm level. Empirical studies that are conducted at the firm level state that privately funded R&D investments have a larger positive impact on productivity growth than publicly funded R&D investments. For example, studies by Griliches (1980), Griliches and Mairesse (1984), and Link (1981a) show that public funded R&D investment effects on productivity growth are lower than privately funded R&D investment. The same result can be observed at the industry level. Scholars, such as Griliches and Lichtenberg (1984), arrived at a similar conclusion; according to their findings, privately financed R&D is relatively more effective at increasing productivity growth than publicly funded R&D investments. Griliches (1984) further confirmed these results in and expanded study using a larger dataset. Scholars have also shown that the positive effect of privately financed R&D investment on productivity does not tend to change over time. The only exception to the consistency of the positive relationship between privately funded R&D and productivity growth was found on studies conducted during the 1970s. The 1973 Oil Crisis and the 1979 Energy Crisis (also known as the second oil shock) resulted in an economic shock which slowed down economic activity, especially in the Unites States. Thus, the economic recession in the aftermath of the oil shock of 73 and 79 made the decade a difficult period to study, particularly since most of the studies on the link between R&D spending and productivity growth were based on data from American firms.

The capacity of an investment to positively affect productivity can also be estimated by the social rate of return. The social rate of return shows the total value of all benefits associated with an investment that accrue to society. A simple way of visualizing the social rate of return is as follows:

Social Rate of Return = Private Rate of Return + External Rate of Return

where the private rate of return is equal to the ratio between annual profit and investment. The external rate of return, in turn, equals the ratio between external benefits and investments.

Technological innovation or R&D speeding is an investment, where the social rate of return to R&D investment is generally much higher than the private rate of return. The social rate of return includes not only private investors' profit, but also external benefits that spill over onto agents in society and who may have never contributed to the original investment. External benefits can also be derived from 'learning by doing.'

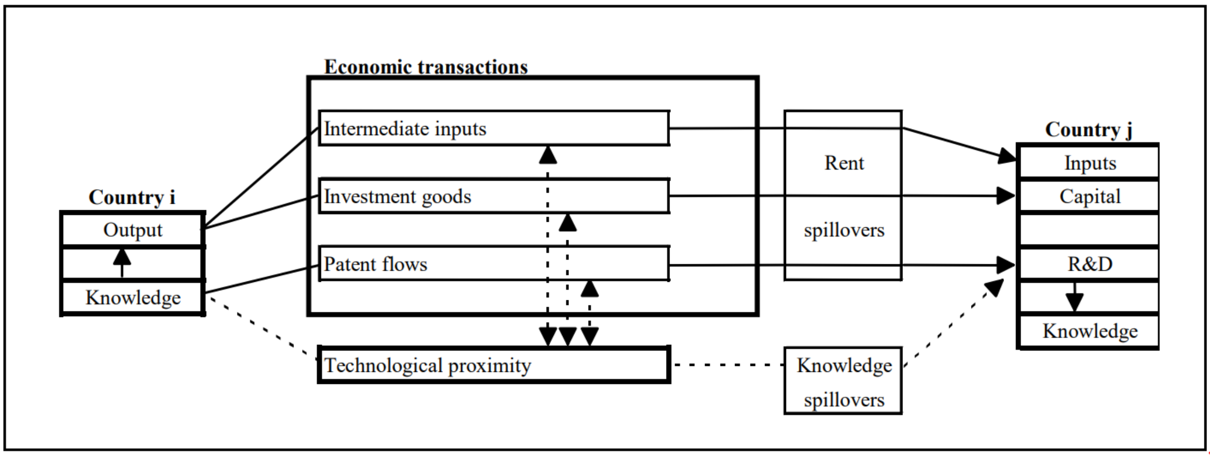
In a knowledge-based economy, knowledge is the only capital that is not subject to diminishing returns. As stated by Stephan (1996, p. 1200) knowledge, "is not depleted when shared, and once it is made public others cannot easily be excluded from its use. Moreover, the incremental cost of an additional user is virtually zero and, unlike the case with other public goods, not only is the stock of knowledge not diminished by extensive use, it is often enlarged."
Knowledge cannot be depleted, yet it can be copied by a competitor. As put by Stephan (1996), there is almost no penalty to an additional user since there is no cost in borrowing ideas, which, in turn, begs the question of what would happen if a country or firm chooses to wait for others to innovate and then replicate their research? (see also Griliches, 1989). If others can easily replicate a technology or research, then trying to prevent it will be costly and firms will not benefit from knowledge creation. This in turn will discourage research, particularly considering the time-lag between investment and return, costs and risks associated with innovation projects. The problems, or spillovers, associated with borrowed or

stolen knowledge are discussed by several authors. Griliches (1979), for instance, identifies two types of spillovers: rent spillovers and knowledge spillovers.

Rent spillovers are linked to the difficulties in capturing the economic benefits of an innovation and arise from the fact that the producer or innovator does not charge a price, which fully reflects the benefits of the new product or new process. Rent spillovers are inevitable unless the innovator recognizes the true nature of the spillover and reacts accordingly. Knowledge spillover refers to the dispersion or sharing of knowledge either from where it is created or from one agent to another. A knowledge spillover might be the result of diffusion of knowledge. This happens when strong and comprehensive patent protection is missing. Failure to protect one's research is another reason for knowledge diffusion. In this case, an agent is borrowing the knowledge from another without his or her permission. The high point of a knowledge spillover occurs when an R&D project creates new knowledge, which can be useful to another firm's research. Therefore, the firm that 'owns' the knowledge is constrained in its ability to stop another firm from exploiting (or 'borrowing') this new knowledge, without paying for the benefit.

Knowledge spillovers also arise between countries. There are two main ways knowledge can spillover between countries – spillovers from purchased inputs and knowledge leeks (Verspagen, 1997). International knowledge spillover occurs when knowledge created in a country by one of its R&D teams contributes to innovative processes in another. It might happen due to theft, borrowing, or simply sharing of knowledge. Empirical evidence shows that R&D spillovers from technologically advanced countries, have a significant impact on other nations (Coe & Helpman, 1995). For instance, a country can benefit from R&D spillovers if it imports inputs, such as capital goods, from countries with a relatively high domestic R&D capital stock. Nevertheless, Coe and Helpman (1995, p. 863) cautions that: " it might be expected that whenever two countries have the same composition of imports and face the same composition of R&D capital stocks among trade partners, the country that imports more relative to its GDP may benefit more from foreign R&D." Figure 1 below summarize how innovation from country 'i' might be beneficial to country 'j'.

Figure 1: Rent and Knowledge Spillovers



Source: Cincera and Van Pottelsberghe, 2001, p. 3.

- Input-related rent spillovers: this is usually in the form of country 'j' imports of intermediate inputs from country 'i', or technology goods purchased by firm 'j' from firm 'i'.

- Investment-related rent spillovers: it happens in the form of transactions of investments goods between country ‘i’ and country ‘j’.
- Patent-related rent spillovers: this can in the form of purchases of patents (or licenses) granted to country ‘i’ by country ‘j’.

Spillovers are shown by the horizontally dotted lines and take place at countries’ or firms’ technological proximity. Knowledge spillover also occurs in the absence of any economic transaction. When a nation’s firm purchases patent rights or goods from other nations, firms and countries can benefit from other’s innovation. However, it is important to keep in mind that the three cases discussed above may in fact not occur, since the process depends on the price the innovator country (or firm) will charge. The next chapter moves the discussion to the approaches used to estimate the link between research and development spending and productivity growth.

2.2 Approaches to Estimating Productivity Growth

This section reviews the models often used by scholars in estimating the effects of R&D investment on productivity growth. There are two main approaches used throughout the empirical literature: the production function and cost function. The section also discusses the similarities and differences between these two approaches as well as their advantages and disadvantages.

