The Economic Value of Knowledge and Inter-firm Technological Linkages: An Investigation of Science-Based Firms

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Abstract

This paper estimates the effects of the 'knowledge capital' on the performance of the chemical and electronics 'Fortune 500' North American, European and Japanese firms between 1993-1997. The novelty of this paper is that, apart from the R&D and patent stocks of the firms, we measure the knowledge capital of the firms by also including a measure of the value of the stock of their external technological linkages (licenses, technological alliances and joint-ventures, and minority participations in technology-based smaller firms). We estimated the effects of the growth of the stocks of R&D, patents, and technological linkages on firm sales growth, profit rates and cash flow, controlling for the growth of physical inputs (capital and labour). We also analysed the effects of our three knowledge assets on the market value of the firm. Both traditional total factor productivity analyses, and our estimation of the effects of these assets on market value, suggest that external technological linkages contribute to firm's performance beyond the effects of R&D and patents. The comparable results obtained using these two different approaches provide a fairly solid evidence of the importance of such technological linkages.

Keywords: innovation, inter-firm agreements, firm growth, market value

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1. Introduction

There is a fairly established empirical literature which aims to estimate the effect of the 'knowledge capital' on firm performance. A first set of studies explores the effects of technological activities on total factor productivity or profit growth (e.g., Norsworthy and Jang, 1992; Mairesse and Mohen, 1995). Another stream of the literature uses the market value of the firm as a measure of performance (Griliches, 1981; Griliches et al. 1991; Hall, 1993 and 1999; Hall et al. 1998; Blundell et al., 1995; Stoneman and Toivanen, 1997). As discussed in Section 2, the market value approach has recently gained importance in the empirical literature.

To our knowledge, however, there is no systematic attempt at measuring quantitatively the effects of alliances, and particularly of technological alliances, on firm performance. This is surprising if one considers the importance of networks in firm growth strategy during the 1980s and 1990s, especially in science-based sectors (Teece, 1986, Hagerdoorn, 1996). This papers aims to fill this gap by analysing the joint impact of in-house technological activities and external technological linkages on firm performance. Since both R&D and inter-firm linkages accumulate over time and produce long term effects on firms' performance, we distinguish between the 'knowledge capital' of the firm, measured by R&D and patents stocks, and the 'technological network capital', measured by the stock of inter-firm technological relationships (mainly licensing agreements and technology-related alliances and joint ventures). We also combine the two aforementioned approaches – total factor productivity and market value. Thus, to assess the effects of the knowledge and network capitals we used different indicators of performance -- sales growth, profit ratios and the firm market valuation. Our sample is composed of 98 publicly-traded firms in the chemicals-pharmaceuticals and electronics sectors between 1993 and 1997. These are all the Fortune 500 firms in these two industries.

We find that the two approaches yield similar results. This suggests first that in the long run investments in internal and external sources of technology affect the firm performance, and secondly that the capital markets take into account these effects, especially in science-based industries. The paper is organised as follows. Section 2 summarises the background literature of the paper. Section 3 illustrates the data and section 4 discusses the empirical results. Section 5 concludes.

2. Previous empirical studies and theoretical motivations

To estimate the economic returns to innovative activities, a series of studies have examined the impact of innovation on total factor productivity or profit growth (see Mairesse and Mohen, 1995, for a survey). Others have focused on the valuation of R&D and patent stock relative to physical assets in the stock market (see Hall, 1999 for a survey). The two approaches have both merits and weakenesses.

Total factor productivity is simply the ratio of outputs to inputs both expressed in real terms. This ratio is an appropriate measure of productivity under some special conditions (particularly competitive markets for inputs and outputs). The linkages between R&D and productivity change have been explored in several studies (e.g., Gold, 1977, Mansfield, 1968, and Griliches, 1979), which have generally shown that technology is an important determinant of the growth of total factor productivity. Apart from the strong assumptions on which the total factor productivity approach relies, a major problem with it is that the lag between R&D and its impact on productivity or profits is usually long and difficult to predict. This gives rise to measurement problems when the data are not available in long time series.

