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R&D SPILLOVERS AMONG FINNISH MANUFACTURING FIRMS:

A Cost Function Estimation with Random Coefficients**

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Abstract: We study the effects of R&D spillovers on the cost and production structures of Finnish manufacturing firms using the cost function approach. A four-equation translog system of two variable and two quasi-fixed (capital) inputs as well as two spillover measures is estimated by maximum likelihood with random coefficients.

The results suggest that intra-industry spillovers are present in Finnish manufacturing – finds regarding inter-industry spillovers are inconclusive. As compared to previous studies, the variable cost reduction associated with spillovers is relatively low – one per cent increase in the intra-industry (inter-industry) spillover stock reduces variable cost by .01% (.03%). Spillovers reduce the demand for labor but increase the demand for materials. Spillovers also reduce the willingness to pay for the capital inputs. The gross rates of return on the physical and R&D capital stocks are, respectively, 16.9% and 18.2%. There is some indication that the social rate of return on R&D exceeds the private one by 10%.

Keywords: R&D, spillovers, externalities, cost function, cost structure, panel data, Finland, Finnish, manufacturing, firms, random coefficients, rate of return.

JEL codes: D24, L6, and O33.

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Tiivistelmä: Tarkastelemme tuotekehityksen (T&K:n) ulkoisvaikutuksia suomalaisten teollisuusyritysten kustannus- ja tuotantorakenteisiin. Translog-kustannusfunktiosta, jonka muodostavat työvoimapanos-, materiaali-, pääoma- (2 kpl) ja teknologiavirtamuuttujat (2 kpl), on johdettu neljän simultaanisen yhtälö ryhmä. Estimoinnissa on käytetty suurimman todennäköisyyden menetelmää ja osa kertoimista on mallitettu satunnaisina.

Tuotekehityksellä näyttää olevan tilastollisesti merkitseviä ulkoisvaikutuksia ainakin samalla teollisuudenalalla toimivien yritysten kesken; eri toimialoilla toimivien yritysten välisten ulkoisvaikutusten todentaminen vaatii jatkotutkimuksia. Ulkomaisilla aineistoilla tehtyihin tutkimuksiin verrattuna T&K:n ulkoisvaikutukset ovat pienehköjä. Yhden prosentin kasvu saman (toisten) toimialan osaamisvarannossa pienentää muuttuvia kustannuksia 0,01 % (0,03 %). Ulkoisvaikutukset vähentävät työvoiman mutta lisäävät materiaalien kysyntää. Ulkoisvaikutukset myös vähentävät pääomahyödykkeiden kysyntää. Pääoman bruttotuotto on 16.9 % fyysisen pääoman ja 18.2 % T&K-pääoman osalta. Tuotekehityksen yhteiskunnallinen tuotto lienee noin 10 % yksityistä tuottoa korkeampi.

Avainsanat: Tuotekehitys, T&K, teknologiavirrat, ulkoisvaikutukset, kustannusfunktio, kustannusrakenne, tuotantorakenne, paneeli, Suomi, teollisuus, yritykset, satunnaiskerroin, tuottoaste.

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Petri Rouvinen
September 8, 1999

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INTRODUCTION

Research and development (R&D) is widely recognized as an important source of technological change and productivity growth. New products and improved processes are outcomes of innovative activity, a major component of which is R&D by private enterprises.

A peculiar feature of R&D is that a firm investing in it is often unable to exclude others from freely obtaining some of the benefits. In other words, the fruits of R&D partially *spill over* to other firms in the economy, although the recipients have not fully compensated the original source for the use of the knowledge. Mohnen (1996, p. 40) gives a more formal definition:

> "…R&D externalities [or spillovers] occur when the knowledge derived from the R&D activities of one producer has unintended consequences on the performance measures (profits, productivity, market shares, and so on) of other producers."

There are incentive problems and property right issues raised by the less than full appropriability of R&D. While legal remedies (patents, etc.) have been suggested to prevent involuntary transfer of information, it is unlikely that any amount of legal protection could make information fully appropriable (Arrow, 1962). On the more positive side, the new growth theory, where various externalities and other sources of increasing returns are considered major sources of long-term economic growth, assigns a central role for information spillovers (Grossman & Helpman, 1991; Romer, 1990). Thus spillovers, while reducing a private firm's incentive to innovate, are socially desirable and advantageous to the receiving firms for a **given** level of innovative activity.[1]

The ability to emit and absorb spillovers is in part a function of firms' operating environment. The following **Historical Background** section gives an overview of some 'spillover-relevant' aspects of the Finnish economic history.

Case and regression-based studies are considered the two main subgroups of the empirical R&D spillover literature (see, e.g., Griliches, 1992; Mohnen, 1990; Mohnen, 1996; Nadiri & Prucha, 1993). The latter is further divided into the **cost function** (or dual approach) and **technology flow** (or primal approach) studies. We conduct a study in the cost function tradition.

Cost function studies rest on (a) the neoclassical theory of investment, (b) the duality theory, (c) the advances in flexible functional forms, and (d) the various developments in the intertemporal modeling of adjustment costs (Nadiri & Prucha, 1999). Jorgenson (1963) is one of the original contributions in (a) the neoclassical theory of investment, introducing the concept of user cost of capital and refining the idea of lagged response of investment to the changes in capital demand (for review see, e.g., Jorgenson, 1996). Nadiri and Rosen (1969) incorporate these ideas to a formal model where disequilibrium on one factor market may have consequences on others. Flexible functional forms (c) were introduced in economics to avoid restrictive features in, e.g., Cobb-Douglas and Leontief specifications. Seminar contributions include Diewert’s (1971) generalized Leontief as well as Christensen, Jorgenson, and Lau’s (1973) transcendental logarithmic functional forms (for review see, e.g., Lau, 1986). Shephard (1953) laid the foundations of (b) the duality theory in economics. More recent contributions since the early 1970s have closely related to advances in flexible functional forms. Dual presentations of production functions, i.e., profit or cost functions, have been popular in econometric modeling since explicit derivation of demand systems from production possibilities can be avoided (McFadden, 1978). For review of the early contributions see Fuss and McFadden (1978). Eisner and Strotz (1963) considered (d) adjustment cost in the neoclassical theory of firm. Lucas (1967) and others further refined the idea. Berndt, Morrison, and Watkins (1981) recognizes three generations of dynamic factor demands models. The ones in the third generation explicitly incorporate dynamic optimization and thus provide well-defined results on the short, medium, and long run (see, e.g., Galeotti, 1996).

Due to the huge volume of related works, the Literature Review section only considers studies that apply the cost function approach and include R&D spillovers. Thus, studies considering R&D and applying the cost function approach, without explicitly modeling spillovers, are excluded. There are also a number of studies directly estimating a Cobb-Douglas or other types of production functions, as well as studies regressing spillover and other variables on a measure of productivity or its growth; likewise, these are not reviewed. Furthermore, agricultural studies or spillovers from public/institutional sources are not considered. After the review section we present our theoretical model, methodology as well as present and analyze our results.

SOME TERMINOLOGY

Griliches (1992, p. S36) notes that the current economic literature employs two distinct notions of R&D spillovers. He writes:

> "In the first, R&D intensive inputs are purchased from other industries at less than their full "quality" price. … If capital equipment purchase price indices reflect fully the improvements in their quality, i.e., were based on hedonic calculations, there would be no need to deal with it. … But these are not real spillovers. They are just consequences of conventional measurement problems. True spillovers are ideas borrowed by research team of industry *i* from the research results of industry *j*."

However, as Nadiri (1993, p. 19) notes,

> "While in principle these two notions are quite distinct, in practice it is very hard to distinguish between them either analytically or statistically…".

Estimations commonly capture both types of spillovers, i.e., inputs may be bought at less than their full quality price and knowledge acquired through R&D may be transmitted to other firms without adequate compensation. In what follows, *spillovers* refer to the involuntary leakage of R&D generated knowledge regardless of the transmission channel.

Domestic R&D spillovers are commonly divided into *intra-industry spillovers*, originating from firms within the same industry, and *inter-industry spillovers*, originating from firms outside the representative firm's industry. Spillovers may also originate from foreign sources.

HISTORICAL BACKGROUND[2]

Finland has a relatively short history as independent nation and an even shorter one as an industrialized country. From the 13th century to the early 19th century Finland was a part of Sweden, after which it remained a grand duchy of Imperial Russia for about hundred years, before gaining independence in 1917.

Finland entered the industrialization phase in the mid-1800s – considerably later than the leaders of this 'revolution' (Vartia & Ylä-Anttila, 1996). Many of the economic institutions originate from the same era; although Finland was still a part of Imperial Russia at the time, its relatively autonomous status gave it considerable freedom in conducting internal matters. Finland got its own currency (*Markka*), and advances were made in transportation (railroad and waterways) and communications (telegraph). The dawn of Finnish industrialization was boosted by the removal of many previous restrictions on commercial activities as more liberal ideas took over mercantilism. Unsurprisingly for one of the most forested countries in the world, the forest industry formed the backbone of the economy. Steam- and hydro-powered sawmills were complemented by pulp and paper mills since the 1860s. Russia was a lucrative market, especially since import duties could be avoided.[3] Although the textile and metal industries also boomed at the time, Finland remained agrarian – as late as 1950 nearly half of the population was engaged in primary production.

During World War II Finland lost its war(s) against the Soviet Union but nevertheless remained one of the precious few countries in Europe not to suffer occupation. The price of independence was a loss of over one tenth of the territory, and payment of war reparations, mainly defined in terms of industrial goods.[4] This set the somewhat lagging industrialization of the country to a new course. Since physical capital stock as well as social and economic institutions remained functional during the war, Finland had a reasonably good starting point for paying its debt to the world and the war preparations to the Soviet Union. The government, which even in the pre-war era had a considerable role in many branches, had to step in to aid the necessary expansion of especially the metal industries, the output of which had to be doubled almost over night. By the mid-1950s the war preparations had been paid in full and the country could start earning desperately needed foreign currency through exports. As a historical consequence, the country had a relatively government and bank-centric economic structure until the early 1980s.

In the dawn of Finnish industrialization Britain, France, Germany, and the United States were the technology leaders of the world. Neither the Swedish Crown nor the Tsar of Russia had taken interest in promoting the technological development of Finland. A history of foreign subordination, harsh climate, lacking natural resources (with the notable exception of forests), and low standards of living did not give the nation promising prospects upon its birth. Even in the early post-war era, practically all industrial machinery and equipment were imported, and the final products remained standard. Yet, the Finnish ‘economic miracle’ is solidly founded on innovation and technology. Finns proved to be fast learners and in many areas they were able to catch, and sometimes even surpass, the early forerunners. According to Myllyntaus (1992, Table 1 in p. 199) eight historically most significant channels of this learning, or technology transfer, are:[5]

1. receiving foreign direct investment,
2. importing foreign machinery and equipment,
3. acquiring turn-key plants,
4. acquiring foreign licenses and patents,
5. setting up joint ventures,
6. recruiting professionals from abroad and permitting immigration,
7. encouraging and supporting nationals' professional and scholarly journeys abroad, and
8. utilizing low-cost or 'natural' diffusion of easily accessible technologies through trade and scientific publications, analysis of competitors products, etc.

While this list applies to any country in the world, social and cultural features of the nation determine the role of various channels of technology transfer.[6] In what follows we will discuss the role of each of the 'eight channels' in some detail.[7]

Many developing countries have little or no success in implementing even the simplest and freely available western innovations, i.e., they are unable to benefit from the afore-mentioned natural diffusion. While nearly all Finns could read in the beginning of the 20th century, the Finnish language, quite unlike major languages of the world, posed a problem to natural diffusion. Luckily, basic technical literature was available in Swedish, which was read by roughly one-fifth of the population. These people became, quite literally, transmitters. The 19th century Finns were aware of possible negative influences of foreign technology and wanted to implement it in their own terms. As Myllyntaus (1992, p. 208) puts it,

> "The Finns wished to strengthen their economy with rapid industrialisation but without loosing their national and cultural identity. For them, these goals were not conflicting."

Introduction of new technologies also included the definition of new terminology. As Finns had little knowledge of Indo-European languages, foreign terms lacked meaning to ordinary citizens. The Finnish professionals deliberately looked for native terms that would at least hint to the technology's use, making it easier for laymen to understand and accept technological advance. From the 1880s the inflow of German and Swiss scientific and technical literature expanded. World War II initiated the Anglo-American dominance in science and technology.

Traditionally Swedish immigrants have been the largest western group in the country. The Swedes, frequently skilled individuals, introduced many significant innovations to the Finns. Under the Russian rule military personnel was the biggest group of foreigners in the country. Their presence accelerated the modernization of administrative centers. Despite these historical developments, the immigrant population remains small: in the early 1990s roughly one per cent of the population were of foreign origin – the lowest figure in Western Europe. The relatively few foreigners have nevertheless had a significant role in technology transfer. On more than few occasions Finnish industrialists ordered a machine from a foreign engineering workshop and convinced the competent mechanic installing it to say for good (Myllyntaus, 1992, p. 215). Swedish immigrants contributed to development of virtually all branches; Britons pioneered textile, engineering and paper industries; Germans contributed to engineering, glass, wood-processing, and printing; Russians promoted food and beverage industries as well as hydro-powered sawmills; Norwegians improved timber floating, sawmills, and wood pulping; Danes and Swiss contributed to the dairy industry; etc. After World War II the role of foreign experts has steadily decreased due to the growing domestic knowledge stock.