The literature on R&D investments and productivity can be divided into two approaches. One approach estimates the impact of R&D spending on productivity using the Cobb-Douglas production function and its variations. The other approach, in turn, is based on the production costs function – or cost function theories. Both the cost function and the production function deal with R&D stock as a factor of production as if it were any other production input – such as capital and labour. Even though these two approaches are related, the statistical methods are different. The cost function approach is more complex; for instance, in order to get reliable results, it requires a comprehensive data set. Another difference between these two approaches is the fact that a sub estimation of a cost function, or a dynamic cost function, requires fewer limiting assumption on producer behaviour than the Cobb-Douglas production function (Link & Siegel, 1997, p. 65; see also Berman, Bound & Griliches, 1994, for a detailed discussion). Even though these two approaches are related, the statistical methods are different from each other.

The cost function is associated with costs of production as well as with relative prices of factor input and fixed factors, such as physical capital and R&D expenditures. Cost functions establish a link between R&D spending and production costs to determine whether R&D investments lower production costs. Statistical significance is essential for the estimated coefficient of cost functions, so unless R&D projects decrease the costs of production, results will not be statically significant.

There are several advantages associated with the cost function approach. First, in this approach, other factors of production interact with R&D. Second, cost functions’ estimates are not subject to multicollinearity. Researchers can also use smaller datasets. The cost function approach also provides a richer framework for researchers to measure substitution patterns between internal and external capital inputs. There are, however, a few disadvantages. For instance, all explanatory variables must be exogenous otherwise estimated parameters may be biased. As far as data (input prices) are concerned, it is hard to find comprehensive data since it differs across firms as well as over time. Also, the equation should be modelled carefully since the absence of key variables might result in biased estimates. Yet, despite disadvantages, the cost function framework permits an examination of the dependent variable and changes over time in the relative share of highly skilled or highly educated workers (Link & Siegel, 1997; see also Berman, Bound & Griliches, 1994). The focus of this paper, however, is on the production function, which is the prevalent approach used in the literature.

The production function is linked to innovation. As stated by Schumpeter (1939, p. 62) "the production function describes the way in which quantity of product varies if quantities of factors vary. If, instead of quantities of factors, we vary the form of the function, we have an innovation." There are several ways of specifying the production function. Its general form can be expressed as:

$$Q = f\,(X_1, X_2, X_3, X_4, X_5, X_6, \ldots X_{n-2}, X_{n-1}, X_n)$$

where, Q is output and $X_1, X_2, X_3, X_4, X_5, X_6, \ldots X_{n-2}, X_{n-1}, X_n$ are factor inputs, such as capital and labour.

The Cobb-Douglas production function, proposed by Knut Wicksell (1851- 1926) and tested against statistical evidence by Charles Cobb and Paul Douglas in 1900-1928, shows the relationship between output and input factors. A thorough discussion of the Cobb-Douglas production function, its many variations, as well as the main problems encountered by scholars when estimating models investigating the relationship between R&D and productivity can be found in chapter 4 below.

3 Measuring the Impact of R&D Spending on Productivity Growth

The chapter is divided into three sections. The first section examines the models and the statistical frameworks used throughout the literature. This is followed by a discussion of the issues associated with measuring output, and finally, by a discussion of the problems associated with measuring R&D capital. Particular attention will be paid to three main issues found throughout the literature. The first issue is related to the relatively long time required to carry out research and development activities and the time-lag it takes for such research to have an effect on productivity. The second relates to the fact that past R&D activities and investments becomes obsolete overtime. And the third deals with the large amount of 'borrowed' or stolen knowledge across firms and across countries.

3.1 The Model Specifications

The starting point of most econometric studies that focus on the link between R&D investments and productivity growth is the production function. The production function shows the relationship between output and labour and capital. The basic version of the production function is as follows:

(1) $$Q = A(t)\, F(K, L)$$

where Q is output, A(t) is a time related shift factor, K is capital input and, L is labour input.

The Cobb-Douglas production function (at the aggregated level) is expressed as,

(2) $$Y = AK^{\alpha} L^{\beta}$$

where Y is aggregated output (total production), K is capital input, L is labour input, A is total factor productivity, α is the elasticity of labour output, and β is the elasticity of capital output. Output elasticities measure the response of output when labour or capital used in production change (increase of decrease) assuming other factors are constant (*ceteris paribus*). Therefore,

$\alpha + \beta = 1$, when the production function has constant returns to scale
$\alpha + \beta < 1$, when returns to scale are decreasing and
$\alpha + \beta > 1$, when returns to scale are increasing.

Another version of the production function is presented by Solow (1957). One of the main features of the Solow model is the assumption of constant returns to scale. In other words, if we increase labour input and capital stock, we will increase the level of output by the same measure. According to Solow (1957)

(3) $$Q = A(t)\, K^{\alpha} L^{\beta}$$

where, in the condition of perfect competition and constant returns to scale, α is the share of income distributed to capital and β refer to the share of labour income.[1]

After rearranging the basic version of the production function at the firm level and adding the firm's technical capital stock, equation (1) can be stated as:

(4) $$Q = A(t)\, F(K, L, T)$$

where in addition to capital (K) and labour (L) variables, T refers to the stock of technical capital.

Another specification of the production function assumes that R&D is the primary investment flow of stock of technical capital. This model and its variations are referred to as R&D capital stock model by Griliches and Lichtenberg (1984).

(5) $$A'/A = \lambda + \rho\, (RD/Q)$$

where A'/A refers to total factor productivity (TFP) and ρ is the return to R&D investment.

According to Siegel and Link (2007, p. 45), there are three important points regarding the model formulation and the interpretation of the estimated value of ρ in equation (5). First, the equation is hardly understood because stock of technical knowledge can come from alternative sources, not only from private funded R&D. A firm can invest in R&D and carry out R&D activities privately as well as in collaboration with other firms. The firm might also buy technology from other firms; hence, it can access other firms' R&D knowledge. Furthermore, the firm can acquire technology and knowledge from the government as well as through publicly funded R&D investments (Charles River Associates, 1981; and Tassey, 1982). Second, as stated by Scherer (1982) and Link and Siegel (2007), since the R&D stock of technical knowledge depreciates over time, ρ could be a conservative estimate of private returns to R&D investments. Finally, most studies fail to separate labour and physical capital outputs from labour and capital inputs. Schankerman (1981, pp. 454-460) argues that labour and physical capital are used to produce R&D and when researchers measure labour and

[1] Equations (3) and (4) are adapted from Link and Siegel, 2007, pp. 30-31.

physical capital, as well as R&D capital, they double count; thus, ρ is the measure of the excess rate of return to R&D. Schankerman's (1981) study was one of the first to address this double counting problem and the interpretation and prediction problem it had on the regression results. According to Schankerman's (1981) the effects of the double counting bias on the productivity regression depend on actual pattern of covariances across the regressors. (Hall, Mairesse (1995) predicts in a situation where the uncorrected data are used, and under the assumption that the R&D capital and R&D labour corrections are positively correlated with the measured R&D capital itself; the coefficient on R&D capital will be biased downward. (Hall, Mairesse (1995) p.275)

There are two approaches to estimate equation (4) and (5). The first approach is called the production function approach. To apply it to their study, researchers should directly estimate the production parameters from any version of equation (4), including a proxy for the level of R&D investment. This approach is referred to as the production function approach. It has been used by several scholars, namely Minasian (1969); Griliches (1980a; 1980b); Link (1980); Schankerman (1981); Link (1982b); Link (1982c); Griliches and Mairesse (1983); Link (1983); Griliches and Mairesse (1984); Griliches (1986); Griliches and Mairesse (1986); Bernstein and Nadiri (1989b); Lichtenberg and Siegel (1991); Griliches and Regev (1995); Crepon, Duguet, and Mairesse (1998); and Medda, Piga and Siegel (2003; 2005) (as cited by Link & Siegel, 2007, pp. 45-46).