The market value approach draws on the idea that firms are bundles of assets (and capabilities) which are difficult to disentangle and to price separately on the market. These assets include 'ordinary plants and equipment, inventories, knowledge assets, customer networks, brand names and reputation, and so forth' (Hall, 1999, p. 4). The market value approach draws on the restrictive hypothesis, introduced by the hedonic price models, that financial markets assign a correct value to the bundle of firms assets. This approach has been used to calculate the marginal shadow value of the knowledge assets from the estimation of market value equations (Griliches, 1981; Griliches et al. 1991; Hall, 1993 and 1999; Hall et al. 1998). As shown by Wildasin (1984), the marginal returns to knowledge asset from an intertemporal maximisation programme with many capital goods is extremely difficult to determine (see Wildasin, 1985). In several econometric studies this difficulty has been tackled by assuming that the market value equations take a linear form or a Cobb-Douglas one. This produces an expression for the market value of the firm when many capital assets are involved in which the market value of the firm V is simply equal to the sum of the N assets K_1, K_2, ... K_N, weighted by their shadow values, a_1, a_2, …. a_N, i.e. $V = \sum_{i=1}^{N} a_i K_i$. In econometric studies, the shadow values of the assets are then estimated.

Not surprisingly, the empirical studies which follow this approach have used data from the US and the UK, where the stock markets are efficient compared with other countries. Studies based on the US also benefit from the availability of large sets of firm-level panel data. For instance, Hall and her colleagues used data on about 5,000 US manufacturing firms between 1976 and 1995. These data were obtained by merging files provided by Compustat and the US Patent Office. These works find that R&D expenditures or the R&D stock have a significant effect on the firm market value beyond that of physical assets. They also show that patent counts have an additional effect on market value beyond that of R&D, even though the correlation is less strong. Finally, citation-weighted patents were found to be more informative than patent counts (see Hall, 1999, for a survey).

In these studies, the typical linear market value model takes the following form

$$V_{it}(A_{it}, K_{it}) = q_t(A_{it}, + \gamma_t K_{it})^{\sigma t} \quad (1)$$

where A represents the physical assets and K the knowledge assets of firm i at time t. Under constant returns to scale (σ_t=1) equation (1) in log form can be written as

$$\log V_{it} = \log q_t + \log A_{it}, + \log(1+\gamma_t K_{it} / A_{it}) \quad (2)$$

or

$$\log V_{it}/A_{it} = \log q_t + \log(1+\gamma_t K_{it} / A_{it}) \quad (3)$$

The left hand side of (3) is the log of Tobin's q, while in the right hand side γ_t is the marginal or shadow value of the ratio of knowledge capital to physical assets. The intercept represents the average Tobin's q for the sample firms during the period (Hall, 1999, p. 8).[1]

A specific reason to investigate the long-run returns to innovation in the capital market is that the financial markets (both banks and stock markets) influence innovation and economic growth, as pointed out by the economic theory since Schumpeter's seminal work (Schumpeter, 1934). More recently, Levin

[1] The Tobin's q is defined as the ratio of market value to the replacement cost of the firm. In the literature the replacement cost is proxied for by the replacement value of firm's physical assets. An attractive property of Tobin's q is represented by the combination of capital market data with accounting data, which allows to account for the correct risk-adjusted discount

and Zervos (1998) have showed that banking development and stock market liquidity are both strongly correlated with current and future rates of economic growth, capital accumulation, and productivity growth. Particularly, they argue that more liquid stock markets (i.e., markets where it is less expensive to trade equities) favour investment in long-term, higher-return projects which in turn increase productivity (p. 537).

The main weakness of the market value approach is that it can be used only for private firms quoted in well-functioning stock markets. However, this approach avoids the problem of time lag of the productivity approach, and this is one important reason why most empirical literature adopts the market value approach. Moreover, the market value approach rests on restrictive hypotheses concerning the efficiency of the capital markets. In fact, financial markets are imperfect and the evolution of a firm market value may reflect factors different from the value of its assets, such as the firm market power in the product market. However, the imperfections in the product markets in general tend to persist over time. This is a reason for ignoring them when the analysis focuses on variations of the market value over time. To be sure, this is a potential problem in our paper, as the cross-sectional dimension of our sample is much more substantial than its time dimension. Therefore, our estimates depend mostly on variations across firms rather than over time. However, this paper deals with sectors where market power draws to a large extent on investments in knowledge assets, whose effect on the market value of the firm is explicitly taken into account in our analysis. Finally, accounting measures of firm performance fail to account for the effects of differences in systematic risk, temporary disequilibrium effects, tax laws and accounting conventions. These limitations of accounting data have made other measures of performance, such as Tobin's q which combines market value data with accounting data, attractive to industrial organisation scholars (Linderberg-Ross, 1981; Montgomery-Wernerfelt, 1988).