Regularly a surprising number of Finns acquire knowledge abroad and then return to their home country. According to a 1911 study (Myllyntaus, 1992, p. 217), ten per cent of Finnish engineering workers had worked abroad and stayed there on average three years. While studies abroad have remained ‘in fashion’ with the possible exception of the inter-war period, the role of studies abroad as a channel of technology transfer has diminished since Word War II. Even today, however, post-graduate studies have a significant role in this respect.

The role of imported machinery can hardly be exaggerated as a channel of technology transfer in Finland. From early on Finns were competent users of imported technology, frequently making improvements on the acquired machinery. For over hundred years, the imports of capital goods exceeded exports. A turn took place in the early 1980s. Finns have gone from machinery importers to licensed producers to developers of genuine technologies.

Nowadays foreign direct investment is considered one of the more efficient ways of technology transfer. In the historical perspective we have adapted here, however, it constitutes of a relatively new phenomenon. Foreigners have owned plants in Finland as long as there has been industrial activity. In the dawn of Finnish industrialization mainly Russians owned ironworks and sawmills in Finland. In the 1870s Russian-owned ironworks accounted for as much as one fourth of pig iron production (Myllyntaus, 1992, p. 227). In sawmills foreign ownership (mainly Russian and Norwegian) reached similar heights in 1910s. In other industries foreign control was less pronounced. From 1930s to 1960s the government severely restricted foreign investment. Some restrictions on inward foreign direct investment remained in place until 1993 (Pajarinen, Rouvinen, & Ylä-Anttila, 1998). Outward foreign direct investment from Finland did not start in major scale until the early 1980s. It did so, however, with a bang. According to Pajarinen, Rouvinen, and Ylä-Anttila (1998) there is currently a considerable imbalance with inward and outward foreign direct investment; in 1997 the outward stock was two times greater than the inward stock.

Historically patents have played a minor role in Finnish technology transfer. The first patent in Finland was granted in 1842. Although patent laws were modernized in two occasions towards the end of the century, Finns seem to have patented at random or not at all. Most patents were granted to foreigners. Finns also acquired relatively few patents – in fact, many innovations were not patented at all in Finland and the ones that were, were frequently imitated or circumvented without permission. Patenting, and acquisition of patents, increased considerably since the 1960s. In the Finnish case licenses proved to be a more purposeful vehicle of technology transfer than patents. The importance of licensing peaked in the 1940s and 1950s – during the war preparations. Due to strict control on imports many foreign manufacturers were willing to license their technologies. As Finland has become more competent in applying acquired knowledge, and have also become an important source of technology itself, the role of patenting and licensing is currently on the rise.

Due to linguistic and socio-economic reasons, joint ventures have been commonplace in Finland. Traditionally, however, the Finnish participation has been limited to the ‘lending’ of a suitable name and nationality for conducting business. Until recently, the legislation has restricted foreign involvement in firms and has thus hindered joint ventures. While joint ventures have a minor role historically, they may prove to be important in the future as the Finnish telecommunications saga advances.

‘Turn-key’ plants have played a minor role in Finland, partly because of the relatively low number of joint ventures and volume of inward foreign direct investment. It has also been a source of national pride to contribute to the adaptation of foreign technologies. Deliveries of nuclear power plants in Olkiluoto and Loviisa, however, have been the few turn-key projects that have been recognized as important sources of technology transfer (Rouvinen, 1994, p. 20–1).

All-in-all it can be said that Finns have benefited greatly from imported technology and they have proved to be relatively fast learners. Their learning seem to take place by ‘doing’, manifested by the fact that licensing and imported equipment seem to be the relatively more important channels of technology transfer. Finns are accustomed to ‘coming-from-behind’ when it comes to technology – the country has historically been a receiver rather than a source of technology transfers. The rising level of technological expertise is, however, about to turn the tide. Rouvinen and Ylä-Anttila (1999, p. 375) note that

> “The competitive advantage of the Finnish economy and the firms in it has changed significantly as the Finnish industrial structure has shifted away from slow-growth industries towards knowledge-driven industries and clusters.”

The structural change has been exceptionally rapid and was made possible by the ability of firms and individuals to benefit from foreign knowledge via technology transfer and spillovers. Against the historical background, we would expect that spillovers would play a considerable role in the Finnish industry. On the other hand, shifting balance-of-powers in the technology sense, recent membership in the European Union, and increasing role of multinational enterprises may considerably change channels and magnitude of technology transfers and spillovers.

LITERATURE REVIEW

As mentioned above, we will only include studies that apply the cost function (dual) approach and consider R&D spillovers. Although the chosen scope is rather narrow, we were able to find more than a dozen of articles to be reviewed. About half of these studies involved Canadian data and/or authors. Besides research interests of influential scholars, this may be attributable to the availability of high quality data. With the exception of Mohnen (1992), none of the studies considered uses other than Canadian, Japanese or U.S. data.

Some data sets used span over almost thirty years, while the number of cross-sectional units is often rather limited. Since none of the estimations includes time-varying coefficients, one should perhaps prefer, if available, shorter time spans with a larger cross-section. Furthermore, with the data sets used, the degrees of freedom are lost rather rapidly due to the structure imposed.

Three studies (Bernstein, 1989; Bernstein & Nadiri, 1988; Bernstein & Nadiri, 1991) estimate the ‘weights’ on sources and beneficiaries of R&D spillovers rather than using some *a priori* assumption. Of the rest Mohnen and Lépine (1991) contradict the common practice of using unweighted sums of R&D stocks as spillover measures. Bernstein (1997) is an intermediate case were a separate spillover coefficient is assigned to one industry – electrical and electronic products.

All studies estimate parametric equation systems with fixed coefficients and, if imposed, deterministic parameter restrictions using either full information maximum likelihood (FIML), generalized methods of moments (GMM), or three stage least squares (3SLS). All apply neoclassical flexible or semi-flexible functional forms: close to half of the studies used a full or truncated translog; cost function specifications in the spirit of Diewert and Wales (1987; 1988) are applied equally often. The latter has a convenient feature that several theoretical conditions implied by microeconomic theory can be imposed explicitly, while, e.g., translog results have to be tested afterwards. On the other hand, the flexibility of this functional form, especially after imposing additional parameter restrictions to guarantee identification, is subject to dispute. Bernstein and Nadiri (1989) apply an interesting function form: it is quadratic in prices, linear in other variables, and happens to be self-dual, i.e., the form of the function is preserved over the production, cost, and value functions.

Approximately one-third of the studies consider the adjustment speeds or costs associate with physical and R&D capital stocks. Evidence is found for rather slow adjustment processes:

21–42% of the desired physical capital adjustment takes place within one year; figures for R&D capital are in the range of 14–36%. Furthermore, tens of per cents of the actual amount invested can be absorbed by adjustment costs.

Studies estimating spillover flow matrices seem to suggest that spillovers typically originate from a narrow range of industries. These results may, however, be driven by the collinearity of spillover measures across industries. Effects of spillovers on input intensities depend on the type of industry and the period in question.

Spillovers generally decrease average and variable costs. A negative impact on (i.e., an increase in) variable cost is, however, possible, since spillovers may reduce capital and R&D intensities, which may increase variable factor usage. A one per cent increase in spillovers causes a variable cost reduction in the range of -0.06 to 1.34%; a typical value is 0.10%. Bernstein & Nadiri (1991) present estimates on the effects of spillovers on price (through quality improvements) and on variable profit (through variable cost and price effects). Social net returns on R&D are found to be up to 12 times higher than the net private returns; a typical value is 50%.

In what follows we discuss the articles in detail. Studies considering intra-industry spillovers, which take place among firms within the same branch of industry, comprise the first group. The second group covers works dealing with inter-industry spillovers taking place between firms in different industries. The third group includes all other studies, i.e., those incorporating both spillover types or adding an international dimension of the spillover issue. Two adjacent paragraphs discuss each paper: the first gives some technical details of the paper while the second summarizes the results.

INTRA-INDUSTRY SPILLOVER STUDIES

Bernstein and Nadiri (1989) study intra-industry spillovers in four U.S. manufacturing industries from 1965 to 1978. Spillovers are defined as the sum of R&D capital stocks of all other firms in the industry. A firm minimizes the present value of costs over an infinite horizon, subject to technology constraints and adjustment costs of quasi-fixed factors, by selecting the rates of physical and R&D capital accumulation given the relative prices, output, and other firms' spilloverable knowledge capital. The suggested cost function is quadratic in factor prices and linear in output, capital stocks, and R&D spillovers. It has a convenient property of being self-dual (Lau, 1976), i.e., the form of the function is preserved over the production, cost, and value functions. Furthermore, it is consistent with aggregation across technologies (Epstein & Denny, 1983). A variable factor, physical and R&D capital demand equations define a three-equation system, which is estimated by non-linear FIML. Industries are considered separately and the model is estimated with and without firm effects.

The speed of adjustment of physical capital that occurred within a single year is found to be between 33% and 42%. The corresponding figures for R&D capital are 22% and 36%. With the exception of the machinery industry, the adjustment processes of the two types of capital are separable. The spillover coefficients are generally significant. Across industries intra-industry R&D spillovers substitute for both physical and R&D capital. Spillover receiving firms gained 0.05 to 0.13% reduction in average costs as a result of one per cent increase in the intra-industry spillovers. The social net rates of return on R&D are found to exceed the private ones by 30 to 123 percentage points.

Suzuki (1993) studies the effects of technology transfer and R&D spillovers within and among vertical *keiretsu* group firms in Japanese electrical machinery industry. His model is a variant of Bernstein and Nadiri (1991). The sample includes information on 9 core firms, i.e., *keiretsu* leaders, and 17 of their subcontractors from 1981 to 1989. Physical capital and R&D stocks are quasi-fixed; their adjustment costs are assumed quadratic and separable. The spillover stock is defined as the sum of other firms' R&D capital. Two variable cost share equations are determined using Shephard's lemma.[8] Euler equations are used to determine the demands for the quasi-fixed factors. A truncated translog variable cost equation, labor cost share equation, physical and R&D capital demand equations determined a four equation system estimated using GMM. The specification was estimated with and without branch effects.

For the core firms the marginal adjustment costs per unit of physical and R&D capital are, respectively, 2 and 12%. The corresponding figures for the subcontracting firms are 2 and 7%. Thus, fixity of the R&D capital is rather strong. It is shown that the technology transfer from the core firm to the subcontracting firms is significant: a one per cent increase in technology transfer reduces the variable cost of the subcontracting firm by 0.09%. The transfer is labor-using but material-reducing. Thus, the focus of technology transfer seems to have been on improving input material efficiency. Spillovers from subcontracting firms of other *keiretsu* groups magnify the effect of cost reduction from 0.09 to 0.11%. There is also positive spillovers from the R&D activities of other keiretsu groups, which are especially noteworthy among the core firms of competing *keiretsu*s: a one per cent increase in other core firms' R&D stocks causes a variable cost reduction of 0.08%. This spillover seems to be labor reducing but material using. There are no significant effects from the subcontractors of other *keiretsu* groups to the core firm.

INTER-INDUSTRY SPILLOVER STUDIES

Bernstein and Nadiri (1988) investigate the effects of inter-industry spillovers with data on five U.S. high-tech industries from 1958 to 1981. Each industry is treated as a separate spillover source. This enables the authors to evaluate a matrix of spillover sources and beneficiaries. A truncated translog cost function, without second order terms, is used. Variables cost shares of labor, materials, and physical capital are determined using Shephard's lemma.[9] The R&D capital is assumed quasi-fixed, and therefore short-run costs are not minimized with respect to it.[10] Each industry is considered separately. The cost function, labor and physical capital variable cost shares define a three-equation system, which is estimated by FIML. R&D capital and spillover variables are lagged by one period. Each spillover source was considered first separately, then in groups of two, three, and lastly four. The criteria for acceptance of an industry as a spillover source were the statistical significance and satisfaction on regularity conditions.

The authors find that there are significant differences among industries as both senders and receivers of spillovers. Across industries, variable cost shares are reduced by R&D spillovers. Spillovers typically emanate from a narrow range of industries: there is a single spillover source for three industries and the remaining two are affected by three industries. In four of the five industries there were factor bias effects associated with the spillovers. The biases for the labor and materials were always in the same direction and opposite to that of physical capital. In 1961 a one per cent increase in spillovers would have cause a variable cost decline from 0.03 to 0.21%, in 1971 from 0.04 to 0.12%, and in 1981 from 0.06 to 0.12%. The social rates or return varied greatly across industries. In electrical products and transportation equipment the social rates of return exceeded private ones only by 10 to 20%, while in scientific instruments the social rate or return was app. ten times higher than the private one.

Bernstein (1989) estimates the effects of inter-industry R&D spillovers on the production cost of nine major Canadian industries from 1963 to 1983. The paper applies Bernstein & Nadiri (1988, see above) framework.