Below follows some of the variations of the of the production functions that one can find in the empirical literature.

- $Q = A \ldots K^a . L^b$
- $Q = A \ldots K^a . L^b$
- $Q = a..K + bL$
- $Q = ln(a.K + b.L)$
- $Q = a.L + b. L^2 + c.K.L + d.K + e. K^2$
- $Q = a.L.K + b.\ L^2 .K + c.L.\ K^2\ - d. L^3 .K - e.L.\ K^3$
- $Q = f(K, L) + c$
- $Q = A(t). f(K, L)$
- $Q = f(K, L) + c\ L. Q_L + K.\ Q_K\ = n.Q$

In the second approach, researchers estimate a reduced version of R&D capital stock, similar to equation (5). This method is called R&D intensity approach (Link & Siegel, 2007, pp. 45-46). Scholars that conducted studies using the R&D intensity approach include Mansfield (1980); Link (1981a); Link (1981b); Link (1982a); Odagiri (1983); Clark and Griliches (1984); Griliches (1986); Lichtenberg and Siegel (1991); Loof and Heshmati (2002); and Medda, Piga and Siegel (2003; 2005).

The vast majority of empirical studies use the production function or a variation of it as presented in equations (1) to (5). However, an alternate version of the production function is also found in the literature and shown below as specified by equation (6).

(6) $$Q_{t=Ae^{\lambda y}} K_{t-1}^{\alpha} L_t^{\beta} R_{t-1^{\ell^{\varepsilon}}}$$

where Q is real output, A is total factor productivity (TFP), K is stock of physical capital, L is labour input, and R is a measure of R&D. It, however, should be noted that the variables in the equation differs according to each study. For example, some studies use real GDP as their measure of output, while others use firm-level data, usually revenues; thus, variables can change according to the purpose of the study. In addition to output measurement, the ideal measure of labour input is hours-worked. Yet, some researchers use number of employees when data on working hours is cannot easily be found.

Another design of the Cob-Douglas production function is the logarithmic function. It has been used by scholars, such as Griliches (1980); Schankerman (1981); Griliches and Mairesse (1984; 1990); Jaffe (1986); Hall and Mairesse (1995); Husso (1997); Bartelsman et al. (1996); Cuneo and Mairesse (1984); Griliches (1986; 1995); and Sassenou (1988), among others. These authors estimated the logarithmic production function as:

(7) $$\log(Y) = a + \lambda t + \alpha \log(K) + \beta \log(L) + \gamma \log(C) + \varepsilon$$

where Y is a measure of output (production or sales), L is a measure of labour input and t is a trend variable. C and K are measures of the accumulated research effort (capital) and other physical capital, and λ, α, β and γ are the unknown parameters to be estimated. C is normally approximated as a weighted sum of current and past R&D expenditure. Consequently, γ is the output elasticity of R&D. The error term, in turn, expresses total factor productivity.

Another variation of the production function that has been proposed as a way to solve or avoid common problems that occur while measuring R&D capital stock is the specification shown below in equation (8), where capital (C) is replaced by growth rates.

(8) $$dlog(Y)= \lambda + \alpha\ dlog(K) + \beta\ dlog(L) + \rho\ (R/Y) + \mu$$

where $(dlog(x) = (dx/dt)/x)$ and R refers to the annual expenditure on R&D, net depreciation of the previously accumulated R&D capital. The parameter ρ can be understood as the rate of return to investments in R&D capital; therefore, $\rho = \gamma\ (Y/K)$. An important issue regarding this specification is that any wrong interpretation of the parameters can lead to false conclusions. In order to avoid this and further problems, the researcher should be careful while interpreting the parameters as well as measuring the output variable.

Similar to equation (7), many scholars and researchers have chosen to use equation (8). The studies that use equation (8) and and examined in detail in the next chapter are Odagiri and Iwata (1986); Mansfield (1965); Griliches and Mairesse (1990); Link (1983); Hall and Mairesse (1995); Clark and Griliches (1984); Griliches (1986); and Sassenou (1988).

Before moving into the next section on estimating rates of returns, it is important to mention that while some researchers estimate regressions based on equation (6) or other log forms of the production function, they usually use aggregate data at the industry level for a cross section of individual firms. For instance, Griliches and Mairesse (1984) were the first ones to use panel data for a cross section of individual firms in their studies on productivity and R&D at the firm level (Griliches, 1998, p. 339). A brief discussion of time series and panel data analysis and cross-section analysis is in order, as the specifications used by researchers (discussed in the following chapter) and the issues they encountered vary according to the model specification used. Therefore, a basic understanding of the differences between time series and panel data and cross-sectional analysis and their advantages and disadvantages is necessary.

As mentioned above, studies on the relationship between R&D investments and productivity growth are based on time-series/panel data analysis or cross-sectional analysis. Cross-sectional studies are based on data gathered at a single point in time, giving the researcher a ‘snapshot’ of the topic (see also Congressional Budget Office; 2005, pp. 10-14). Time series analysis, in turn, can be defined as an approach that collects data about a firm or individual at multiple time periods, providing for a dynamic analysis. Panel data, or longitudinal data, incorporates the time series and cross section dimension as it includes observations of a collection of individuals, countries, or firms at multiple time periods (Baltagi, 2011).

Conversely, Cross-section analysis is a snapshot of a population at a single point in time. It can be defined as “any collection of data from a sample of individual (or groups) at a particular point in time as a basis for inferring the characteristics of the population form which the sample comes” (Jupp, 2016, p. 53). In other words, unlike time-series, where data consists of observations over multiple points in time (same variable over time) or panel data (multiple individuals and multiple time periods), cross-sectional analysis comprises of observations of multiple firms, countries, or individuals at a single point in time (multiple variables at the same period).

Cross-section analysis, therefore, provides the researcher with the possibility of using several variables, removing this way assumptions. A cross-sectional analysis is also less costly and less time consuming. It, however, only provides a snapshot, which may not be representative of the population. Unlike times-series or panel data analysis, which provides for the possibility of uncovering trends or patterns in the data, it cannot be used to study behaviour or patterns over time.

Jupp (2006, p. 301) defines time-series analysis as “research design in which measurements of the same variables are taken at different points in time.” Highlighting the dynamic features of time series analysis, Nausser (2016, p. 3) adds that it “is an integral part of every empirical investigation which aims at describing and modelling the evolution over time of a variable or set of variables in a statistically coherent way.” Panel data analysis incorporates this dynamic cross time dimension of time series analysis with a cross section of individuals. According to Baltagi (2011, p. 305) the advantages of panel data ranges from the greater amount of information found in pooled data, “their ability to control heterogeneity,” to their capacity “to identify and estimate effects that simply are not detectable in pure cross-sections or pure time-series data.” In the next section, we move on to a discussion of the estimation of rate of returns.

3.2 Estimating Rate of Returns

Another important point worth mentioning related to the specifications above mentioned is the estimated values of equations (7) and (8). In equation (7), in general, the estimated elasticity of output of R&D capital (Y), falls between 0.05 and 0.2; nevertheless, when comparing older studies with relatively recent ones, recent estimates tend to be higher. Table 1 and Table 2 below clearly show the elasticity estimates of selected studies, meaning, the estimation of the elasticity of the private rate of return to R&D investment. Data at the firm and industry level can also be found on Table 1 and 2. Elasticity of the rate of return to R&D is considered significant when it falls between 0.10 and 0.20.