3. Description of data

Our basic sample is composed of 98 large firms operating in two broad sets of industries, namely 'electronics' (computers and office equipment, telecommunications equipment and services, electronic components and consumer electronics) and 'chemicals' (chemicals, pharmaceuticals, petroleum refining, rubber and plastic products, soaps and cosmetics).

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rate and equilibrium returns. Moreover, it reduces the typical distortions arising from accounting conventions and tax laws

Table A in the Appendix lists the sample firms. These firms were drawn from 'Fortune 500', 1990 edition (1989 annual reports). Some firms are from 'Fortune 500', 1997 edition. These firms were not among the largest Fortune 500 in 1990 or they were classified in sectors different from those included in our database (e.g., ABB in industrial and farm equipment). The inclusion of these firms in the sample is justified by their importance in the industries examined in our research. The overall geographical distribution of the sample firms by country of origin is slightly unbalanced in favour of North America (US and Canada) -- 44 firms are from North America, 32 are from Western Europe, 22 are from Japan. Moreover, in our sample there are 57 electronics firms and 41 chemical firms.

There are notable differences in our sample across countries and sectors. Table 1 shows the level of technological activity (average number of patents filed with the US Patent Office between 1970 and 1992), and the technological diversification of the sample firms measured by the Herfindahl index. The latter is based on patents counts classified in 34 SPRU technological classes. (See Table B in the Appendix.) Similarly, we classified the 1992 subsidiaries of the sample firms according to their primary four-digit SIC code. The North American firms have a larger average number of patents than their Japanese and European counterparts. The European firms appear to be more specialised in 'upstream activities' (patents) than the American and Japanese firms. But they are also more diversified in 'downstream activities' (subsidiaries) than the American firms. As far as the industries are concerned, Table 1 shows that there are no significant differences in the diversification of technological activities between electronics and chemical firms. However, the chemical firms appear to be more diversified in 'upstream activities' (and to a lesser extent in downstream activities) compared with electronics firms.[2]

We collected information on inter-firm technological linkages which involved the sample firms for the period 1993-1997. We found that during the period under examination our sample firms set up 5,625 technological agreements. We identified these agreements from a larger sample of 11,171 agreements and external operations of the firms (M&A, joint ventures, strategic alliances, minority participations and licenses) which we obtained from the IAC's Insite Promt data base. Particularly, we looked at the description of these agreements in our data base, and identified those that had a predominant

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(Montgomery and Wernerfelt, 1988, p. 627).

[2] It is worth noting that technological and business diversification cannot be compared directly due to differences in the level of aggregation. Technological diversification is calculated by using 34 SPRU technological classes which roughly correspond to the 2-digit USPC classification. On the other hand, business diversification is calculated at the level of four-digit SIC classification.

technological objective. (See the Appendix for details.)[3] In what follows we then refer to the stock of technological linkages of our firms as their 'technological network capital'.

Table 1: Technological performance and diversification by region or industry of the sample firms

Regions or Industry	Average US Patents granted, 1970-1992	Herfindhal Index of 1970-1992 US patents (technological diversification)*	Herfindhal Index of the existing subsidiaries in 1992 (business diversifications)**
North America	4637.7	0.183	0.116
Japan	3683.0	0.179	0.064
Western Europe	3622.3	0.208	0.080
Chemicals	4078.9	0.216	0.094
Electronics	4095.6	0.172	0.091
Total	4088.7	0.190	0.093

* Herfindhal Index calculated with patents classified in the 34 SPRU technological classes

** Herfindhal Index calculated from the 4-digit SIC sectors of the 1992 stock of subsidiaries of the firms

Table 2 reports the number of technological linkages of our sample firms during 1993-1997, as well as their breakdown by sectors (electronics and chemical firms), and by regions of origin of our companies (North America, Europe, Japan). The average number of technological agreements per firm is the highest in the case of the Japanese firms (87.7 agreements per firm) followed by the North American (51.4) and the European firms (44.8). If anything, this suggests that there is no significant bias in favour of Anglo-Saxon companies in our data set. We also find no appreciable difference in the average number of technological agreements per firm in the chemical and electronics sectors (respectively 57.7 *vs* 57.2).