In each industry at least some of the R&D spillover coefficients are significant at one per cent level. In six industries production costs are affected by at least two other source industries. Nonelectrical machinery, rubber and plastics, and chemical products are the main sources of inter-industry spillovers. Production cost reductions attributable to spillovers range from 0.005 to 1.082%. The private rates of returns on R&D generally exceeded those of physical capital by two and half times. The social rates of return on R&D were from two to four times higher than the private rates of return.

Bernstein and Nadiri (1991) estimate a model of inter-industry spillovers using data on six U.S. industries from 1957 to 1986. As in Bernstein and Nadiri (1988) and Bernstein (1989), each industry is treated as a distinct spillover source. Interestingly the authors also specify a representative inverse product demand function where R&D capital and spillovers are among the factors affecting demand. This is due to the assumption that embodied R&D has implications on product quality. Both capital types are assumed quasi-fixed. Firms make production decisions to maximize the expected present value of the flow of funds. A truncated translog cost function is used. Equilibrium conditions for variable cost, output, non-R&D capital input, and R&D capital input determined a four-equation system, which is estimated by using nonlinear 3SLS.

Marginal adjustment costs of physical capital ranged from 25 to 87% per unit of investment. For R&D capital, the range was from 7 to 46%. Each industry is a receiver of spillovers and, with the exception of fabricated metals, each is found a spillover source. Four industries were affected by a single, one by two, and one by three sources. R&D spillovers cause product prices to rise in the range of 0.05 to 0.16% for one per cent increase in spillovers. A similar increase in spillovers causes a variable cost reduction of 0.05 to 0.24%. With the exception of chemical products spillovers increase variable profit in the range of 0.050 to 0.086%. The social rate of return on R&D was 20 to 200% higher than the private net returns.

Mohnen and Lépine (1991) examine the interplay of R&D, spillovers, and foreign technology payments using data on 12 two- and three-digit Canadian industries in 1975, 1977, 1979, 1981, 1982, and 1983. Spillover stocks are constructed as patent flow weighted sums of other industries' R&D stocks. Besides labor and materials, foreign technology payments are modeled as a variable input. Physical capital and R&D stocks are treated as being quasi-fixed. A translog variable cost function is used. A system of two cost share equations and the variable cost function form a three equation system estimated with iterative 3SLS. The authors were careful in satisfying theoretical conditions for a cost function, which lead to the rejection of some potentially interesting second-order and cross terms.

It is found that higher R&D stocks are associated with higher foreign technology payments and labor usage. This complementary suggests that in order to benefit from imported technology own R&D is needed. Since second order terms for physical and R&D capital as well as for spillovers are excluded from the model on theoretical grounds, the authors are unable to reject the null hypothesis that these three variables are substitutes. The social rate of return on R&D turn is found to be on average app. 50% above the private one.

Bernstein (1997) considers the effects of inter-industry spillovers from electrical and electronic products for 10 Canadian manufacturing industries from 1966 to 1989. Electrical and electronic products industry is recognized as one inter-industry spillover source and all others except the representative one as a second one. Capital inputs are assumed quasi-fixed. A generalized McFadden type cost function is used (Diewert & Wales, 1987; Diewert & Wales, 1988). Two variable input and two capital demand equations determine a four equation system, which is estimated by FIML. Each industry is estimated separately.

A one per cent increase in spillovers from the non-electrical products industries reduces variable cost in the range of 0.04 to 0.89%. The effect of these spillovers on capital intensities is mixed. Spillovers increase R&D capital intensity in six industries. In seven industries physical capital intensity decreases as a response to spillovers. Non-capital inputs are typically complementary to the spillovers from the non-electrical products industries. A one per cent increase in spillovers from the electrical products industry reduces variable cost in the range of 0.01 to 0.45%. Again, the effect of these spillovers on capital intensities is mixed. R&D intensity decreases in five industries as a response to spillovers. Physical capital intensity decreases in six industries as a response to spillovers. Non-capital inputs are typically substitutes to the spillovers from the electrical product industry. Social rates of return on R&D are estimated to be 5 to 11 times greater than the private net returns on R&D.

OTHER SPILLOVER STUDIES

Bernstein (1988) estimates the effects of intra- and inter-industry R&D spillovers on the cost and production structures of seven Canadian SIC two-digit manufacturing industries using annual firm-level data from 1978 to 1981. Intra-industry R&D spillovers are defined as the sum of capital stocks of all firms in the industry except the representative one. Inter-industry spillovers are defined as the sum of firms' R&D capital stocks in all other industries. A translog cost function is used. The cost share of each factor is derived using Shephard's lemma. The R&D capital is accumulated by a series of stochastic and irreversible investments. Furthermore, none of the inputs is quasi-fixed; thus, the configuration denotes a long-run equilibrium. The three cost share equations,[11] one for labor as well as for physical and R&D capitals, and the translog production cost function determine a four-equation system to be estimated by FIML. Each industry is estimated separately. Two specifications, with and without firm effects, are considered.

The average production cost in the 'High-tech' industries (those with relatively large R&D cost shares) seem to be more responsive to intra-industry spillovers, while 'low-tech' industries are relatively more dependent on inter-industry spillovers. As for factor demands, inter-industry spillovers turn out to be substitutes for own R&D, i.e., firms 'free ride' on the efforts of other industries. The effect of intra-industry spillovers on R&D is smaller than that of inter-industry ones in absolute value: in the 'low-tech' industries substitution effect dominates whereas in the ‘high-tech’ industries intra-industry spillovers complement own research. Across industries labor demand decreases as a response to inter-industry spillovers. The same holds for materials with the exception of the aircraft and parts industry. The response of physical capital depends again on the R&D-intensity of the industry: substitution effect dominates in the low-tech industries while complementarities are found in the ‘high-tech’ branches. Intra-industry spillover effects are generally weaker than those of inter-industry ones and no clear patterns emerge. The social rates of return are also calculated; it is found that they exceed the net private returns by 25% to 115%. Intra-industry spillover effects dominate inter-industry ones; contributions to the social rate or return are 38% and 10%, respectively.

Mohnen (1992) studies the existence and magnitude of cross-country R&D spillovers among five leading R&D performing countries, i.e., the U.S., Japan, France, West Germany, and the U.K., using annual manufacturing data from 1964 to 1985. The spillover stock is defined as the sum of other countries’ R&D stocks and for a given country its supply is assumed to be fixed. Capital and R&D stocks are assumed to be quasi-fixed. The stock variables are lagged by one period. Inputs are chosen to minimize the present discounted value of variable and investment costs over an infinite horizon. The symmetric generalized McFadden functional form is applied (Diewert & Wales, 1987; Diewert & Wales, 1988). Two variable cost equations are derived using Shephard’s lemma. Optimal demands of the two quasi-fixed factors are given by Euler equations. The four-equation system is estimated using GMM.

The foreign R&D spillover decreases the demand for labor in all five countries. This is the case for intermediate inputs only in Japan and France. Foreign R&D yields greater cost reduction than own, and own and foreign R&D are complementary; spillovers partly explain convergence across countries. A complementarity between foreign R&D and own physical capital is also found.

Bernstein and Mohnen (1994) study how international spillovers between Japan and the United States affect the production structure, capital accumulation, and productivity in the two countries from 1962 to 1988. Two-digit data on eleven manufacturing industries for each country is aggregated using Fisher indexes. A bilateral model of production is developed by modifying

Jorgenson and Nishimizu (1978) and Jorgenson et al. (1990). Capital stocks are assumed to be quasi-fixed. An extension of the cost function suggested by Diewert and Wales (1987; 1988) is used. Variable factor demands are derived using Shephard's lemma. The demands of capital inputs are derived by minimizing the expected discounted stream of costs. A four-equation system is estimated using nonlinear MLE.

In the U.S. 21% of the physical capital adjustment takes place during the first year, while the corresponding figure for the R&D capital is 15%. In Japan, the figures are 22% and 14%, respectively. The adjustment parameters suggest that the two types of capital are adjustment complements, i.e., there is a benefit in adjusting them simultaneously. In the short run 1% increase in U.S. R&D capital decreases Japanese variable cost by 0.63%. In the U.S. the effect is only about 0.05%. International spillovers seem to reduce both labor and physical capital intensities. R&D intensities in both countries increase as a result of spillovers. In the long run 1% increase in U.S. R&D capital decreases Japanese variable cost by 1%. In the long run Japan decreases its R&D intensity as a response to the U.S. spillovers. In the U.S. the long run response is similar to the short-run one, i.e., U.S. does not substitute spillovers for own R&D. Analysis of the total factor productivity growth rates reveals that the U.S. spillovers contribute about 60% of Japanese total factor productivity growth, while Japanese spillovers have about 20% effect in the U.S.

Yan's **(1995)** dissertation considered R&D spillovers between Japanese and Canadian industries. Part of this work was refined in **Bernstein and Yan (1995)**, and published in its 'final' form in **Bernstein and Yan (1997)**. The discussion in the paragraph is based on the last paper mentioned. The effects of intra- and international R&D spillovers on the cost and production structures for ten Canadian and Japanese manufacturing industries from 1962 to 1988 are studied. Capital inputs are assume to be quasi-fixed. The authors pool Canadian and Japanese data and are thus dealing with a bilateral model of production (see, e.g., Jorgenson & Kuroda, 1990). Each industry is estimated separately. An extension of the functional form suggested by Diewert and Wales (1987) is being used. A four-equation system, with variable and capital input demands, is estimated using FIML.

International spillovers from Japan to Canada or *vice versa* seem to be rather weak. Domestic spillover effects dominate the international ones. A one per cent increase in domestic R&D spillover stock reduces the average variable cost in Japan from –.03 to .58%;[12] in Canada the range is from –.43 to .86%. International spillovers generally decrease average variable cost. R&D is the factor most influenced by spillovers. In Japan spillovers and R&D capital are complements; in Canada this is the case in six out of ten industries. With respect to other inputs, the effects of spillovers are mixed. In Canada the social rate of return on R&D is up to 12 times the private net return. In Japan the social rate of return can be over four times the private one.

THEORY

Modern microeconomic theory of firms distinguishes between production possibilities that are 'immediately feasible' and 'eventually feasible' (Varian, 1992, p. 2). In the short run some production possibilities are not feasible because some inputs can not be adjusted immediately and/or costlessly to their desired levels. These inputs are *quasi-fixed*; while adjustable over time, they are fixed in the short run. The remaining inputs are variable; an optimizing firm will maintain their desired levels at all times. Restricted technologies can be used to account for the distinction between the short run and the long run. Assuming some initial allocation of inputs and some technology of transferring inputs to output, a firm's production function is

$$y = F(\boldsymbol{q}_v, \boldsymbol{q}_f), \tag{1}$$

where y is output, $\boldsymbol{q}_v$ is a vector of variable and $\boldsymbol{q}_f$ is a vector of quasi-fixed inputs.[13] An optimizing firm will minimize the spending on variable inputs given the levels of output and quasi-fixed inputs. Assuming that the firm is a price-taker in the **input** markets, a restricted variable cost function can be defined as follows:

$$C^v(\boldsymbol{p}_v, \boldsymbol{q}_f, y) = \min_{\boldsymbol{q}_v}\{\boldsymbol{p}_v \boldsymbol{q}_v\}, \text{ given } y = F(\boldsymbol{q}_v, \boldsymbol{q}_f), (\boldsymbol{q}_f, y), \text{ and } \boldsymbol{p}_v, \tag{2}$$

where $\boldsymbol{p}_v$ is a vector of variable input prices.[14] Under certain conditions (see Appendix B) the cost function in Equation (2) is a 'sufficient statistic' to summarize the features of the firm's production structure. Shedhard's lemma conveniently gives us the optimal short-run demands of variable inputs:

$$\boldsymbol{q}_v^* = \frac{\partial C^v(\boldsymbol{p}_v, \boldsymbol{q}_f, y)}{\partial \boldsymbol{p}_v} = \boldsymbol{q}_v(\boldsymbol{p}_v, \boldsymbol{q}_f, y), \text{ given } (\boldsymbol{q}_f, y). \tag{3}$$

There are two main advantages of using a restricted cost function. First, the explicit solution of first order conditions of Equation (2) is avoided. Second, temporary equilibrium can be analyzed. The optimal amount of quasi-fixed inputs in obtained as a solution to the long-run maximization problem:

$$C(\boldsymbol{p}_v, \boldsymbol{p}_f, y) = \min_{\boldsymbol{q}_f}\{C^v(\boldsymbol{p}_v, \boldsymbol{q}_f, y) + \boldsymbol{p}_f \boldsymbol{q}_f\}, \text{ given } y, \tag{4}$$

where $\boldsymbol{p}_f$ is a vector of user costs or implicit rental prices of quasi-fixed inputs. The first order conditions of the optimization problem are:

$$\boldsymbol{p}_f = -\frac{\partial C^v(\boldsymbol{p}_v, \boldsymbol{q}_f, y)}{\partial \boldsymbol{q}_f} = \boldsymbol{\mu}(\boldsymbol{p}_v, \boldsymbol{q}_v^*, y) \tag{5}$$

As the asterisk (*) indicates, $\boldsymbol{\mu}(.)$ holds for the cost minimizing $\boldsymbol{q}_v$. Equation (5) is the well-known 'envelope condition'.[15] Functional $\boldsymbol{\mu}(.)$ is the shadow value of quasi-fixed factors. Under certain conditions the optimal demands of quasi-fixed inputs can be derived and the total cost minimizing demands of variable inputs solved.