Table 1: Selected Estimates of the Elasticity of Private R&D from Cross-Sectional Studies

Study	R&D Elasticity	Sample
Minasian (1969)	0.11 - 0.26	17 U.S. firms (chemical industry); 1948 to 1957
Griliches (1980a)	0.03 - 0.07	39 U.S. manufacturing industries; 1959 to 1977
Griliches (1980b)	0.07	883 U.S. firms, 1957 to 1965
Schankerman (1981)	0.10 - 0.16	110 U.S. firms (chemical and oil industries); 1963 cross section
Sveikauskas & Sveikauskas (1982)	0.22 - 0.25	144 U.S. manufacturing industries; 1959 to 1969
Cuneo & Mairesse (1984) Subsample 1 Subsample 2	0.20 0.21 0.11	182 French manufacturing firms; 1972 to 1977 98 firms in scientific sectors 84 firms in non-scientific sectors
Griliches & Mairesse (1984) Sample 1 Sample 2	 0.05 0.19	 133 U.S. firms; 1966 - 1977 77 U.S. firms (scientific sectors); 1966 to 1977
Griliches (1986) Subsample 1 Subsample 2	 0.11 0.09	491 U.S. firms 1972 cross-section 1977 cross-section
Jaffe (1986	0.20	432 U.S. firms; 1973 and 1979
Englander, Evenson & Hanazaki (1988)	(0.16) - 0.50	16 industries across six countries; 1970 to 1983
Mansfield (1988)	0.42	17 Japanese manufacturing industries1960 to 1979
Griliches & Mairesse (1990) Sample 1 Sample 2	 0.25 - 0.41 0.20 - 0.56	 525 U.S. manufacturing firms; 1973 to 1980 406 Japanese manufacturing firms; 1973-1980
Hall and Mairesse (1995)	0.05 - 0.25	197 French firms; 1980 to 1987
Wang and Tsai (2003)	*0.19*	136 Taiwanese manufacturing firms; 1994- 2000

Source: Congressional Budget Office, 2005; Mairesse and Sassenou, 1991; and all related articles.
Note: values in parenthesis indicate negative numbers.

Table 2: Selected Estimates of the Elasticity of Private R&D from Time-Series Studies

Study	R&D Elasticity	Sample
Minasian (1969)	0.08	17 U.S. firms; 1948 to 1957
Griliches (1980b)	0.08	883 U.S. firms. 1957 to 1965
Cuneo & Mairesse (1984)	0.05	182 French manufacturing firms; 1972-1977
Subsample 1	0.14	98 firms in scientific sectors
Subsample 2	0.03	84 firms in non-scientific sectors
Griliches & Lichtenberg (1984b)	(0.04)	27 U.S. manufacturing industries; 1959-1976
Griliches & Mairesse (1984)	0.09	133 U.S. firms; 1966 to 1977
Griliches (1986)	0.12	652 U.S. firms; 1966 to 1977
Jaffe (1986)	0.10	432 U.S. firms; 1973 and 1979
Bernstein (1988)	0.12	7 Canadian manufacturing industries;1978 - 1981
Hall & Mairesse (1995)	0 - 0.07	197 French firms; 1980 to 1987
Verspagen (1995)	(0.02) - 0.17	14 industries in 11 OECD countries

Source: Congressional Budget Office (2005), Mairesse and Sassenou (1991) and all related articles.
Note: values in parenthesis indicate negative numbers.

Table 1 and Table 2 show the range of estimations of R&D elasticity, which varies from about 0.05 to 0.60 for the studies at the firm level and from 0 to 0.50 for industry level studies. Most elasticity estimates are statistically significant, meaning companies that have more R&D capital (or greater R&D intensity) have higher levels of productivity than similar firms.

Table 2 also states that when researchers change from cross-sectional data to time-series data, estimations change as well. When researchers use time-series analysis, elasticity estimates are usually lower and consequently not statistically significant. Also, important to note that in a study of French firms between 1980 and 1987, Hall and Mairesse (1995) found that elasticity results were around 0.25. This leads us to believe that during the 1970s and the 1980s, measuring the effect of R&D was not as straightforward as it might be nowadays, particularly due to the lack of reliable data and economic stagnation brought by the twin oil-shocks. As stated by Fitzgerald Dowd (1993, p. 172), in 1973, OECD countries had double figure inflation rates and in 1974 only West Germany and Switzerland did not have high rates of inflation.

In addition, there is one important point of comparison between the two tables. The increase in the level of productivity occurs when companies invest in R&D, meaning that the higher the rate of R&D investment, the higher the level of productivity growth. The rationale is that the estimates of R&D elasticity are usually lower in studies which use time-series or panel data than for those which use cross-sectional data, since R&D elasticity measures the percentage increase in output. Thus, lower R&D elasticity indicates lower percentage increase in output. For example, Minasian (1969) conducted two studies with a dataset of 17 US firms for the period 1948-1957, using both cross sectional and time-series analysis. The R&D elasticity for the time-series study is 0.08, while in the cross-sectional study, the R&D elasticity is between 0.11 and 0.26. Therefore, different statistical frameworks, affect the results of studies using similar samples and in similar industries.

On the other hand, empirical evidence shows that the statistical significance also changes when time-series or panel data studies and their estimations are conducted. Meanwhile, productivity growth might be the result of other factors, which are correlated with R&D and output. In such case, any increase in R&D investments may not be reflected on productivity growth. The following section examines the measurement problems encountered by scholars when estimating the relationship between R&D investment and productivity growth. it also looks at the solutions that were proposed to avoid these problems.

3.3 Measurement Issues in Empirical Studies of R&D and Productivity

Researchers have used two different methods for measuring the impacts of R&D expenditures and investments on productivity growth, namely historical case studies and mathematical methods (or econometrics) Case studies are widely used in a range of fields. They usually involve an in-depth analysis of a phenomenon. While they can allow for powerful in-depth insights into an issue, they have several limitations. For instance, historical case studies have been criticized for at times being biased and not representative. They are also data and time consuming. Therefore, researchers usually prefer to investigate industries, which are associated with productive innovation. Data are often readily available and accessible in highly productive industries; thus, they will avoid possible biases (Griliches, 1979, pp. 93-95).

Econometric studies, on the other hand, are conducted to test hypothesis, further develop theories, forecast trends or in the studies presented in this pater, to explain a recurring relationship between R&D expenditures and productivity growth (see Griliches, 1979). Econometric studies based on the production function focus on total factor productivity (TFP) or/and total output as a function of past R&D investments as well as other variables. Nevertheless, 'more variables' also means more issues that have to be addressed by researchers because every additional variable requires complex estimates, and such complex estimates usually come with their own problems attached. To sum up, regardless of which estimating technique or model is used to estimate the relationship between R&D investments and productivity growth, certain measurement problems occur. This section, therefore, examines in detail the main measurement issues associated with measuring output and measuring R&D capital.

3.3.1 Issues Associated with Output

To estimate the impact of R&D on productivity growth, researchers must be able to measure any increase in the output of a firm or industry. This, however, is not an easy task since the purpose of an R&D effort is to improve the quality of goods and services or to create entirely new products or new processes. Hence, capturing improvements in a somewhat abstract concept such as quality is usually a challenge for researchers. A suggestion in such cases is to use price indices, as they will reflect quality improvements embedded in new products or services. Simply put, the assumption is that increases in quality will lead to small increases in the product's price. Consequently, any increase in nominal sales will be categorized as increases in real output instead of increases in price. Therefore, the rate of productivity growth will be higher. Science-based industries, such as computers, microprocessors, or pharmaceutics, are highly dependent on constant innovation and improvement of existing products. Firms in such industries have shown higher rates of productivity growth since researchers replaced their regular price indices with hedonic price indices (Congressional Budget Office, 2005, p 11) In order to understand the rationale for hedonic prices, let us think about personal computers. Since personal computers were introduced, the quality improved quickly and substantially; however, much of the improvement in hardware and software depended on components' improvements, as for instance the speed of microprocessors or the capacity of hard drivers. Even though improvement in the quality of personal computers have been reflected in computer prices, improvements in components might not. So the improvements in computer components might be associated (or confused) with the productivity of computers, and as a result, with the productivity of computer manufacturers. According to Klette and Griliches (1996), since the only alternative to avoid such problem is to deflate each firm's revenues by an industry wide or economy wide price index, it is likely that estimations will be biased. Some of the issues related to R&D intensity arise at the measurement of output for complex goods in the private goods sector. According to Griliches (1979) these issues are basically the "quality change" problems in the construction of price indices, as the more R&D intensive is an industry, the more likely its output will be subject to such measurement problems (for a detailed discussion see Griliches, 1979).