[3] In so doing, we excluded all the M&A from our sample of technological agreements on the ground that M&A typically involve acquisition of assets well beyond purely technological ones. Although this means that we probably ruled out some M&A with a specific technological objective, it was not possible to identify such technological M&A from the available descriptions. We also excluded licenses which were clearly licenses given out by our companies, since they are more likely to represent outputs of our firms rather than received technological capital. By contrast, we retained licensing in and cross- technological licenses. We included minority stakes in our technological agreements, as we noted that most of them were options into a new or technologically dynamic firm, especially in science-based sectors. In sum, our technological agreements were joint ventures and strategic alliances with a clear technological content, licensing in and cross-licenses, minority stakes.

Table 2: Number of technological linkages by region or industry of the sample firms[*]

	1993	1994	1995	1996	1997	Total
North America	670	365	498	254	474	2261
Japan	98	451	788	180	412	1929
Western Europe	136	342	544	232	181	1435
Chemicals	397	337	994	368	268	2364
Electronics	507	821	836	298	799	3261
Total	904	1158	1830	666	1067	5625

[*] Technological linkages = licensing-in and cross-licensing agreements, technological alliances & joint-ventures, minority participations

4. Econometric analysis

4.1. The effects of the R&D, patents and technological network capital on firms' growth and profits

This section analyses the effect of the growth of knowledge capital (R&D and patents) and the technological 'network' capital on real sales growth and other measures of firm's economic performance (cash flow and profits on sales). Our regressors include time, sector (chemicals and electronics) and region dummies (North America, Western Europe and Japan), real GDP growth in the country of origin of the company (to account for domestic market effects), real physical assets growth, and the growth in the number of employees of the companies. We also controlled for the effects of pre-sample technological and business diversification. (See Table 3 for variable definitions. See the Appendix for a description of the variables and their sources.)

As mentioned earlier, technological linkages include licensing agreements (including cross-licensing agreements), technological strategic alliances (with a predominant technological content, e.g., joint R&D contracts), technological joint ventures (e.g., set up of a joint R&D laboratory), and minority stakes. To estimate the value of the investments in inter-firm technological networks we weighted the number of linkages of any category (e.g., joint ventures) by the average value of the transaction for the corresponding category obtained from another data set (SDC, 1998). SDC reports various information on strategic alliances, licensing, and joint ventures worldwide during the 1990s. It also codes whether a significant technology transfer took place in the operation, which enabled us to select the technological agreements. We then took the technological inter-firm operations in SDC in electronics (SIC 35, 36 and

38 industries) and in chemicals (SIC 28 industries) for which the value of the transaction was reported (about 20% of the SDC transactions), and computed the average value of the transaction, in each of the two industries, for the following SDC 'events': a) equity purchase and R&D funding (which correspond to minority stakes in our dataset); b) licensing agreements; c) joint R&D or joint development agreements (which we matched with our technological strategic alliances and joint ventures).[4] The average value of these transactions in the two sectors were used to weight the number of inter-firms linkages of similar types in the two industries in order to compute the value of the investments in inter-firm technological networks of our sample firms.

Table 3 List of variables

- NAM=Dummy for US and Canadian Firms
- WE= Dummy for Western European firms
- CHEM= Dummy for chemical firms
- GGDP= Real GDP growth rate in the country of origin of the firm
- GNPPE= Growth rate of real net property, plants & equipment
- GEMP=Growth rate of the number of employees
- GKRD=Growth rate of the real R&D stock of the firms
- GKPAT= Growth rate of the patent stock
- GKTALL= Growth rate of the stock of technological linkages
- TDIV = Herfindahl index across 34 SPRU US patent technological classes using the patent stock of the firm in 1990
- STDIV=TDIV/1990 employees
- BDIV= Herfindahl index across the 4-digit SIC codes of the subsidiaries of the companies in 1992
- SBDIV=BDIV/1990 employees

The technological stocks for R&D and patents, as well as the one for net property plant and equipment (as a proxy for physical assets), were calculated by using the perpetual inventory method with a 15 per cent depreciation rate. For the 'network' capital we used a higher depreciation rates (33 per cent). A non negligible number of these transactions fail rapidly after they are set up, which prompted us to assume that on average their lifecycle is shorter than that of the internal assets. However, our estimated results are robust to alternative specifications of all these depreciation rates.