One of the shortcomings of the above derivation is that it does not explicitly account for time (Berndt et al., 1981). In order to expand the stocks of quasi-fixed inputs, they have to be acquired through investment. Furthermore, existing stocks wear out in the production process. Let us define $\boldsymbol{i}_f$ as a vector of gross investments on quasi-fixed inputs purchased at prices $\boldsymbol{c}_f$ and assume that the firm minimizes the present value of production cost over an infinite horizon. *Ex ante* the firm expects output, prices and user costs to be equal to current prices.[16] Formally, the firm chooses a time path

$$\int_{\tau}^{\infty} e^{-r(t-\tau)}[\boldsymbol{p}_v \boldsymbol{q}_v^t + \boldsymbol{c}_f \boldsymbol{i}_f^t]dt = \int_{\tau}^{\infty} e^{-r(t-\tau)}[C^v(\boldsymbol{p}_v, \boldsymbol{q}_f^t, y) + \boldsymbol{c}_f(\dot{\boldsymbol{q}}_f^t + \delta \boldsymbol{q}_f^t)]dt \tag{6}$$

taking $\boldsymbol{q}_f^\tau$ and period τ values of exogenous variables as given. Term $(\dot{\boldsymbol{q}}_f^t + \delta \boldsymbol{q}_f^t)$ breaks the gross investments on quasi-fixed inputs ($\boldsymbol{i}_f^t$) to net investments ($\dot{\boldsymbol{q}}_f^t$) and replacement investments ($\delta \boldsymbol{q}_f^t$), where δ is the depreciation rate. The optimality condition turns out to be quite similar to the 'envelope condition' above, i.e.,

$$-\frac{\partial C^v(.)}{\partial \boldsymbol{q}_f^t} = (r+\delta)\boldsymbol{i}_f = \boldsymbol{p}_f \,, \tag{7}$$

but it is required to hold at every *t*. The above derivation does not explicitly account for adjustment cost. The presence of adjustment cost would seem to suggest that we should specify Equation (1) as $y = F(\boldsymbol{q}_v, \boldsymbol{q}_f, \dot{\boldsymbol{q}}_f)$. The cost function and variable input demands could still be specified as above, but the short run demand functions would be affected by the costs associated with the adjustments of quasi-fixed inputs. However, if we assume strong separability of quasi-fixed inputs ($F_{q_v \dot{q}_v} = G_{q_v \dot{q}_v} = 0$, subscripts here denote partial differentiation) the production function takes the following form:

$$y = F^1(\boldsymbol{q}_v, \boldsymbol{q}_f) - F^2(\dot{\boldsymbol{q}}_f)\,. \tag{8}$$

In this case we can think of Equation (1) as being observed net of adjustment costs,[17] and derive the model as done above. Since our focus in not on the explicit derivation of the adjustment paths of the quasi-fixed factors, we maintain the assumption of strong separability. Alternatively the Euler equations could be derived explicitly. This spoils down to specifying and solving a standard Hamiltonian system. While this is not difficult analytically, empirically this leads to a system that is nonlinear in both variables and parameters, making it difficult to reach reliable results (McCullough, 1999). As will be discussed below, our methodology will allow for random deviations from the stated envelope conditions via random coefficients and error terms.

METHODOLOGY

Parametric applications of duality theory require some assumptions regarding the functional form of the underlying technology. The Cobb-Douglas (1928) functional form (CD), first used in dual form by Nerlove (1963), is the best known and still widely used in econometric modeling producer behavior. Its main benefit is that it allows substitution among inputs. One of the shortcomings of the CD specification is that elasticities of substitution between inputs are always equal to unity. Arrow *et al.* (1961) offered a solution to this problem as they introduced the constant elasticity of substitution (CES) production function. Although elasticities of substitution were not constrained to unity, they would nevertheless be equal to each other. It was left to Diewert (1971) to introduce a functional form that would place no prior restrictions on substitution elasticities. Diewert's generalized Leontief functional form was a starting point of empirical literature on flexible functional forms exploiting duality between cost and production functions. Shortly thereafter Christensen, Jorgenson, and Lau (1973) introduced the transcendental (or translog) logarithmic functional form, which became the most popular alternative in the family of flexible functional forms. The translog cost function can be characterized as being a second-order Taylor series expansion of logarithms of an arbitrary cost function. This functional form is non-homothetic, and thus the combination of cost minimizing input quantities depends on the level of output. While the translog function is rather flexible, it does not guarantee that some of the desired properties of a cost function are satisfied. Furthermore, the number of parameters to be estimated grows quite rapidly as the number of productive inputs increase. Later contributions, e.g., the generalized McFadden cost function by Diewert and Wales (1987; 1988), tackle these issues.

In his *Handbook* Chapter Lau (1986, p. 1520) specifies five criteria for selecting functional forms in econometric model building:

1. theoretical consistency,
2. domain of applicability,
3. flexibility,
4. computational facility, and
5. factual conformity.

Theoretical consistency (1.) means that the chosen algebraic form must be capable of possessing the required theoretical properties for an appropriate choice of parameters. Domain of applicability (2.) refers to the set of values of the independent variables over which the functional form satisfies theoretical properties. In our context flexibility (3.) means that own and cross price elasticities can assume arbitrary values. Computational facility (4.) means that unknown parameters are easily estimated, functions of interest are expressed in explicit closed form, different functions in the system have the same algebraic form, and/or the number of parameters is the minimum number required to reach the desired effect. Factual conformity (5.) implies the consistency of the functional form with empirical facts.

As the literature review section indicates, the previous studies have generally applied either translog or symmetric generalized McFadden (SGM) cost functions. Let us concentrate on these two. SGM is capable of possessing desired theoretical properties; with translog we have to impose a few parameter restrictions and conduct some testing *ex post*. We can nevertheless confirm that translog indeed satisfies theoretical consistency. SGM can be forced to satisfy theoretical conditions globally. Imposing this requirement on translog may cause us to loose the flexibility of the model (this is illustrated in Mohnen & Lépine, 1991). It is, however, quite likely that the theoretical conditions are satisfied over the relevant domain also in the translog case. Translog remains flexible even after the standard parameter restrictions are imposed. From the outset SGM is semi-flexible. If quasi-fixed inputs are modeled, this flexibility is typically further reduced in order to guarantee the identification of the parameters in the system. SGM scores rather miserably in the computational facility department, at least when quasi-fixed inputs are included. It violates all by the last of Lau's four conditions of computational facility. Translog, on the other hand, performs nicely on the first three of these conditions, but may include a few extra parameters in some cases. How severe this shortcoming is, obviously depends on the degrees of freedom available. Following Lau's guidelines does not give a conclusive answer on the relative goodness of the two functional forms. A Monte Carlo study by Gagné and Ouellette (1998), however, convincingly shows that translog may be preferred over SGM. The authors (p. 123) state, that

> "When we constrained the SMF [i.e., SGM in our terminology]… to respect the curvature properties, these forms lost their capacity to test the other theoretical properties and to measure technological characteristics even when there are no errors in the data. At best, these forms should be considered as competing with the other forms, like the TL [translog], when curvature restrictions are not imposed."

This statement causes SGM to lose one of the two advantages it poses over translog. The other advantage of SGM over translog, parsimony in parameters, is not of great importance due to the data set at hand. Thus, in what follows we will use the translog cost function.[18]

A firm produces exogenously give output Q_y using two variable inputs subject to short-run cost minimization: *labor* (quantity: Q_l, price: P_l) and *materials* (quantity: Q_m, price: P_m). Thus, total variable cost is $C^v = P_m Q_m + P_l Q_l$. Two quasi-fixed inputs, *physical capital* (stock: Q_k, user cost: P_k) and *R&D capital* (stock: Q_r, user cost: P_r), are fixed in the short-run but adjustable over time. We also have measures for intra-industry (stock: S_1) and inter-industry (stock: S_2) spillovers.[19] As discussed above, we assume that our technology, presented by a dual cost function, has the translog form (Christensen et al., 1973; Jorgenson, 1986). After imposing symmetry (i.e., setting $\beta_{p_l p_m} = \beta_{p_m p_l}$, etc.) and defining lower case variables as natural logs (i.e., $p_l = \ln(P_l)$, etc.), we can write the variable cost function as follows:

$$\begin{array}{lllllll}
c^v = \beta_0 & & & & & & \\
+\beta_{p_m} p_m & +\beta_{p_l} p_l & +\beta_{q_k} q_k & +\beta_{q_r} q_r & +\beta_{s_1} s_1 & +\beta_{s_2} s_2 & +\beta_{q_y} q_y \\
+\beta_{p_m p_m} \frac{p_m^2}{2} & +\beta_{p_l p_m} p_l p_m & +\beta_{q_k p_m} q_k p_m & +\beta_{q_r p_m} q_r p_m & +\beta_{s_1 p_m} s_1 p_m & +\beta_{s_2 p_m} s_2 p_m & +\beta_{q_y p_m} q_y p_m \\
 & +\beta_{p_l p_l} \frac{p_l^2}{2} & +\beta_{q_k p_l} q_k p_l & +\beta_{q_r p_l} q_r p_l & +\beta_{s_1 p_l} s_1 p_l & +\beta_{s_2 p_l} s_2 p_l & +\beta_{q_y p_l} q_y p_l \\
 & & +\beta_{q_k q_k} \frac{q_k^2}{2} & +\beta_{q_r q_k} q_r q_k & +\beta_{s_1 q_k} s_1 q_k & +\beta_{s_2 q_k} s_2 q_k & +\beta_{q_y q_k} q_y q_k \\
 & & & +\beta_{q_r q_r} \frac{q_r^2}{2} & +\beta_{s_1 q_r} s_1 q_r & +\beta_{s_2 q_r} s_2 q_r & +\beta_{q_y q_r} q_y q_r \\
 & & & & +\beta_{s_1 s_1} \frac{s_1^2}{2} & +\beta_{s_2 s_1} s_2 s_1 & +\beta_{q_y s_1} q_y s_1 \\
 & & & & & +\beta_{s_2 s_2} \frac{s_2^2}{2} & +\beta_{q_y s_2} q_y s_2 \\
 & & & & & & +\beta_{q_y q_y} \frac{q_2^2}{2}
\end{array} \quad .(9)$$

Homogeneity can be imposed in two equivalent ways. We can either set $\beta_{p_m} + \beta_{p_l} = 1$ and $\beta_{p_m p_m} + \beta_{p_l p_m} = \beta_{p_l p_m} + \beta_{p_l p_l} = \beta_{q_k p_m} + \beta_{q_k p_l} = \beta_{q_r p_m} + \beta_{q_r p_l} = \beta_{s_1 p_m} + \beta_{s_1 p_l} = \beta_{s_2 p_m} + \beta_{s_2 p_l} = 0$ or normalize the variable cost and factor prices with respect to one variable input price. Imposing homogeneity reduces the cost function in Equation (9) to

$$
\begin{array}{llllll}
c^v - p_m = & & & & & \\
\beta_0 + \beta_{p_m} p_{ml} & +\beta_{q_k} q_k & +\beta_{q_r} q_r & +\beta_{s_1} s_1 & +\beta_{s_2} s_2 & +\beta_{q_y} q_y \\
+\beta_{p_l p_l} \frac{p_{ml}^2}{2} & +\beta_{q_k p_l} q_k p_{ml} & +\beta_{q_r p_l} q_r p_{ml} & +\beta_{s_1 p_l} s_1 p_{ml} & +\beta_{s_2 p_l} s_2 p_{ml} & +\beta_{q_y p_l} q_y p_{ml} \\
 & +\beta_{q_k q_k} \frac{q_k^2}{2} & +\beta_{q_r q_k} q_r q_k & +\beta_{s_1 q_k} s_1 q_k & +\beta_{s_2 q_k} s_2 q_k & +\beta_{q_y q_k} q_y q_k \\
 & & +\beta_{q_r q_r} \frac{q_r^2}{2} & +\beta_{s_1 q_r} s_1 q_r & +\beta_{s_2 q_r} s_2 q_r & +\beta_{q_y q_r} q_y q_r \\
 & & & +\beta_{s_1 s_1} \frac{s_1^2}{2} & +\beta_{s_2 s_1} s_2 s_1 & +\beta_{q_y s_1} q_y s_1 \\
 & & & & +\beta_{s_2 s_2} \frac{s_2^2}{2} & +\beta_{q_y s_2} q_y s_2 \\
 & & & & & +\beta_{q_y q_y} \frac{q_y^2}{2}
\end{array}
,\quad (10)
$$

where $p_{ml} = (p_m - p_l)$.[20] Lets us redefine, for notational convenience, $p_l = p_{ml}$ and $vc = c^v - p_m$. Now the cost function can be written as follows:

$$
\begin{array}{lllllll}
vc = \beta_0 & +\beta_{p_l} p_l & +\beta_{q_k} q_k & +\beta_{q_r} q_r & +\beta_{s_1} s_1 & +\beta_{s_2} s_2 & +\beta_{q_y} q_y \\
 & +\beta_{p_l p_l} \frac{p_l^2}{2} & +\beta_{q_k p_l} q_k p_l & +\beta_{q_r p_l} q_r p_l & +\beta_{s_1 p_l} s_1 p_l & +\beta_{s_2 p_l} s_2 p_l & +\beta_{q_y p_l} q_y p_l \\
 & & +\beta_{q_k q_k} \frac{q_k^2}{2} & +\beta_{q_r q_k} q_r q_k & +\beta_{s_1 q_k} s_1 q_k & +\beta_{s_2 q_k} s_2 q_k & +\beta_{q_y q_k} q_y q_k \\
 & & & +\beta_{q_r q_r} \frac{q_r^2}{2} & +\beta_{s_1 q_r} s_1 q_r & +\beta_{s_2 q_r} s_2 q_r & +\beta_{q_y q_r} q_y q_r \\
 & & & & +\beta_{s_1 s_1} \frac{s_1^2}{2} & +\beta_{s_2 s_1} s_2 s_1 & +\beta_{q_y s_1} q_y s_1 \\
 & & & & & +\beta_{s_2 s_2} \frac{s_2^2}{2} & +\beta_{q_y s_2} q_y s_2 \\
 & & & & & & +\beta_{q_y q_y} \frac{q_y^2}{2}
\end{array}
.\quad (11)
$$