Finally, before discussing issues associated with econometric models, it is important to point out the difficulties inherent in assessing rates of productivity growth. It is difficult to measure total factor productivity, particularly when it is calculated from publicly available information, such as from firms' financial statements. This is due to the fact that publicly available financial information is not reliable or provide precise information on a firm's capital and investments. In addition, inputs and outputs must be assessed in constant dollars in order for them to lead to real and accurate input and output measurements. The reliability of TFP measures depends on the accuracy of input and output price deflators (Link & Siegel, 2007, pp. 44-50). Measurement issues are also problematic for high-tech industries and other industries that invest significant amounts on R&D and on information technology (IT). Increased rates of investment lead to higher quality of inputs and outputs; however, as discusses previously, improvements in quality of products or services are not necessarily reflected in price indices. This problem can cause a quality bias, and it may falsify estimations related to the marginal productivity of investments in technology Link and Siegel (2007) pp:30-31)Another issue pointed out by Link and Siegel (2007) is whether a firm's internal research projects translate into higher rates of internal returns when compared to external research projects, in which a firm collaborate with or contract with other organizations.

Besides measurement issues, there are also econometric issues that arise from models based on the production function and its variables. Griliches (1998, p. 33) states two common econometric problems – multicollinearity and simultaneity – which can significantly impact estimates. Multicollinearity refers to problems that arise from the fact that some of the variables used in the regression model move together; the independent variables are in this case correlated. It is, therefore, difficult (if not impossible) to determine or distinguish the impacts of such variables. As a result, a high degree of correlation can create problems with the fit of the model and the interpretation of the estimation results (Baltagi, 2011). Possible solutions for multicollinearity problems include either "less-collinear data, more prior information, or a reduction in the aspiration level of the questions to be asked of the data" (Griliches, 1998, p. 33).

Multicollinearity affects most time-series analysis at the industry level. Therefore, to reduce the possibility of multicollinearity, the use of 'micro-time-series data' at the individual level of the firm is recommended. Data at the firm level has more variability than at the industry level. Such variability, according to Griliches (1998, p. 33), can then be used to address issues related to "R&D lag structure,[2] the relative effects of government – versus privately financed

[2] It refers to the "relative contribution of past and current research and development levels" (Grilliches, 1998, p. 20).

R&D, or of basic versus applied research and so on." However, if a researcher decides to use micro level data without the availability of detailed information on social returns to R&D, but only with data on private returns to research and development, he or she can still estimate the social rate of returns to R&D at the micro level, but this will require a more detailed database (Mansfield et al., 1977). In other words, it will require a database that includes information on the size of the actual technological breakthroughs and estimates of the relevant demand elasticities.

A problem, however, arises when determining the precise shape of the R&D lag structure (Griliches, 1998, p. 33). Thus, researcher need annual R&D data for a long period of time and consider each period as a separate variable (Griliches, 1998, p. 33). This, however, is unlikely to happen since annual R&D expenditures are likely to be highly correlated. Therefore, according to Griliches (1998, pp. 33-34),

> it is probably best to *assume* a functional form for the lag distribution on the basis of prior knowledge and general considerations and not to expect the data to answer such fine questions. That is, a "solution" to the multicollinearity problem is a moderation of our demands on the data – our desires have to be kept within the bounds of our means (emphasis added in the original).

Another issue that plague econometric models based on the production function is simultaneity. Simultaneity occurs when a study's explanatory variable is correlated with the model's error or disturbance term (Baltagi, 2011). Statistically speaking, the right-hand side and the left-hand side variables of a function are jointly determined. In R&D and productivity studies, it refers to causality problems between future output and R&D. More precisely, future output and its profitability depend on past R&D investments. R&D expenditure, in turn, depends on past output and on future output expectations (see Grilliches, 1998, p. 33). There are, however, ways to address simultaneity problems. A common approach to deal with this simultaneity is to use instrumental variables regressions or indirect least squares (Grilliches, 1998; Baltagi, 2011). Instrumental variables "are used to determine an exogenous part of the variability from the endogenous predictors. In other words, this technique allows the use of only that part of the variation in the predictor that is 'arguably random'" (Pokropek, 2016, p. 4). Indirect least squares is an estimation technique which involves estimating the coefficients of the model in the reduced form using ordinary least squares. These reduced forms of the parameters are then put back into the equation system (Black, Hashimzade & Myles, 2009). Accordingly, researchers need to be careful in the formulation of their respective regression models and consider the dependency of R&D investments on past output and expected future output. Data should be detailed enough to support the use of complicated estimations. If researchers neglect these issues, "one may wind up reporting something as an estimate of the effect of R&D on output which may be mostly a reflection of the effect of output on R&D rather than vice versa" Griliches (1979, p. 36).

3.3.2 Issues Associated with R&D Capital

R&D capital is calculated from accumulating past R&D investments. R&D capital is essential in order to measure R&D effort and return to R&D spending. However, unlike physical capital, which can be easily quantified, R&D capital is difficult to measure. R&D capital is a body of knowledge that grows in various ways – from education, knowledge acquired and exchanged on conferences, own research, and so on. Hence, it is difficult to gather information from such varied set of activities into a single measure of R&D capital. Other issues include spillovers, which has been discussed in chapter 2, R&D lag structure and depreciation of past R&D investments.

R&D lag, the delays inherent in a R&D project structure, is complicated and it can occur for various reasons. It does not matter whether the R&D is directed towards new products or new processes. Usually, research projects take time, even in some cases it may take at least more than a year to complete. Even though a project has been completed and the output is ready and successful, there is still the issue of using it or producing it. Once a decision is made, there might be another lag regarding revenue flows. In this particular situation, two different issues occur depending on the type of innovation.(Zoltman, Duncan and Holbek, 1973; p.53) If it is a process innovation, it might be introduced step by step only with an effect on the firms costs' structure at the beginning phase. On the other hand, if it is a product innovation, then it may take a longer time for consumers to adapt the innovation.[3] In addition, Griliches (1979) argues that in cases where consumers are not aware of the product, there is a time-lag before they adapt to the new product; this process might be speeded up by marketing and commercializing techniques – considering that the product is a consumer good, not complex and may be used in households To sum up, there are situations which will lead to a delay or a time-lag between R&D investments and its effects on productivity. These lag-effects are important and require careful estimations and comprehensive on firms' R&D investments, which are not always available due to lack of data.

Depreciation or obsolescence is another issue that researchers must face. Firm knowledge capital diminishes over time, either because of improved products or because new processes become available .When an innovation – either in the form of a product or process – becomes (intentionally or unintentionally) available to other firms, private rates of return to the firm which originally developed such new product or process will decrease over time as other firms will eventually replicate and adapt the new product or new process. Furthermore, products might be replaced by new ones (the implementation of new technology)[4] invented by a firm's competitors. Therefore, R&D capital will eventually depreciate. For instance, inkjet printers have been replaced by laser printers while the steam engine was replaced by the internal-combustion engine, which has higher thermal efficiency.

A major issue regarding the measurement of spillovers is that they cannot be precisely measured. Krugman (1991, p. 53) states that knowledge flows are invisible; there are no paper trails to be measured or tracked; yet, a researcher has to take into account knowledge spillovers while measuring the impact of R&D investments on productivity growth. If not, the study might be miscalculated. Finally, as discussed in chapter 2, R&D capital can be found in labour and physical capital inputs; therefore, there is a risk of double counting labour and physical capital inputs. The following chapter with examine a selection of relevant empirical studies, both at the firm level and the industry level.