[4] The reason why we resorted to the SDC dataset for calculating the value of inter-firm operations is that Insite Promt dataset provides this information only occasionally.

Table 4: OLS estimates of sales growth

Variables	Estimated Param.s	Estimated Param.s	Estimated Param.s
Constant	0.017	0.019	0.014
	(0.021)	(0.022)	(0.021)
NAM	0.005	-0.017	0.003
	(0.020)	(0.020)	(0.019)
WE	-0.018	-0.034	-0.023
	(0.021)	(0.022)	(0.021)
CHEM	0.021	0.031	0.029
	(0.015)	(0.016)	(0.015)
GGDP	0.507	0.562	0.532
	(0.133)	(0.137)	(0.131)
GNPPE	0.043	0.053	0.044
	(0.018)	(0.018)	(0.017)
GEMP	0.041	0.053	0.041
	(0.018)	(0.018)	(0.017)
GKRD	0.684	--	0.569
	(0.096)		(0.103)
GKPAT	--	0.359	0.205
		(0.069)	(0.072)
GKTALL	0.031	0.033	0.031
	(0.018)	(0.018)	(0.017)
STDIV	-3.554	-1.254	-2.628
	(2.255)	(2.339)	(2.255)
SBDIV	3.724	-0.696	0.764
	(5.144)	(5.414)	(5.194)
Adj. R^2	0.286	0.239	0.301
F statistic (zero slopes)	11.453	9.174	11.226

Standard errors in parenthesis. 340 observations corresponding to a balanced panel of 85 firms for 1994-1997 (13 firms excluded because of missing data). Observations for 1993 used to compute growth rates, and hence not included in the regressions. All equations include time dummies.

OLS estimations for sales growth are reported in Table 4. In this and the following estimations we used only 85 of our 98 firms in the sample because of missing data. Since growth rates require the use of variables in 1993, our balanced sample is composed of 340 observations – 85 firms during 1994-1997. The growth of both internally accumulated knowledge stocks (R&D and patents) and external technological linkages produce significant positive effects on firm's sales growth, beyond the effect of the growth of physical capital and employees. Pre-sample technological and business diversification have insignificant effects on sales growth. These results confirm the importance of technology for the growth of total factor productivity. OLS estimations of cash flow/sales and profit/sales equations (not reported here) confirm the importance of R&D and patent stock but reveal insignificant effects of the 'network' capital. These results are not surprising if one considers that both current profits and cash flow are sensitive to the amount of investment undertaken by a firm in a given year. As a result, cash flow or accounting profits may decline for a firm that makes larger investments in a given year. In short, there are reasons to believe that these are less reliable measures of longer run firm performance than sales growth, and this also prompts the use of other measures of firm's profitability like market value.

4.2. Estimating the effects of knowledge capital and the technological network capital on the market value of the firms

Following Wildasin (1984), we can write our market value equation as a linear specification of the four assets of our firms,

$$V = a_1K_1 + a_2K_2 + a_3K_3 + a_4K_4 \qquad (4)$$

where the parameters a_i are the shadow values of the *physical capital*, the '*knowledge capital*' (R&D and patent stocks), and the *technological network capital* of the firm. To obtain the equation we actually estimated, however, we have to note that our measure of external technological linkages can give rise to double counting problems. As a matter of fact, investments in external technological alliances are most likely to be included in the reported R&D expenditures of our firms. For example, if some researchers or research equipment of the firms are engaged in the R&D operations of the alliance, their cost shows up in the R&D budget of the company. One could make a similar statement about the cost of the licenses acquired by a firm, which are likely to be accounted for, at least in part, in its R&D expenditures. Clearly, we have no way to measure how much of the value of the alliance is included in the reported R&D figures. Neither can we estimate an independent parameter accounting for that share, as we would be unable to identify it. We then resorted to the assumption that the value of these assets has to be subtracted from the value of the R&D stock of the firm. While this is admittedly an extreme case, we estimated our market value equation below using alternative assumptions. The equally extreme assumption that no value of the external technological operations of the firm is accounted for by its R&D figures yields insignificant effects of alliances on market value. Intermediate cases produce a higher level of significance. We believe however that, for the reasons mentioned earlier (notably that external technological investments show up at least in part in the R&D budget of the firms), the value of the stock of technological alliances has to be substracted from the R&D stock of the company.[5]