As discussed in the Theory section, Shepard's lemma conveniently gives us the variable cost share equations.[21] The variable cost share of labor (s_l) can be written as follows:

$$s_l = \beta_{p_l} + \beta_{p_l p_l} p_l + \beta_{q_k p_l} q_k + \beta_{q_r p_l} q_r + \beta_{s_1 p_l} s_1 + \beta_{s_2 p_l} s_2 + \beta_{q_y p_l} q_y . \quad (12)$$

Similarly, from the envelope conditions we get the 'variable cost shares' of quasi-fixed inputs (s_f), i.e., the ratios of quasi-fixed input related expenditures ($p_f q_f$) and variable cost. These 'shadow equations' of quasi-fixed inputs can be written as follows:

$$
\begin{array}{lllllll}
s_k = -\beta_{q_k} & -\beta_{q_k p_l} p_l & -\beta_{q_k q_k} q_k & -\beta_{q_r q_k} q_r & & -\beta_{s_1 q_k} s_1 & -\beta_{s_2 q_k} s_2 & -\beta_{q_y q_k} q_y \\
s_r = -\beta_{q_r} & -\beta_{q_r p_l} p_l & & -\beta_{q_r q_k} q_k & -\beta_{q_r q_r} q_r & -\beta_{s_1 q_r} s_1 & -\beta_{s_2 q_r} s_2 & -\beta_{q_y q_r} q_y
\end{array}
.\quad (13)
$$

Equations (11), (12), and (13) form a four equation system to be estimated by using an appropriate econometric method. We are facing three challenges in choosing the econometric method:

1. how to account appropriately for the panel nature of the data,
2. how to account for the fact that firms may differ in other respects besides having different levels of observed variables, and
3. how to allow for random deviations from the stated optimality conditions.

Most previous studies have assumed a common coefficient structure, possibly with some 'fixed effects', e.g., unit specific intercepts. A number of studies simply pool time-series cross-section observations and in the process implicitly place considerable restrictions on the variance-covariance structure of the error term(s), i.e, do not account for the panel nature of the data. In our context allowing for any type of unit-specific fixed effects would introduce hundreds of additional parameters to be estimated. Furthermore, we expect the heterogeneity to take a complex and unpredictable form, since we are not limiting ourselves to a specific industry or type of firm.

The *random coefficient approach* proposed in Biørn, Lindquist, and Skjerpen (1998) is one attractive alternative in our case.[22] It can be applied to unbalanced panels and systems of equations while allowing for unit specific heterogeneity in some coefficients. As will be discussed shortly, it will address all the three issues listed above. Furthermore, since this approach is in fact a special case of the 'mixed' modeling approach – combining both fixed and random effects – it can be extended to include some fixed effects, degrees of freedom permitting of course.

The idea of the random coefficient approach is that, rather than arguing that a coefficient is common across the sample units, it is thought that we observe a sample of true coefficients drawn from some distribution. A 'random' coefficient has a mean, which can be interpreted as the coefficient estimate of an average unit, and an error term associated with it. The ultimate variance-covariance matrix will measure heterogeneity in both the 'regular' error term and the heterogeneity associated with the random coefficients. Let us concentrate on firm i at time t. The four equation system discussed above can be expressed compactly as follows:

$$\boldsymbol{y}_{it} = X_{it}\boldsymbol{\beta}_{it} + \boldsymbol{u}_{it} \, , \tag{14}$$

where $\boldsymbol{y}_{it}$ is a vector of dependent variables, X_{it} is a matrix of independent variables, $\boldsymbol{\beta}_{it}$ is a coefficient vector, and $\boldsymbol{u}_{it}$ is the 'composite' error term of firm i at time t. More precisely,

$$\boldsymbol{y}=\begin{bmatrix} s_r \\ s_k \\ s_l \\ vc \end{bmatrix},\ X'=\begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & p_l \\ 0 & -1 & 0 & q_k \\ -1 & 0 & 0 & q_r \\ 0 & 0 & 0 & s_1 \\ 0 & 0 & 0 & s_2 \\ 0 & 0 & 0 & q_y \\ 0 & 0 & p_l & \frac{1}{2}p_l^2 \\ 0 & -p_l & q_k & q_k p_l \\ -p_l & 0 & q_r & q_r p_l \\ 0 & 0 & s_1 & s_1 p_l \\ 0 & 0 & s_2 & s_2 p_l \\ 0 & 0 & q_y & q_y p_l \\ 0 & -q_k & 0 & \frac{1}{2}q_k^2 \\ -q_k & -q_r & 0 & q_r q_k \\ 0 & -s_1 & 0 & s_1 q_k \\ 0 & -s_2 & 0 & s_2 q_k \\ 0 & -q_y & 0 & q_y q_k \\ -q_r & 0 & 0 & \frac{1}{2}q_r^2 \\ -s_1 & 0 & 0 & s_1 q_r \\ -s_2 & 0 & 0 & s_2 q_r \\ -q_y & 0 & 0 & q_y q_r \\ 0 & 0 & 0 & \frac{1}{2}s_1^2 \\ 0 & 0 & 0 & s_2 s_1 \\ 0 & 0 & 0 & q_y s_1 \\ 0 & 0 & 0 & \frac{1}{2}s_2^2 \\ 0 & 0 & 0 & q_y s_2 \\ 0 & 0 & 0 & \frac{1}{2}q_y^2 \end{bmatrix},\ \boldsymbol{\beta}=\begin{bmatrix} \beta_0 \\ \beta_{p_l} \\ \beta_{q_k} \\ \beta_{q_r} \\ \beta_{s_1} \\ \beta_{s_2} \\ \beta_{q_y} \\ \beta_{p_l p_l} \\ \beta_{q_k p_l} \\ \beta_{q_r p_l} \\ \beta_{s_1 p_l} \\ \beta_{s_2 p_l} \\ \beta_{q_y p_l} \\ \beta_{q_k q_k} \\ \beta_{q_r q_k} \\ \beta_{s_1 q_k} \\ \beta_{s_2 q_k} \\ \beta_{q_y q_k} \\ \beta_{q_r q_r} \\ \beta_{s_1 q_r} \\ \beta_{s_2 q_r} \\ \beta_{q_y q_r} \\ \beta_{s_1 s_1} \\ \beta_{s_2 s_1} \\ \beta_{q_y s_1} \\ \beta_{s_2 s_2} \\ \beta_{q_y s_2} \\ \beta_{q_y q_y} \end{bmatrix},\ \text{and}\ \boldsymbol{u}=\begin{bmatrix} u_{s_r} \\ u_{s_k} \\ u_{s_l} \\ u_{vc} \end{bmatrix}. \tag{15}$$

The system has G=4 equations and K=28 coefficients. The coefficient vector of firm i takes the form

$$\boldsymbol{\beta}_i=\boldsymbol{\beta}+\boldsymbol{\delta}_i\,, \tag{16}$$

where $\boldsymbol{\beta}$ is a common vector and $\boldsymbol{\delta}_i$ is a zero mean disturbance vector associated with firm i. By inserting Equation (16) in Equation (14) we get

$$\boldsymbol{y}_{it}=X_{it}\boldsymbol{\beta}+X_{it}\boldsymbol{\delta}_i+\boldsymbol{u}_{it}\,. \tag{17}$$

We will assume that $\boldsymbol{u}_{it}\sim \mathrm{IIN}(\mathbf{0}_{G\times 1},\Sigma^u_{G\times G})$, $\boldsymbol{\delta}_{it}\sim \mathrm{IIN}(\mathbf{0}_{K\times 1},\Sigma^\delta_{K\times K})$,[23] and that both are independent of each other and X_{it}. While Σ^u is a full-rank positive definite matrix, Σ^δ may have less than full-rank if some coefficients are not assumed to be random. Let us assume that the firm is observed for p years and stack up the p of firm i. Now we can express the 'gross disturbance' variance-covariance matrix of firm i as follows:

$$\Omega_i = X_i \Sigma^{\delta} X_i^{'} + I_p \otimes \Sigma^u .^{24} \tag{18}$$

The joint log-density of $\boldsymbol{y}_i$ conditional on X_i is

$$L_i = -\tfrac{Gp}{2}\ln(2\pi) - \tfrac{1}{2}\ln\left|\Omega_i\right| - \tfrac{1}{2}\left[\boldsymbol{y}_i - X_i\boldsymbol{\beta}\right]'\Omega_i^{-1}\left[\boldsymbol{y}_i - X_i\boldsymbol{\beta}\right]. \tag{19}$$

Let us order the firms in our sample by the number of years (p) they are observed.[25] The log-likelihood function of all observations can be written as

$$L = \sum_{p=3}^{P}\sum_{i=1}^{N} L_i = -\tfrac{Gn}{2}\ln(2\pi) - \tfrac{1}{2}\sum_{p=3}^{P}\sum_{i=1}^{N}\ln\left|\Omega_i\right| - \tfrac{1}{2}\sum_{p=3}^{P}\sum_{i=1}^{N}\left[\boldsymbol{y}_i - X_i\boldsymbol{\beta}\right]'\Omega_i^{-1}\left[\boldsymbol{y}_i - X_i\boldsymbol{\beta}\right]. \tag{20}$$

The unknown elements in Equation (20), $\boldsymbol{\beta}$, Σ^u, and Σ^{δ}, are obtained by maximizing L with respect to these parameters. We use maximum likelihood to obtain the parameter estimates. The problem at hand is quite complicated, especially if the number of random coefficients in large. In what follows we allow for four random coefficients, namely β_0, β_{p_l}, β_{q_k}, and β_{q_r}, which correspond to the intercepts in each of the four equations.

Our main data sources are *Statistics Finland*'s R&D surveys and industrial statistics from 1985 to 1997. We formed a firm-level unbalanced panel of all manufacturing firms included in the 1995 R&D survey and having sufficient and consistent information on at least three consecutive years. Our sample includes 437 firms observed for three to thirteen years. We have a total of 2573 time-series cross-section observations. See Appendix A for further details.

RESULTS

Table 1 presents the estimation results of the system discussed above. The coefficients are generally statistically significant at any conventional level. The constant term, β_0, is significant only at 10% level, but since it is of no interest to us this is not an issue of concern. Slightly more alarming is insignificance of the first and second order terms for inter-industry spillovers (β_{s_2} and $\beta_{s_2 s_2}$) – this may also be an indications of multicollinearity between the two spillover measures. Due to the presence of cross and second order terms, some coefficients of the translog system are not directly interpretable. The first order seem to have expected signs; higher stocks of quasi-fixed inputs or spillovers all reduce variable cost.

Table 1. Coefficient estimates, standard deviations, and t-values of the model.

Coefficient	Value	Std. dev.	t-value	Prob.
β_{0}	23.071	14.009	1.650	0.100
β_{pl}	1.498	0.129	11.600	0.000
β_{qk}	-0.578	0.059	-9.720	0.000
β_{qr}	-0.311	0.046	-6.720	0.000
β_{s1}	-0.841	0.217	-3.880	0.000
β_{s2}	-1.907	1.553	-1.230	0.219
β_{qy}	1.654	0.191	8.650	0.000
β_{plpl}	0.027	0.006	4.150	0.000
β_{qkpl}	0.032	0.002	15.070	0.000
β_{qrpl}	0.012	0.002	6.250	0.000
β_{s1pl}	-0.010	0.003	-3.750	0.000
β_{s2pl}	-0.021	0.007	-2.820	0.005
β_{qypl}	-0.096	0.003	-33.200	0.000
β_{qkqk}	-0.048	0.001	-36.300	0.000
β_{qrqk}	-0.001	0.001	-0.980	0.329
β_{s1qk}	0.003	0.001	2.350	0.019
β_{s2qk}	0.024	0.003	7.130	0.000
β_{qyqk}	0.048	0.002	30.410	0.000
β_{qrqr}	-0.028	0.001	-26.100	0.000
β_{s1qr}	0.004	0.001	3.970	0.000
β_{s2qr}	0.010	0.003	3.870	0.000
β_{qyqr}	0.027	0.001	23.620	0.000
β_{s1s1}	-0.025	0.005	-5.160	0.000
β_{s2s1}	0.069	0.012	5.720	0.000
β_{qys1}	-0.004	0.003	-1.330	0.183
β_{s2s2}	0.062	0.088	0.700	0.481
β_{qys2}	-0.043	0.010	-4.180	0.000
β_{qyqy}	-0.048	0.004	-11.630	0.000

Model information:	A FIML estimation of a 4 equation system (variable cost function, labor cost share, and the 'envelope conditions' for physical and R&D capital stocks) with 28 param.	
Overall fit:	Log likelihood value:	17723.49
	Akaike's information criterion:	17703.49
	Schwarz's Bayesian criterion:	17631.10
Sample information:	Number of cross-sectional units (firms):	437
	Number of time-series observations (years):	3–13
	Number of time-series cross-section observations:	2573

Note: Estimated using PROC MIXED in SAS/STAT version 6.12 in an IBM Unix mainframe computer.