4 The Empirical Studies

This chapter analyses several studies, both at the firm and industry level. It starts by classifying the studies accordingly to their data selection. In order to understand the importance and aim of each empirical study, it is essential to be able to grasp the comprehensiveness of the dataset used. For instance, a quick look at the dataset allows one to verify whether a study was based on firm level data or industry level data. In addition, one

[3]For details regarding innovation adaptation, see Mahajan, Muller & Bass (1990).

[4] According to Siegel (1991) (1997) (2007) (2003) implementation of a new technology leads to downsizing and a shift in labour composition in favour of skilled workers.

can also find the geographical range of the study. It must be noted that the large majority of studies have been conducted in the United States and therefore based on American firms and sectors of the economy. The chapter proceeds with an examination of the main findings and conclusions of such studies in terms of rates of return to R&D and R&D elasticities. It also looks at the estimation methods used by these selected studies. Below follows a list of the studies (30 in total) that have been examined in this study.

- Minasian (1969)
- Terleckyj (1974)
- Mansfield (1980)
- Terleckyj (1980)
- Griliches (1980b)
- Link (1981b)
- Scherer (1982)
- Odagiri (1983)
- Griliches and Mairesse (1983)
- Clark & Griliches (1984)
- Griliches & Lichtenberg (1984a)
- Griliches & Lichtenberg (1984b)
- Cuneo and Mairesse (1984)
- Griliches and Mairesse (1984)
- Odagiri and Iwata (1986)
- Odagiri and Iwata (1986)
- Griliches (1986)
- Jaffe (1986)
- Mansfield (1988)
- Bernstein (1988)
- Englander, Evenson, and Hanazaki (1988)
- Goto and Suzuki (1989)
- Sterlacchini (1989)
- Griliches and Mairesse (1990)
- Lichtenberg and Siegel (1991)
- Griliches (1994)
- Verspagen (1995)
- Hall and Mairesse (1995)
- Jones and Williams (1998)
- Wang and Tsai (2003)

4.1 Overview of Empirical Studies

This section focuses on selected empirical studies. It is important to point out that, the aim of this paper is to investigate the impact of R&D investments on productivity growth; hence, given the large body of literature on the subject, some studies, although important, have been omitted from this paper. In addition, the studies which have already been extensively discussed in chapters 3 and 4 have also been omitted from the discussion, as their findings, estimation models, and measurement issues have already been thoroughly analysed. This way there is no repetition and time and space can be allocated to an examination of the rates of return to R&D and R&D elasticities of other empirical studies considered relevant by the literature.

Table 3 and Table 4 shows the details of empirical studies carried out at the industry level and at the firm level as well as the timeframe which they focus on. Among the industry level studies investigated in this chapter, Griliches & Lichtenberg (1984b) is the one carried out during the earliest period, as it examined 27 American manufacturing firms from 1959 to 1976. In contrast, the study with the longest timeframe was conducted by Griliches (1994); the author examined a set of American manufacturing firms along a 31 years' time interval (1958 to 1989). Furthermore, the most comprehensive study was done by Griliches and Lichtenberg (1984a) with a sample of 193 manufacturing industries in the United States during the period 1959-1978. Considering the number of industries included in the dataset and the problems related to data, the study's sample size, especially for that time period, is astonishing. Besides studies analysing industries in the United States, the other papers evaluated in this chapter were conducted in Canada, Japan, and other OECD countries. For instance, Bernstein (1988) carried out a study across 7 Canadian manufacturing industries during the period 1978-1981. Another example is Verspagen (1995), who examined 14 industries spread across 11 OECD countries between 1973 and 1988. Mansfield (1988), in turn, studied 17 Japanese industries during the period 1960-1979.

At the firm level, the earliest study was conducted by Minasian (1969) with a sample of 17 American firms between 1948 and 1957. The most comprehensive study, however, was done by Lichtenberg and Siegel (1991). Lichtenberg and Siegel's study include a dataset of 2,207 firms in the period 1972-1985. Similarly, to studies at the industry level, most studies at the firm level focus on American firms. However, there are also a number of studies carried out with Japanese firms. There are five papers with a particular focus on Japanese manufacturing firms among the selected papers studies analysed in this chapter: Odagiri (1983), Odagiri and Iwata (1986), Goto and Suzuki (1989), and Griliches and Mairesse (1990 sample 2). The most comprehensive study on Japanese firms was conducted by Griliches and Mairesse (1990 with a sample of 406 Japanese manufacturing firms between 1973 and 1980. There are also three studies conducted with French manufacturing firms. Mairesse co-authored several studies on French firms with several authors, including Griliches and Mairesse (1983), Hall and Mairesse (1995), and Cuneo and Mairesse (1984). The study by Griliches and Mairesse (1983), however, covers not only French firms, but also American ones. The study with the longest timeframe was conducted by Mansfield (1980) with 16 American firms in the chemical and petrochemical sectors between 1960 and 1976. In comparison to studies at the industry level, studies at the firm level have shorter timeframes. This is mostly due to data restrictions or unavailability.

Table 3: Empirical Studies at the Industry Level

Author	Characteristics of the Study
Griliches & Lichtenberg (1984b)	27 U.S. manufacturing industries; 1959 to 1976
Bernstein (1988)	7 Canadian manufacturing industries; 1978 to 1981
Verspagen (1995)	14 industries in 11 OECD countries; 1973 to 1988
Terleckyj (1974)	33 U.S. industries; 1948 to 1966
Terleckyj (1980)	20 U.S. manufacturing industries; 1948 to 1966
Scherer (1982)	87 U.S. manufacturing industries; 1964 to 1969 and 1973 to 1978
Griliches & Lichtenberg (1984a)	193 U.S. manufacturing industries; 1959 to 1978
Mansfield (1988)	17 Japanese industries; 1960 to 1979
Sterlacchini (1989)	15 U.K. manufacturing industries; 1954 to 1984
Griliches (1994)	142 U.S. manufacturing industries; 1958 to 1989
Jones & Williams (1998)	12 U.S. manufacturing industries; 1961 to 1989
Englander, Evenson, & Hanazaki (1988)	16 industries across six countries; 1970 to 1983

Source: Mairesse and Sassenou, 1991; and relevant articles.

Table 4: Empirical Studies at the Firm Level

Author	Characteristics of the Study
Minasian (1969)	17 U.S. firms; 1948 to 1957
Griliches (1980b)	883 U.S. firms; 1957 to 1965
Cuneo & Mairesse (1984) Subsample 1 Subsample 2	182 French manufacturing firms; 1972 to 1977 98 firms in scientific sectors 84 firms in non-scientific sectors
Griliches & Mairesse (1984)	133 U.S. firms; 1966 to 197
Griliches (1986)	652 U.S. firms; 1966 to 1977
Jaffe (1986)	432 U.S. firms; 1973 and 1979
Hall & Mairesse (1995)	197 French firms; 1980 to 1987
Mansfield (1980)	16 U.S. firms (chemical & petroleum industries);1960-1976
Link (1981b) Subsample 1 Subsample 2	 174 U.S. firms; 1971 to 1976 33 U.S. firms (chemical industry); 1971 to 1976
Griliches & Mairesse (1983) Regular sample Industry dummies	 528 U.S. and French firms; 1973 to 1978b 528 U.S. and French firms; 1973 to 1978b
Odagiri (1983) Subsample 1 Subsample 2	370 Japanese firms 123 Japanese firms (scientific sectors); 1969 to 1981 247 Japanese firms (other sectors); 1969 to 1981
Odagiri & Iwata (1986) Regular sample Industry dummies	270 Japanese firms 135 Japanese firms; 1966 to 1973 135 Japanese firms; 1966 to 1973
Odagiri & Iwata (1986) Regular sample Industry dummies	336 Japanese firms 168 Japanese firms; 1974 to 1982 168 Japanese firms; 1974 to 1982
Goto & Suzuki (1989)	40 Japanese manufacturing firms; 1976 to 1984
Wang & Tsai (2003)	136 Taiwanese manufacturing firms; 1994 to 2000
Lichtenberg & Siegel (1991)	2,207 U.S. firms; 1972 to 1985
Clark & Griliches (1984)	924 U.S. manufacturing plants; 1970 to 1980
Griliches & Mairesse (1990) Sample 1 Sample 2	 525 U.S. manufacturing firms; 1973 to 1980 406 Japanese manufacturing firms; 1973 to 1980

Source: Adapted from Link and Siegel, 2007, pp47-48. and from Mairesse and Sassenou, 1991, pp. 12-13.