This implies that in our estimation equation (4) has to be rewritten as

$$V = a_1 K_1 + a_2 (K_2 - K_4) + a_3 K_3 + a_4 K_4$$

or

$$V = a_1 K_1 + a_2 K_2 + a_3 K_3 + (a_4 - a_2) K_4$$

After a simple transformation, the Tobin's equation in logs becomes

$$\text{Log}(V/K_1) = \log(a_1) + \log[1 + (a_2/a_1)(K_2/K_1) + (a_3/a_1)(K_3/K_1) + ((a_4-a_2)/a_1)(K_4/K_1)] \qquad (5)$$

where the left hand side is the log of Tobin's q and the coefficients (a_i/ a_1) are the shadow values of each asset relative to K_1 (physical assets).

We estimated (5) using non linear least squares (NLLS). We also accounted for the possibility that the right hand side assets in this equation are endogenous, and estimated (5) by the Generalised Method of Moments (GMM) using the following instruments – constant; time dummies; dummies for North American, Western European and chemical firms; log of the real GDP in the country of origin of the

[5] In principle we should substract the value of the investments in alliances from the R&D flows, while in fact we subtracted the value of the stock of alliances from the R&D stock. This however is unlikely to imply any significant difference, given that we are in any case making exploratory assumptions to compute these variables.

company; the stock of patents of the company in 1990 over the stock of R&D in 1990; the log of sales of the firm in 1990; the Herfindhal indices for technological and business diversification, STDIV and SBDIV, over the number of employees of the company in 1990. We also estimated both the NLLS and GMM versions using time dummies in (5), with no appreciable changes in results. Two other specifications of our estimated equation have to be mentioned here. First, in order to account for the effects of the overall dynamics of stock market prices we deflated the market value of the firms by a price index of the firm's country stock exchange market (1990=1). Second, all our assets but the patent stock are expressed in values. To provide a convenient expression of the patent stock in values we computed the average of the patent stock to R&D stock ratio (in real million USD) for all our sample firms and years. We obtained an average value of 0.38, which means that the average cost of a patent is about 2.63 million USD. We then multiplied our patent stock measures of the firms by this average cost to obtain an expression of the patent stock in dollar figures, which provides a more direct interpretation of the estimated shadow price of the patent stock in terms of monetary figures, like for the other assets[6]

Before showing our estimation results, Table 5 reports the descriptive statistics of our market value and asset stocks.

Table 5: Descriptive statistics (in billions USD)

Asset	Sample Mean	Standard Error	Minimum	Maximum
Market Value (V)	20.846	22.334	0.097	184.833
Net Prop. Plants & Equipm. (K_1)	7.666	10.060	0.005	63.852
R&D Stock (K_2)	6.372	6.838	0.194	41.724
Patent Stock (K_3)	4.489	4.779	0.168	20.048
Technological Network Stock (K_4)	1.314	2.059	0.000	18.370

425 observations corresponding to a balanced panel of 85 firms for 1993-1997 (13 firms excluded because of missing data). The values of stocks are calculated by averaging stocks across years and firms.

Note that on average Net Property Plants & Equipment is the largest asset of these companies, even though the size of the R&D stock in these science-based sectors is not that distant from the overall size

[6] We computed the average R&D cost of a patent for the electronics and chemical firms separately, and found that these

of the physical capital. In addition, the value of the patent stock in terms of R&D costs is close to the value of the R&D stock itself, and the value of the technological network capital is, as one would expect, lower on average then the value of the internal assets. Most notably, the sum of these assets tend to be on average slightly smaller than the market value of the firms, which suggests that our sample firms are probably in good part companies whose market evaluation is above the value of our measured assets. Put simply, this suggests that we are dealing with a sample of companies that in the expectations of the capital markets account for significant levels of profitability in the long-run. Given the firms and the industries we are dealing with, this is only to be expected.[7]

Table 6 reports the results of our estimation of equation (5) using both NLLS and the instrumental GMM procedures. Most interestingly, these results show that all three variables measuring the knowledge capital of the firm (i.e. R&D stock, patent stock, and the technological network capital of the firm) have positive and significant effects. The results about R&D and patents confirm previous findings in the literature, notably that patents have an effect on market value beyond that of R&D. Our result about the effects of the technological network capital is entirely new, and it shows that the latter also has an effect on the evaluation of the firms. Clearly, as in the case of patents, we cannot rule out that this variable does not account for other (technological) factors that may affect the evaluation of the companies, and possibly their long-run profitability. However, if one is to provide a structural interpretation of our finding, the financial market seems to react positively to the fact that companies engage in technological alliances, joint-ventures, or similar arrangements.