Table 2 presents the mean estimates of the variance-covariance matrix elements of both the genuine error term and the random coefficient related error components. As can be seen, the error components associated with the R&D capital stock are, relatively speaking, quite high.

Table 2. Covariance matrix estimates of the genuine error terms and random coefficients.

The covariance matrix estimates of the genuine error terms (averages).

	u_r	u_k	u_l	u_{vc}
u_r	0.379973			
u_k	-0.007244	0.009332		
u_l	-0.022782	0.000671	0.001851	
u_{vc}	-0.011258	0.000069	0.000198	0.000990

The covariance matrix estimates for random coefficients (averages).

	β_0	β_{pl}	β_{qk}	β_{qr}
β_0	0.000253			
β_{pl}	0.000118	0.000461		
β_{qk}	0.000261	0.000220	0.001820	
β_{qr}	-0.000530	-0.000298	-0.002038	0.012260

Note: See Table 1 for model and estimation information.

The results become much more readily interpretable once we define and calculate a few statistics familiar from the microeconomic theory of firm. Caves, Christensen, and Swanson (1981, p. 995) define *returns to scale* (RTS) as

> "…the proportional increase in all outputs resulting from a proportional increase in all inputs… $RTS = -\sum F_{Xi} \big/ \sum F_{Yi}$."[26]

For a translog variable cost function this translates to (the summation in the denominator collapses to a single term in case of a single output) [27]

$$\sigma = \left\{ 1 - \sum_f \widehat{\frac{\partial vc}{\partial q_f}} \right\} \bigg/ \widehat{\frac{\partial vc}{\partial q_y}} . \tag{21}$$

The Allen-Uzawa (Allen, 1966 (first edition 1938); Uzawa, 1962)[28] partial and cross substitution elasticities among variable inputs can be define as follows (Berndt, 1991; Nadiri, 1982):[29]

$$\begin{aligned} e_{ij} &= \frac{\hat{\beta}_{p_i p_j} + \hat{s}_i \hat{s}_j}{\hat{s}_i \hat{s}_j}, \text{ for } i, j = l, m \text{ and } i \neq j \\ e_{ii} &= \frac{\hat{\beta}_{p_i p_i} + \hat{s}_i^2 - \hat{s}_i}{\hat{s}_i^2} + 1, \text{ for } i = l, m \end{aligned} \quad . \tag{22}$$

Note that parameter estimates and fitted shares are used above. This implies that estimated elasticities will vary across observations. Since parameter estimates and fitted share have variances and covariances, the substitution elasticities have stochastic distributions that are nonlinear functions of these parameter estimates and fitted shares. Price elasticities may be preferred to the partial elasticities, as they are more readily interpretable. The price elasticities of demand are defined to be $de_{ij} = \hat{s}_j e_{ij}$, i.e.,

$$\begin{aligned} de_{ij} &= \frac{\hat{\beta}_{p_i p_j} + \hat{s}_i \hat{s}_j}{\hat{s}_i}, \text{ for } i, j = l, m \text{ and } i \neq j \\ de_{ii} &= \frac{\hat{\beta}_{p_i p_i} + \hat{s}_i^2 - \hat{s}_i}{\hat{s}_i} + 1, \text{ for } i = l, m \end{aligned} . \tag{23}$$

The variable cost (or productivity) elasticities associated with each of the R&D spillovers can be calculated a partial derivative of the translog variable cost function with respect to the (log of) spillover measures, i.e., $\widehat{\partial vc/\partial s_{1,2}}$. Factor bias elasticities with respect to variable inputs can be studied by calculating the partial derivatives of the cost share Equation (12), i.e., $\widehat{\partial s_l/\partial x}$, where $x = q_{k,r}, s_{1,2}$. Factor biases with respect to quasi-fixed inputs can be studied similarly. Note, however, that we have to account for the negative signs in Equation (13). The private rate of return on capital is defined by the real value of the variable cost reduction due to an increase in a firm's capital stock. The private rates of return on the capital inputs are calculated as follows (Bernstein, 1989):

$$\rho_f = -\frac{\widehat{\partial C^v / \partial Q_f}}{C_f} = -\frac{\frac{\widehat{C^v}}{Q_f} \frac{\widehat{\partial c^v}}{\partial q_f}}{C_f} . \tag{24}$$

The social rate or return can be obtained by considering the effects an increase in a firm's R&D efforts has on other firms. The concept of the social rate or return is not directly applicable here, since we estimate the model over the whole sample, in which case an increase in a firm's R&D efforts have no effect on the spillover measures of the model. However, if it is found that spillovers reduce variable cost, the social rates of return must exceed the private ones. We can get some fell for the social rate or return on R&D by calculating

$$\gamma_r = \hat{\rho}_r - \frac{\widehat{\partial C^v / \partial S_1}}{C_r} - \frac{\widehat{\partial C^v / \partial S_2}}{C_r} . \tag{25}$$

The above measures may or may not depend on the exogenous variables. If they do, we get a separate value for each firm in each year. In what follows we will calculate the above-discussed measures.

We calculated the fitted cost shares needed to perform some of the afore-mentioned calculations. They are bound between zero and one at all data points as expected, suggesting that the estimated translog system in indeed monotonically increasing in variable input prices (Berndt, 1991, p. 476). Strictly speaking, the concavity and convexity conditions require that the Hessian matrices of $\left[\widehat{\partial^2 C^v / \partial P_i \partial P_j}\right]$, where i and j refer to the variable inputs, and $\left[\widehat{\partial^2 C^v / \partial Q_k \partial Q_l}\right]$, where k and l refer to the quasi-fixed inputs, are negative semi-definite and positive semi-definite, respectively.[30] However, as Dixon, Garcia, and Anderson (1987, p. 625) note,

> "… a validation of [curvature conditions]… is approximate because it is implicitly being assumed that the parameters of the translog are equal to their estimates. It seems that if an observation fails to… [satisfy the curvature conditions]… but is "close" to… [satisfying them], then the hypothesis of [appropriate curvature conditions] would not be rejected…" [31]

For stochastically simulated data, known to satisfy the curvature conditions by construction, the authors note that convexity is rejected for about one third of the translog models. Furthermore, imposing curvature conditions globally or over a large range of variable values restricts the flexibility of functional forms (Terrell, 1996). Against this background, and keeping in find that we have 'less-than-perfect' real world data, it is expected that not every data point will satisfy the curvature conditions. Given our sample size, we could choose to ignore the data points with undesirable theoretical properties, but this could bias our results. Our calculations reveal concavity and convexity conditions are clearly satisfied at the mean values of the exogenous variables. We calculated the elements of the Hessian matrices for each observation in order to further examine the curvature conditions. In four out of 2,573 cases the diagonal elements of $\left[\widehat{\partial^2 C^v / \partial P_i \partial P_j}\right]$ fail to be negative; in a number of cases the determinant fails to be negative even though the diagonal elements are. All in all the concavity condition is satisfied at over 72% of the data points. The convexity condition is slightly more problematic. The diagonal elements of $\left[\widehat{\partial^2 C^v / \partial Q_k \partial Q_l}\right]$ are on average close to zero, causing frequent violations of the convexity conditions, satisfied by 54% of the data points. However, if we add to each diagonal element just one tenth of its standard deviation across observations, over 87% of the data points satisfy convexity. Thus, we conclude that the curvature conditions are sufficiently ‘close to’ being satisfied.

In Table 3 the measures discussed above have been calculated numerically. The system seems to exhibit modest increasing short-run returns to scale. The own price elasticities of substitution indicate that variable input demands are inelastic: one per cent increase in labor (materials) cost would reduce its demand by .66% (.24%). The cross price elasticities indicate that labor and materials are substitutes.[32] Capital inputs and labor are complements. As a consequence of the parameter restrictions imposed, capital inputs and materials must be substitutes.

On average a 1% increase in intra-industry spillover stock reduces variable cost by .01%. The effect of a similar increase of inter-industry spillovers is somewhat larger at .03%, but it is subject to doubt due to insignificant coefficient estimates the first and second order terms in Table 1. Both intra- and inter-industry spillovers seem to be labor reducing and material using – this may be due to the fact that labor saving process innovations may be more readily ‘spilloverable’ than potentially material using product innovations. The ‘shadow elasticities’ of capital inputs with respect to spillovers all have a negative sign, indicating that spillovers reduce the willingness to accumulate and pay for capital inputs. In the case of R&D, this finding is quite intuitive, as it can be thought that spillovers can substitute for own R&D efforts.[33] In the case of physical capital, there were no clear *a priori* expectations. The result with respect to physical capital is not driven by a cross-effect between the two capital inputs (recall that in Table 1 coefficient $\beta_{q_r q_k}$ insignificant and close to zero in absolute value).

Rates of return vary greatly across units and time – so wildly in fact, that the mean estimates of these values do not appear to make much sense. Note that the arithmetic means of private and social rate of return are negative![34] The column indicating minimum values hints, however, that the results may be driving by some extremely low values, e.g., by major R&D efforts of some companies that have gone bust. If we drop the top and bottom 5% tails for each of the rate of return distributions, we get the figures at the bottom of Table 3 (indicated by *mid-90%*). These results seem more intuitive and more in line of previous research. Gross rate on return on physical capital is app. 17% and for R&D capital 18%. The social rate of return on R&D capital exceeds the private one by 10%.

Table 3. Variables derived from the coefficient estimates and exogenous variables.

	Estimate	Std. dev.	Min.	Max.
Short-run returns to scale	1.0487	0.0377	0.9377	1.1476
Price elasticities of substitution	Estimate	Std. dev.	Min.	Max.
Labor (own)	-0.6672	0.5501	-17.956	0.3625
Materials (own)	-0.2439	0.1825	-1.1760	0.3897
Labor and mat. (cross)	0.5986	0.1751	-6.0080	0.6742
Mat. and labor (cross)	0.2545	0.0811	-0.0228	0.4792
Variable factor biases	Estimate	Std. dev.	Min.	Max.
Labor and capital	0.0316	(see coefficient estimate β_{qkpl} above)		
Labor and R&D	0.0120	(see coefficient estimate β_{qrpl} above)		
Labor an intra-industry spillovers	-0.0105	(see coefficient estimate β_{s1pl} above)		
Labor an inter-industry spillovers	-0.0205	(see coefficient estimate β_{s2pl} above)		
Quasi-fixed factor biases	Estimate	Std. dev.	Min.	Max.
Physical capital and intra-industry sp.	-0.0030	(see coefficient estimate β_{s1qk} above)		
Physical capital and inter-industry sp.	-0.0241	(see coefficient estimate β_{s2qk} above)		
R&D capital and intra-industry spillovers	-0.0039	(see coefficient estimate β_{s1qr} above)		
R&D capital and inter-industry spillovers	-0.0101	(see coefficient estimate β_{s2qr} above)		
Effects of spillovers on variable cost	Estimate	Std. dev.	Min.	Max.
Intra-industry spillovers	-0.0128	0.0460	-0.1337	0.0848
Inter-industry spillovers	-0.0325	0.0932	-0.3531	0.1468
Private and social rates of return	Estimate	Std. dev.	Min.	Max.
Physical capital (private)	0.1163	0.3831	-7.9594	0.4338
R&D capital (private)	-0.1327	1.9899	-32.320	1.1018
R&D capital (social)	-0.0642	2.0507	-32.311	10.260
Private and social rates of return (mid-90%)	Estimate	Std. dev.	Min.	Max.
Physical capital (private)	0.1687	0.0682	-0.1660	0.2633
R&D capital (private)	0.1824	0.3279	-1.742	0.4894
R&D capital (social)	0.2015	0.3236	-1.653	0.6292

Note: The standard deviation, minimum, and maximum refer to the series calculated as a function of exogenous variables and coefficients (see above). The are provided in order to give a general feel for the range of the derived variable and as such should not be used to discuss the ‘significance’ of the estimate.

ANALYSIS

Our results suggest that there may be slight short-run increasing returns to scale in Finnish manufacturing. Demands for variable inputs, labor and materials (including intermediate inputs and acquired services), are inelastic with respect to their price changes. The rather high cross price elasticity of substitution between labor and materials is not inconsistent with the argument that firms respond to increases in labor costs by outsourcing their business activities. There seems to be a small, but robust, positive relationship between capital investment and labor demand.