4.2 The Findings of Empirical Studies

Table 5 and Table 6 summarize the findings of the studies mentioned above. At the firm level, Minasian (1969) study of a small sample of 17 firms in the United States during the period 1948-1957 estimated the private rate of return to R&D as 0.54. Griliches, on the other hand, in his two studies in the 1980s – one with a sample of 39 firms in the US (1980a) and another with a larger sample of 883 American firms (1980b), estimated the rate of return as 0.27 for total R&D investment and 0.36 for privately financed R&D investments. Griliches (1980a; 1980b) pointed out that when the public funded portion of R&D investments is excluded, the estimated rates of return were higher. Mansfield (1980) and Link (1981a; 1981b), in turn, separated self-financed R&D according to R&D type of activity – basic research, applied research and experimental development research. Both authors found a higher rate of productivity associated with basic research activities. Griliches (1986) and Lichtenberg and Siegel (1991) reached a similar conclusion, by rejecting the hypothesis that returns to basic research are the same as those that accrue to firms from applied research or experimental development research investments (Link & Siegel, 2007, p. 47). Using data from the US Census, Griliches (1986) found that the estimated rate of return was 39 percent, with a premium return for investments in basic research. Lichtenberg and Siegel (1991) further concluded that the rate of return to privately funded R&D was around 35 percent, which is consistent with their previous studies.

Furthermore, Hall and Mairesse's (1995) investigation of French manufacturing firm in the period 1980-1987 observed that their findings were representative when they used cross-sectional data. According to their findings, when using cross-section analysis, the R&D elasticity was positive and statistically significant (33 percent according to their results). On the other hand, when they used time-series/panel data, the estimate of the elasticity fell and was no longer statistically significant. The authors investigated the effects of various specifications and estimations, including different measures of R&D capital and corrections for the double counting issues. According to Hall and Mairesse's (1995, pp. 286-287) main findings,

> a longer history of R&D expenditures helps improve the quality of the R&D elasticity estimates, but the choice of depreciation rate for R&D capital makes little difference. The correction for double-counting of R&D expenditures in capital and labour is important and may be interpreted under certain conditions as converting a measured 'excess' rate of return to a total rate of return to R&D.

Griliches (1986), Lichtenberg and Siegel (1991), and Link (1981a, 1981b) also confirmed that privately financed R&D has a larger positive impact on productivity growth than public financed R&D. There are at least two explanations for these findings, public funded R&D is by nature developmental, so it might not be associated with productivity growth. Also, instead of a direct relationship, the effects of public financed R&D may be indirect, increasing the efficiency of privately financed R&D.

Furthermore, at the firm level, the study by Crepon, Duguet, and Mairesse's (1998) found that simultaneity seems to interact with selectivity in a four-equation model (CDM model) with selectivity, innovation input (R&D), innovation output, and firm's productivity equations. Loof and Heshmati (2002) also used the same approach and found that the elasticity of innovation output with respect to R&D capital per employee is approximately 0.5 to 0.6, with an estimated rate of return of 13 percent. Crepon, Duguet, and Mairesse's (1998), elasticity of innovation output is about 0.3-0.4, with an estimated rate of return of 33 percent. The only difference between these two studies is that Crépon et. al. (1998) used stock of R&D while Loof and Heshmati (2002, p. 16) used a flow measure of total innovation input. In a study of Italian firms, Medda, Piga and Siegel's (2003) confirmed these results, with estimated rate of return of 33 percent. According to Medda et. al. (2003, pp. 11-13), "greater expenditures in R&D are associated with a more intense growth of productivity. Quite interestingly, when total R&D outlays are broken down in internal – intramuros – and external, the latter seems to have a greater effect on productivity"

Table 5: Rate of Return to R&D – Firm-level Empirical Studies

Author(s)/Year	Specification	Country	Characteristics of the Study/ Key Results
Minasian (1969)	Production function	U.S.	Small sample, 17 firms, estimated rate of return of 54%
Griliches (1980a 1980b)	Production function	U.S.	Large sample, based on linking NSF annual survey of R&D to CM: estimated rate of return of 27% for total and 36.5% for company financed R&D.
Link (1980)	Production function	U.S.	Rate of return to R&D among chemicals firms increases with the size of the chemical firm to a point and then remains constant.
Mansfield (1980)	R&D intensity	U.S.	Estimated rate of return of %28 for privately funded R&D, high productivity premium associated with basic research.
Link (1981a)	R&D intensity	U.S.	Positive and statistically significant relationship between R&D and output, estimated rate of return of 0%.
Link (1981b)	R&D intensity	U.S.	High productivity premium associated with basic research.
Schankerman (1981)	Production function	U.S.	First study to address "double counting" of physical and knowledge capital when assessing the returns to R&D; estimated rate of return of 49%
Link (1982a)	R&D intensity	U.S.	Higher returns to process innovation than product innovation.
Link (1982b)	Production function	U.S.	Small impact from federal R&D on productivity growth of firms, rate of return is low.
Link (1982c)	Production function	U.S.	R&D directed to meeting environmental regulations has no measurable impact on productivity growth of chemical firms.
Odagiri (1983)	R&D intensity	Japan	Large sample, 370 Japanese manufacturing firms; estimated rate of return of 26%, highest returns in the chemicals, drug and electric equipment.
Griliches & Mairesse (198)	Production function	U.S. & France	Panel data econometrics, estimated rate of return of 19%
Link (1983)	Production function	U.S	Technology embodied in purchased capital has positive impact on productivity growth of firms purchasing the capital.
Clark & Griliches (1984)	R&D intensity	U.S	On the basis of the 'PIMS' File - A 'Business Unit' data-set; estimated rate of return of 20%; no evidence of deterioration in returns to R&D during 1970s.

Griliches & Mairesse (1984)	Production Function (levels and first differences)	U.S	Panel data econometrics to deal with simultaneity problem between R&D and productivity; estimated rate of return of 42%
Griliches (1986)	Production function & R&D intensity	U.S	On the basis of a large US Census based sample of firms, estimated rate of return of 39%, productivity premium for basic research.
Griliches & Mairesse (1986)	Production Function (levels and first differences)	U.S & Japan	Panel data econometrics to deal with simultaneity problem between R&D and productivity; estimated rate of return of 33%
Bernstein & Nadiri (1989a)	Dynamic duality approach (dynamic cost function estimation)	U.S	Controls for the ‘quasi-fixity’ of physical capital by allowing for adjustment costs; estimated rate of return of 35%
Bernstein & Nadiri (1989b)	Dynamic duality approach (dynamic cost function estimation)	U.S	Controls for the ‘quasi-fixity’ of physical capital by allowing for adjustment costs; estimated rate of return of 35%
Lichtenberg & Siegel (1991)	Production function & R&D intensity	U.S	Large sample 2207 firms; based on linking NSF annual survey of R&D to ASM; estimated rates of return of 13% to total R&D, 35% privately funded R&D,134% to basic research, impact of R&D on productivity remained strong during productivity slowdown during 1970s
Griliches & Regev (1995)	Production Function (levels and first differences)	France	Rate of return to R&D estimated five times higher that return to investment in physical capital.
Crepon, Duguet, & Mairesse (1998)	Production Function (levels and first differences)	Israel	Controls for simultaneity and selectivity (some firms do not R&D) in econometric analysis; estimated rate of return of 33%
Loof and Heshmati (2002)	R&D intensity	Sweden	Controls for simultaneity and selectivity in econometric analysis; estimated rate of return of 13%
Medda, Piga & Siegel (2003 – 2005)	Production function & R&D intensity two-stage Treatment Effect model	Italy	Controls for simultaneity and selectivity in econometric analysis; estimated rate of return of 33%, external R&D has stronger impact on productivity than internal R&D, especially R&D conducted jointly with universities.

Source: Adapted from Link and Siegel, 2007, pp. 48-49.

Table 6: Rate of Return to R&D – Industry-level Empirical Studies

Study	Specification	Country	Characteristics of the Study/ Key Results
Terleckyj (1974)	small-scale predecessor technology flows matrix & R&D intensity	U.S	33 U.S. industries; 1948 to 1966 cross sectional study, R&D intensity data. Rate of return ranging around 0 - 0.30
Terleckyj (1980)	cross section of estimated rates of total factor productivity	U.S.	20 U.S. manufacturing industries; 1948 to 1966, rate of return to be 0.20 - 0.27
Scherer (1982)	Production function & R&D intensity	U.S.	87 U.S. manufacturing industries; 1964 to 1969 and 1973 to 1978, rate of return to be 0.13 - 0.29
Griliches & Lichtenberg (1984a)	TFP approach	U.S.	193 U.S. manufacturing industries; 1959 to1978, rate of return ranging around 0.04 - 0.30
Mansfield (1988)	Extended production function	Japan	17 Japanese industries; 1960 to 1979, rate of return to be 42%
Sterlacchini (1989)	Production function	U.K	15 U.K. manufacturing industries; 1954 to 1984, rate of return to be 0.10 - 0.30
Jones & Williams (1998)	semi-endogenous, extended production function	U.S.	12 U.S. manufacturing industries; 1961 to 1989 rate of return to be 0.35

Source: Adapted from Mairesse and Sassenou, 1991, pp 7-8., Congressional Budget Office, 2005, p. 18; and all related articles

To summarize, there are five main points which comes across in all studies' on the relationship between R&D investments and productivity growth. First, empirical studies that separate R&D spending into types of activities, namely basic research, applied research and experimental development research, found that rates of return to basic research are higher than rates of return to applied research. For instance, Mansfield (1980, p. 871) found a positive relationship between long-term research and productivity at the firm level with basic research acting as a proxy for long-term R&D in regression models.

Second, some studies, such as Schankerman (1981) and Hall and Mairesse (1982), emphasized that correcting double counting issues is essential in order to obtain precise estimation of R&D elasticity. Evidence have shown increases in R&D elasticities when double counting was corrected (Hall & Mairesse, 1995). Otherwise R&D effort will be double counted if labour and physical capital outputs are not separated from labour and capital inputs. Verspagen (1995), however, argues that the bias does not seem to be large as that found by some authors. Verspagen (1995, p. 132) gives as a possible findings difference sin aggregation level and differences in functional form.

Another point found across studies is related to the changes in the rate or return to R&D investments. (Griliches, 1994) found thatthat R&D elasticities decreased during the 1970s. As mentioned previously, there is a link between a decrease in elasticity and the advent of the twin oil shocks. The oil crisis severely hit R&D intensive sectors, such as chemical, petrochemical, and petroleum exploration and refining. In addition, sub- sequent rise in value of the dollar and the expansion in imports also hit some of the high-tech R&D intensive industries even harder, resulting in declines in "competitiveness," losses of rents, and the appearance of excess capacity. (Griliches, 1994, p. 7).

Also, the empirical studies reviewed in this section clearly show that returns to public funded R&D are lower than the rate of returns to the private financed R&D. There are two reasons for this result. First, public funded R&D may not be correlated with productivity because most often it is developmental. And second, the relationship with public financed R&D and productivity may be indirect. It may work in a complementary way to private funded R&D, so it indirectly impact private R&D which in turn leads to higher rates of productivity growth.

Finally, correcting the simultaneity issue and selection bias decrease the magnitude of estimates of the returns to R&D, but they are still positive and statistically significant. (Link & Siegel, 2007 pp.51-52).

5 Conclusion

This paper investigated the relationship between R&D investments and productivity growth. To do so, the paper reviewed the literature on R&D and its components such as public and privately financed R&D, R&D towards product and process innovation, and R&D types of activities, such as basic research, applied research, and experimental development research. The thesis also analysed a selected set of relevant studies and their findings on the effects of R&D investments on productivity growth, paying close attention to the measurement issued encountered by researchers and the consistency of estimation results. The main findings of this study are as follows:

- R&D investments proved to be positively related to productivity growth regardless of which estimating technique or model is used.
- When compared to other types of R&D activities, basic research proves to be the most relevant for productivity growth, since in the long-run, basic research is often the starting point for any form of applied research.
- Most studies also showed that the elasticity of rate of return estimates for privately funded R&D were consistently higher than the elasticity and rate of return estimates for publicly financed R&D. As pointed out by many scholars, this could be due to the fact that public funded R&D may not be directly correlated with productivity growth since it is often developmental in nature. Another possibility is that public financed R&D may be complementary, so it indirectly impacts private R&D investments, which in turn affect productivity.
- To properly estimate the impact of R&D on productivity growth, researchers must be able to measure any increase in the output of a firm or industry. In this sense, spillovers must be addressed. Unfortunately, they cannot be precisely measured since knowledge flows are invisible and often cannot be properly quantified, measured or tracked. Nevertheless, as many researchers showed in the studies reviewed in this thesis, it is crucial to consider knowledge spillovers while assessing the impact of R&D investments on productivity growth otherwise estimations may be biased.
- Another issue that must be addressed is how to capture quality improvements in products or processes. A solution proposed by many scholars is to use price indices as

the assumption is that prices reflect quality improvements embedded in new products and new services.

- Furthermore, time-lags between R&D investments and their effects on productivity are an inherent feature of R&D projects.
- An additional feature of R&D investments is a firm's diminishing stock of knowledge capital over time, either because of improved or new products and processes become available. Thus, the more technologically intensive and industry, the more likely its output will be subject to measurement problems.
- The reliability of total factor productivity measures depends on the accuracy of input and output price deflators. So, data should be readily available and sufficiently detailed, which in the case of productivity measures at the firm level is an issue since most often than not, researchers have to rely on public available information, which is not accurate or detailed enough.
- It is also important to understanding the dependency of R&D investments on past output and future output because if not addressed, estimates of the effect of R&D on output may be a reflection of the effect of output on R&D instead.
- Also, statistical frameworks (cross-sectional, time-series and panel data analysis), employed in the previous studies do not provide for consistent results, since results of estimations using cross-section analysis were higher and more significant than results obtained with panel data models. This makes it even harder to analyse the relationship between R&D and productivity, paricularly for applied scientists who rely on empirical findings.
- Notwithstanding the measurement problems, lack of reliable data, and lack of consistency among estimates using different statistical frameworks, technological improvement on data collection and storage methods made it possible to overcome some of the measurement issues and inconsistencies discussed in this paper and found in most empirical studies analysed in chapter 4.

For future research, a suggestion would be to employ data-driven statistical methods. For instance, the productivity of a company that operate in online retail can be measured through unorthodox key performance indicators (KPIs), such as number of active users, clicks per minute, abandonment rates, or conversion rates. In addition, KPIs can help address problems the lagged effect of R&D projects and its impact on productivity since the increased availability of information (big data) allows for increased variation in the data.

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