We find evidence for spillovers among Finnish manufacturing firms in the same industry – findings on spillovers across industries are inconclusive. The variable cost reduction associated with spillovers is somewhat lower than what is suggested in the literature. Spillovers reduce the demand for labor but increase the demand for materials. Spillovers also reduce the willingness to pay for capital inputs. As far as R&D capital is concerned, this is rather intuitive: to some extend spillovers are a substitute to own R&D efforts. In the case of physical capital, the interpretation is less obvious. It would seem plausible to argue that any knowledge gathering, whether via own R&D or spillovers, would promote a shift from a capital-intensive to a more knowledge-driven production. This argument, however, does not seem to hold water with respect to own R&D (recall the insignificant cross-term coefficient). The absolute coefficient estimate value would seem to suggest that the inter-industry spillovers in particular are a source of physical capital saving innovations.

We also calculated the rates of return of the capital inputs. The real rate of return on physical capital (gross of depreciation) is on average 16.9%.[35] The private rate of return on R&D is slightly higher at 18.2%. The concept of social rate of return on R&D was not directly applicable here, but we found some indication that it may exceed the private one by 10%.

CONCLUSION

Finland, with its close-knit business community and a history of fast technological learning, provides a useful test bed for studies of domestic spillovers. We indeed find evidence for spillovers, although their magnitude seems to be somewhat smaller than what has been suggested in the literature. Most previous studies have used more aggregate data sets and have been unable to control for the significant double counting among variables. There are some suggestions in the literature that aggregation may be ‘beneficial’ in spillover studies.

Above we did not address the issue of international spillovers, to role of which is undoubtedly on the rise (for discussion see, e.g., Pajarinen et al., 1998). Furthermore, spillovers from a given source are intervened with overall technological development – unless a measure of this technological development is included in the estimations, it is possible that spillover measures capture in part the effect of the overall technological advance.

All business activities, including R&D, are being outsourced increasingly often. It may, e.g., be that a firm concentrates on exploiting its marketing and brand management expertise and outsources other business functions. This study includes measures for **internal** R&D and external 'R&D' received free of charge (spillovers). We did not study the role or purchased R&D, which could be modeled as the third variable input.

Firms are inherently different. We accounted for that by allowing for some random coefficients. Several previous studies have estimated the model separately for each industry, i.e., they have implicitly assumed that, while firms are different across industries, they a sufficiently similar within an industry. There are, however, known shortcomings of the industrial classification, and it would seem that the effects of spillovers with respect to a given firm would rather depend on its innovative characteristics than on the industry it happens to belong to. Relevant dimensions of the innovative characteristics may include the type of innovations the firm focuses on, i.e., whether it is a product and/or process innovator, whether the firm receives public subsidies on its innovative activities or not, and whether the firm cooperates with other or not.

This study has merely scratched the surface of this rich data set. In our further analysis we intend to address, among other things, the issues discussed in this concluding section.

ENDNOTES

[1] We emphasize the word 'given' in order to underline that if the amount of R&D done is reduced as a consequence of spillovers, the desirability of spillovers from the social and receiving firms' point of view is undetermined.

[2] The first few paragraphs of this sections are based on the section added to the English version of the *Advantage Finland* book by the author (ed.) and Laura Paija (Hernesniemi, Lammi, & Ylä-Anttila, 1995; Hernesniemi, Lammi, & Ylä-Anttila, 1996).

[3] Recall that Finland, albeit autonomous, was nevertheless a part of Imperial Russia.

[4] According to the peace settlement, the war preparations were set to $300 million, to be paid in six years. Later it was 'agreed' that the sum was defined in 'war preparation dollars' (1938 world market prices raised by 10–15%). Effectively the burden was $500–550 million. While the figure may seem small, during the first five years war preparations accounted for 5–6% of the annual GDP and for roughly 2% for the remaining three years. In order words, in the late 1940s the total war preparations were equal to one third of the annual GDP of the country! (Pihkala, 1988).

[5] In this section we discuss *technology transfer*s rather than *spillover*s. These two terms are related, but the former is somewhat broader, including also information gathering where the emitting source is compensated for the use of the knowledge.

[6] Myllyntaus calls the combination of these features 'cultural and social filter'.

[7] Below we draw from Myllyntaus (1992) unless otherwise noted.

[8] Since variables cost shares must add up to one, the materials cost share equation can be dropped.

[9] The materials share is dropped since cost shares must sum up to unity.

[10] The authors acknowledge that the physical capital and certain types of labor can also be quasi-fixed. These inflexibilities are not modeled, since "…, the focus of the paper is R&D capital. The model captures the relative inflexibility of R&D capital compared to other factors of production." (Bernstein & Nadiri, 1988, p. 430).

[11] Since cost shares must sum up to unity, the materials cost share equation is dropped.

[12] Negative value implies that spillovers cause variable cost to increase. This is possible since spillovers may decrease capital input intensities which may in turn increase the need for variable inputs and thus the variable cost.

[13] Output and inputs are assumed to be non-negative.

[14] Prices are positive and fixed from the firm's point of view.

[15] Corresponds to the tangency condition between short-run and long-run average cost curves (see, e.g., Varian, 1992, p. 70–6).

[16] *Ex post* values can, and normal will, differ. This assumption suggests that shocks are unexpected.

[17] The output observed empirically or reported by the firm is always net of adjustment cost.

[18] Here we have not concentrated on the considerable computational difficulty associate with a SGM equation system. In our previous experiments we failed to reach convergence in a SGM system of four equations after app. 200 hours of CPU time on a standard PC (Gauss 3.2 in DOS) – we reached convergence only after imposing a constant returns to scale assumption. Other authors have reported similar problems. Furthermore, recent software reviews have doubted (see, e.g., McCullough, 1999) the ability of current packages to reach reliable estimates in nonlinear estimations.

[19] Since spillovers are by definition available free of charge, there are no corresponding prices.

[20] Note that a number of terms drop out completely as they become zero.

[21] As discussed in Equation (2), generally we get short-run demands of variable inputs via the lemma. Getting the variable cost shares this way is a feature of the translog cost function. Note that $Q_v = \frac{\partial C^v}{\partial P_v} \Leftrightarrow Q_v = \frac{C^v}{P_v}\frac{\partial \ln C^v}{\partial \ln P_v} \Leftrightarrow s_v = \frac{\partial c^v}{\partial p_v}$. Since we have only two variable inputs adding up to one and we have imposed some parameter restrictions to impose homogeneity, the variable cost share equation of materials is reduntant.

[22] I am grateful for Jan Larsson for his correspondence on the programming of this procedure.

[23] IIN = identically and independently normally distributed. The subscripts indicate the dimensions of the vectors and matrices.

[24] The latter term is a block diagonal square matrix with dimensions $Gp \times Gp$, where each $G \times G$ block corresponds to the ‘conventional’ error term in the system of equations. The former term is a $Gp \times Gp$ square matrix with a number of zero entries, corresponding to the ‘random elements’ of the random coefficients.

[25] In our case the minimum p is 3 and the maximum P=13.

[26] Subscripts denote partial derivatives.

[27] Braeutigam and Daughety (1983) present a general version of the same formula. For discussion see Panzar (1989).

[28] Uzawa showed that the partial substitution elasticities proposed by Allen can be computed as functions of partial derivatives of the cost function.

[29] The Allen-Uzawa elasticities are the ones most commonly presented, but are not very useful in case of more than two variable inputs. In this case Morishima elasticities may be preferred (Blackorby & Russell, 1989).

[30] While calculating these may seem straight forward, note that

$$\left[\widehat{\frac{\partial^2 C^v}{\partial P_i \partial P_j}}\right] = \left[\widehat{\frac{C^v}{P_i P_j}}\left(\widehat{\frac{\partial c^v}{\partial p_i}}\widehat{\frac{\partial c^v}{\partial p_j}} + \widehat{\frac{\partial^2 c^v}{\partial p_i \partial p_j}} - \omega_{ij}\widehat{\frac{\partial c^v}{\partial p_i}}\right)\right] = \left[\widehat{\frac{C^v}{P_i P_j}}\left(\hat{s}_i \hat{s}_j + \widehat{\frac{\partial^2 c^v}{\partial p_i \partial p_j}} - \omega_{ij}\hat{s}_i\right)\right],$$

where $\omega_{ij} = 1$, if $i = j$ and 0 otherwise. Similarly for $\left[\partial^2 C^v / \partial Q_k \partial Q_l\right]$.

[31] Since the authors discuss dual profit functions and do not model quasi-fixed inputs, the discuss convexity rather than ‘curvature conditions’.

[32] Recall that in our terminology materials also include intermediate inputs and acquired services, i.e., positive cross-price elasticity of labor with respect to materials in not inconsistent with the argument that firms respond to higher labor costs by outsourcing labor-intensive activities.

[33] Recall, however, that Cohen and Levin (1989) argue that **some** own R&D is needed in order to be able to benefit from spillovers. Furthermore, especially inter-industry spillovers could be complementary to own R&D efforts.

[34] Recall too, that our rate of return measures are **gross** of depreciation.

[35] Note that we refer to the *mid-90%* figures here; see discussion above.

APPENDIX A. DATA DOCUMENTATION.

INTRODUCTION

Recently **Statistics Finland** has made its firm-level databases more accessible to researchers. While they still have to be employed by the central statistical office and conduct their work at its premises in order to access the data, this is a significant departure from the old practice of denying *any* access to the officially collected micro-level information.

Personnel accessing the data is bound by the data confidentiality laws, i.e., they can not publish or reveal data in such a form that information regarding a specific firm could be identified. Researchers that are not regular employees of Statistics Finland are bound by an even stricter set of rules and the identity of individual firms is hidden from the outset.

In what follows we document the construction of the data set used in this study. Senior Researcher Olavi Lehtoranta oversaw the work on Statistics Finland's behalf. Lehtoranta also collected the raw data sets and recoded the firm identifiers.[i]

BASIC INFORMATION

Main data sources of this study are Statistics Finland's R&D surveys from 1985 to 1997 and corresponding industrial statistics. The statistical unit of the R&D survey is a firm; the statistical unit of industrial statistics is a plant. Since our goal is to analyze spillovers at the firm level and concentrate strictly on industrial activity, a firm has been defined as the sum of its industrial plants.[ii] Statistics from various sources are match by the (recoded) firm identification code.

In the 1980s R&D surveys were conducted on odd years. Since 1991, additional smaller surveys have been conducted on even years. Up-to-date the 1995 R&D survey has been the biggest (4,048 surveyed firms and 1,722 nonzero R&D expenditure reports – the mean sample size

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[i] Due to the data confidentiality rules we did not have access to the databases with the actual firm identifiers.

[ii] The data aggregation from plant to firm level has been performed by Olavi Lehtoranta at Statistics Finland.

in other years has been app. one thousand). The 1996 R&D figures are based on the 1996 *Community Innovation Survey* (SVT, 1998). We take year 1995 as our starting point and attempt to form the largest possible unbalanced panel around the firms included in the 1995 R&D survey. All steps in constructing our data set are done in a few self-documented SAS and Stata programs (available upon request) – our data set can be easily replicated by simply running the programs at Statistics Finland.[iii] Some basic features of the 'raw' data are documented in Lehtoranta (1998). In what follows we will go over the steps in creating our data set – please see corresponding programs for further details.

CONSTRUCTION OF THE DATA SET

As stated above, we concentrate strictly on industrial activity. Thus, we only include firms for which over two-thirds of output is from industrial activities. We only included firms that were observed for three consecutive years. Firms' industries where determined on the basis of the 1995 R&D survey and industrial statistics. Due to the frequency of R&D statistics, in some cases we where forced to calculate the intermediate R&D figures as an arithmetic mean of the surrounding years. We carefully eliminate any double counting among variables. Variables are constructed as follows:

Output. Gross output in 1990 prices from industrial statistics (in thousands of *Markka*s).

Labor price and quantity. Industrial statistics record the number of persons, working hours, wages, and social expenditures for three types of labor: entrepreneurs, blue (*työntekijät*) and white (*toimihenkilöt*) workers.[iv] First we constructed an overall labor cost index, based on the ratio of the total labor expenditure[v] to working hours and the annual cost shares of each type of la-

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[iii] Please note that these programs comprise of thousands of lines of code and take considerable time to run.

[iv] For entrepreneurs information on working hours etc. is occasionally missing; in this case we assumed that their per person working hours etc. are similar to those of an average white collar worker in the same firm. The share of entrepreneurs is extremely low in our sample so this assumption has no effect on the results or descriptive statistics.

[v] The sum of wage and social expenditures.

bor. The base year 1990 is set equal to 1.00.[vi] This index serves as our measure of labor price and is derived separately for each firm. The problem in measuring labor quantity is considerable double counting with R&D. Luckily the R&D surveys also include detailed information on the structure of R&D expenditure (see Rouvinen, 1998); the down side is that this information is sometimes not reported by the firms. We solved the problem of possibly missing interim observations as with the R&D expenditure figures. Then, for each firm, we calculated the cost shares of each R&D related expenditures. If the information is missing, we use sample averages instead. Once we have determined the R&D cost share of labor input, we calculate the actual R&D related labor input, which is subtracted from the nominal labor related expenditure, defined as the sum of wages and related social costs across the three types of labor. This nominal measure is deflated by the afore-mentioned labor cost index to get the labor quantity in thousands of *Markka*s and 1990 prices.

Materials price and quantity. Materials are defined as the difference between gross output and value added. Thus, *materials* include raw materials, intermediate inputs, acquired services, and energy expenditure. Defining the implicit materials price index, which is used as our materials cost measure, is straight forward since we observed both gross output and value added in nominal as well as in 1990 prices (1990=1.00). As with labor, materials overlap with R&D. Thus, we subtract R&D related materials and supplies expenditure, operating costs of buildings and structures, acquired services, and other operating expenses from the nominal materials expenditure and deflate it by the price index to get materials quantity in thousands of *Markka*s and 1990 prices.

Physical capital stock and its user cost. Our capital stock measure is provided by Mika Maliranta at Statistics Finland (documented in Maliranta, 1997) and is based on fire insurance values and the perpetual inventory method (real stock in 1990 prices, thousands of *Markka*s). The capital

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[vi] Recall that our sample is constructed around the year **1995** rather than 1990. Due to our physical capital stock measure year 1990 is nevertheless the base year. This causes problems in case year 1990 is not observed for a particular firm. Thus, we first formed indices with 1995 as the base year (recall that 1995 is available for all firms in the sample) and then changed the base year to year 1990. If year 1990 is observed, this is straight forward. If not, we used the average of year 1990 values of the 1995 indices for rescaling.

stock refers to machinery and equipment only, i.e., it excludes buildings and land. The user cost of capital is calculated from the following formula (Ali-Yrkkö, 1998):

$$p_k^t = \frac{c_k^t \left(r_i^t - E(\dot{c}_k^t) + \delta \right) \left(1 - \tau^t \frac{\alpha}{r_i^t + \alpha} \right)}{p_y^0 \left(1 - \tau^t \right)},$$

where c_k^t is the purchase price of additional physical capital (implicit industry-level price indices of machinery and equipment from the annual national accounts), r_i^t is the interest rate paid by the firm (banks' average lending rate to the corporate sector), $E(\dot{c}_k^t)$ is the expected change in c_k^t (defined as the change in three-year moving average of c_k^t), δ is the depreciate rate of capital (assumed to be .10), τ^t is the corporate tax rate – the sum of municipal and federal tax rates (Ali-Yrkkö, 1998, tax laws), α is the maximum depreciation rate allowed in accounting (.30 through the observation period) and p_y^0 is the price of output (implicit firm-level price indices).

R&D capital stock and its user cost. Defining R&D capital stocks is a rather complicated procedure. First we used industry-level R&D figures (OECD, 1998) to calculate the R&D capital stocks by industry with perpetual inventory method.[vii] Then we calculated the ratios of firm-level and industry-level R&D expenditures and averaged these over time. Initial values of the firm-level R&D stocks are defined as a product of this ratio and the industry-level R&D stocks. Further values are calculated using perpetual inventory methods and the afore-mentioned depreciation rate. The user cost of capital was calculated according to the same formula as in the case of the physical capital.[viii]

Intra-industry spillovers is define as the representative industry's R&D capital stock excluding the firm in question.

[vii] We assumed a .15 depreciation rate. The initial (1975) values were calculate by dividing the deflated 1975 R&D expenditure by the depreciation rate. Note that the definition of the initial value has a minor influence on the final outcomes since the first observation we actually use is 1985.

[viii] For R&D capital we assumed .15 depreciation rate. Note that the maximum depreciation rate allowed in the accounting laws does not apply here.

Inter-industry spillovers is defined as the total manufacturing R&D capital stock excluding the representative industry.

We took over 100% jumps in output and/or capital variables as a sign of inconsistency in the statistical unit across time and eliminated these observations. We were left with a panel of 437 firms each having 3 to 13 time-series observation; all-in-all the sample has 2573 time-series cross-section observations. Below a few descriptive statistics of our sample.

DESCRIPTIVE STATISTICS

The sample accounts for 57% of manufacturing output in 1995. The firms in the sample seem to be slightly more labor and R&D intensive than manufacturing firms on average. Table 4

Table 4. Data patterns by their frequency in the data set.

Frequency (no. of firms with the data pattern)	Number of observed years	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
89	3											1	1	1
53	7							1	1	1	1	1	1	1
41	5									1	1	1	1	1
37	4										1	1	1	1
27	13	1	1	1	1	1	1	1	1	1	1	1	1	1
26	6								1	1	1	1	1	1
23	3									1	1	1		
16	5							1	1	1	1	1		
14	3										1	1	1	
13	9					1	1	1	1	1	1	1	1	1
11	11	1	1	1	1	1	1	1	1	1	1	1		
11	6							1	1	1	1	1	1	
10	11			1	1	1	1	1	1	1	1	1	1	1
10	5								1	1	1	1	1	
9	12	1	1	1	1	1	1	1	1	1	1	1	1	
9	4									1	1	1	1	
8	9			1	1	1	1	1	1	1	1	1		
8	4								1	1	1	1		
5	6						1	1	1	1	1	1		
4	8						1	1	1	1	1	1	1	1
3	7					1	1	1	1	1	1	1		
3	8					1	1	1	1	1	1	1	1	
2	8				1	1	1	1	1	1	1	1		
1	10				1	1	1	1	1	1	1	1	1	1
1	10			1	1	1	1	1	1	1	1	1	1	
1	10		1	1	1	1	1	1	1	1	1	1		
1	7						1	1	1	1	1	1	1	
1	12		1	1	1	1	1	1	1	1	1	1	1	1
437	3–13											1		

Note: The bottom row refers to the whole sample.

summarizes the dimensions of the unbalanced panel. For 89 firms we observe only the last three years of the sample (the most common data pattern). Twenty-seven firms are observed for all thirteen years.

Table 5 presents basic descriptive statistics of the data set. The quantity is materials input is rather high relative to the quantity of labor input, which is expected due to the broad definition of ‘materials’. At first glance the user costs of capital inputs seem rather high, but appear more reasonable if it is kept in mind that market interest rates were at times around 20% during the observation period.

Labor-intensity has reduced considerably across the observation period, at least if we use the 27 firms observed all 13 years as a reference point. The same subsample suggests that the average physical capital stock has increased by nearly 20% in thirteen years. The R&D capital stock, however, has increased over 70%. As compared to only 10% increase in output, these figures clearly tell the other side of the reducing labor-intensity. Average labor prices have more than double during the observation period whereas material prices have increase by a good 40%. Average user cost of physical capital has reduced by over 30% from 1985 to 1997, reflecting the severe drop in interest rates. The user cost of R&D capital has reduced only slightly between these two points of time. This is explained by the increasing labor costs.

Table 5. Descriptive statistics of the whole sample.

Variable (2573 observations)	Mean	Std. Dev.	Minimum	Maximum
Q_y: Output (1990 prices, FIM 1,000)	526024	1437772	3681	2.0E+07
Q_l: Labor input ('90 p., FIM 1,000)	80558	182739	677	2007351
Q_m: Materials input ('90 p., FIM 1,000)	352837	1006783	851	1.5E+07
Q_k: Physical cap. stock ('90 p., FIM 1,000)	137729	445592	321	5794239
Q_r: R&D capital stock ('90 p., FIM 1,000)	39707	145676	65	4132882
S_I: Intra-ind. spillover stock (FIM 1,000)	3868480	4310611	37022	2.1E+07
S_S: Inter-ind. spillover stock (FIM 1,000)	2.3E+07	5125899	7979394	3.3E+07
P_l: Price of labor (index, 1990=1.00)	1.1730	0.2580	0.4733	2.9202
P_m: Price of materials (index, 1990=1.00)	1.0919	0.1471	0.6287	1.4213
P_k: User cost of physical capital ('90 p.)	0.1809	0.0427	0.1069	0.3210
P_r: User cost of R&D capital ('90 p.)	0.2100	0.0352	0.1205	0.4995

Note: The *Q*s and *P*s for the variable and quasi-fixed inputs have different definitions (stocks versus flows and prices versus user costs).

APPENDIX B. DUALITY AND COST FUNCTIONS.

Economic theory of production is based on the principle of profit maximization, subject to a given profit function (Jorgenson, 1986, p. 1842). One of the main analytical tools is the implicit function theorem (see, e.g., Simon & Blume, 1994, pp. 150, 339, 341).[ix] However, in order to estimate parameters with empirical data, the equations must be specified explicitly. Traditional approach to modeling producer behavior begins with the assumptions of additivity[x] and homogeneity[xi] of the production function (Jorgenson, 1986, p. 1843). The disadvantage of this approach is that it imposes severe constraints on the underlying technology. The dual approach makes it possible to overcome some of the limitations of the traditional approach.

Duality between cost and production functions refer to the fact that under certain conditions either can describe the production technology equally well.[xii] This dual formulation of production theory has been an important source of innovations in econometric modeling (Jorgenson, 1986). In what follows we briefly summarize some aspects of Diewert's (1982, Section 2) comprehensive discussion on dynamic duality.

Suppose we have N nonnegative inputs $x \equiv (x_1, x_2, ..., x_N) \geq 0_N$. We are given a production function $F: u = F(x)$, where u is the amount of output produced. Let us also assume that the producer can purchase inputs at fixed positive prices $p \equiv (p_1, p_2, ..., p_N) \gg 0_N$.[xiii] A cost function

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[ix] The implicit function theorem says that under certain conditions a system of equations implicitly presents each of the endogenous variables as functions of all the exogenous variables.

[x] Additivity means that if two output quantities can be produced with a given technology, also their sum can be produced (for a formal definition see Varian, 1992, p. 21).

[xi] One implication of homogeneity is that the technical rate of substitution among inputs is independent from the scale of production (see Varian, 1992, pp. 17–9).

[xii] The intuition behind duality is as follows: a production function gives the **maximum** amount of output that can be produced given the technology and available inputs. On the other hand, the **minimum** cost of producing an output is a function of that output and input prices given the production technology. If regularity conditions are satisfied, the cost function completely describes the technology of the firm, i.e., a known cost function can be used to define the production function of the firm or *vice versa*.

[xiii] Note that we assume competitive behavior here, i.e., that the producer has no market power in input purchases.

is defined as the minimum cost of producing at least output u given the input prices p:

$$C(u,p) \equiv \min_{x} \{ p'x : F(x) \geq u \}.$$

Minimal regularity condition on the production function F is that it is continuos from above.[xiv] Note that this condition alone does not guarantee that F or its isoquants would be 'nicely shaped'. Given the continuity condition C is nevertheless a concave function of p for a given u. This implies that the cost function can, as Varian (1992, pp. 82-83) puts it, only capture

> "… economically relevant sections… [of the input requirement set], namely those factor bundles that could actually be the solution to a cost minimization problem, i.e., that could actually be conditional factor demands."

Thus, C can only be used to approximate the true F. Empirically, however, this should not be a problem (for discussion see Diewert, 1982, p. 544).[xv] In order to have the true function to coincide with the approximate function, the following two assumptions are necessary: F is nondecreasing (with more inputs same or greater amount of output can be produced), and F is a quasiconcave function (equivalent to a convex input requirement set). The former assumption eliminates 'backward bending' isoquants while the latter eliminates 'dents' in the isoquants.

[xiv] This allows for 'fixed cost type' discontinuities, i.e., 'jumps up', in the production function but not vice versa. Furthermore, it is assumed that u can be produced by the technology, i.e., $u \in$ range of F. The continuity assumption is sufficient for the existence of a solution to the stated cost minimization problem. Based on this assumption **only**, the following seven properties of C can be derived:

1. C is nonnegative function (prices and quantities are nonnegative),
2. C is linearly homogenous in p for any fixed u,
3. if any combination of p increases, the minimum cost of producing u will not decrease,
4. C is a concave function of p for every u ("The cost function will be a concave function of the factor prices since it must always lie below the "passive" cost function." (Varian, 1992, p. 73)),
5. C is continuous in p for every u if prices are strictly positive (follows from the Theorem of the Maximum (see, e.g., Varian, 1992, p. 506)),
6. C is nondecreasing in u for given p, and
7. for strictly positive prices C is continuos from below (C is continuos from below if and only if F is continuos from above).

[xv] "It is clear… that the approximating production function F^* will not in general coincide with the true production function F. However, it is also clear that from the viewpoint of observed market behavior, if the producer is competitively cost minimizing, then it does not matter whether the producer is minimizing cost subject to the production function constraint given by F

Estimations of cost and production functions differ in their assumptions on the exogeneity of variables. If a production function is estimated, output is endogenous and while technology and input quantities are exogenous. In the dual cost function, however, production costs and input quantities are endogenous while input prices, the level of production, and technology are exogenous. Thus, whenever it is reasonable to assume that prices and the output quantity are indeed exogenous, it is preferable to use a cost rather than a production function in estimations. These assumptions seem more reasonable with disaggregate data. (Berndt, 1991, Chapter 9).

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or F^*: observable market data will never allow us to determine whether the producer has the production function F or the approximation function F^*.” (Diewert, 1982, p. 544).

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