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averages were practically identical.

[7] It is worth to note that the sample includes large firms that have been in the market for a long time and therefore enjoy a high reputation in the capital markets. The high market valuation of these firms compared with the value of their measurable assets also suggests that these firms on average possess unique, non measurable assets, such as high profile managers, which affect their expected flow of profits.

Table 6: NLLS and GMM estimation of Market Value Equation (5)

Variable & Estimated Shadow Values	NLLS	GMM
Net Prop. Plants & Equipm. (a_1)	2.001 (0.137)	1.813 (0.158)
R&D Stock (a_2)	0.539 (0.115)	0.384 (0.160)
Patent Stock (a_3)	0.555 (0.135)	0.755 (0.182)
Technological Network Stock (a_4)	0.318 (0.124)	0.737 (0.321)

Standard errors in parenthesis. 425 observations corresponding to a balanced panel of 85 firms for 1993-1997 (13 firms excluded because of missing data). See list of instruments for GMM in the text. Time dummies are included among the regressors.

Note that our GMM estimates produce some differences with respect to the NLLS results. Notably, the importance of R&D declines compared to the patent stock and the network capital. In value terms, our GMM estimates suggest that an increase in the R&D stock of 6.8 million dollars (one standard deviation from the mean – see Table 5) implies an increase in market value of about 2.6 million dollars (0.384*6.8), i.e. circa 12.5% over the average market value of 20,846 million dollars in Table 5. Similar calculations indicate that an increase in the patent stock by one standard deviation from the mean (4.8 million dollars) implies an increase in the market value of 3.6 million dollars, i.e. about a 17% increase from the average market value of the firms in our sample. As far as the technological network capital is concerned, a one standard deviation increase (2.1 million dollars) implies an increase in market value of the order of 1.5 millions, or about 7% over the average for the sample. In short, these results suggest that the internal technological assets still appear to be the most important determinant of the long-run profitability of the leading chemical and electronics companies worldwide. However, the external technological capital plays a non-trivial role in enhancing the long run values of these firms as well.[8]

[8] From Table 6, the estimated parameter of the physical assets, a_1, appears to be excessively high. This is probably because there are other company assets that may well affect the market value of the firms (including M&As) which we are not taking into account. In econometric terms, it appears that the constant term in equation (5) is estimating the non-zero

5. Conclusions and suggestions for further research

This paper investigated the relationships between the 'knowledge capital', the stock of inter-firm technological linkages and the performance of the firm. Our sample is composed of 98 Fortune 500 firms in chemicals and electronics during 1993-1997, which reduced to 85 firms in our estimation because of missing data. We analysed different measures of firm's performance, notably purely accounting measures such as sales growth and profit rates, and the Tobin's q, i.e. the ratio of the firm market value to the replacement costs of its assets. The latter has been largely used in earlier empirical studies (hedonic price regressions in presence of many capital goods) because the combination of capital market data with accounting data helps reduce the distortions associated with purely accounting data.

Specifically, we estimated the marginal effect (shadow price) on Tobin's q of the following 'capital' goods: the 'knowledge capital', measured by the firm R&D and patent stock, and the 'technological network capital' of the firm, that is the stock of relationships with competitors and other companies. The latter was obtained by combining the stock of investments of the companies in minority stakes, licensing agreements, strategic alliances and joint-ventures with predominant technological contents. While previous empirical research on the market evaluation of the firm used R&D and patent stocks, the novelty introduced by this paper is the use of the technological network capital stock. Our main result is that the technological network capital of the firms has a positive and significant effect on the market evaluation of the firms in our sample. This effect appears to be smaller than that of the internal knowledge stocks (R&D and patents). However, it is not negligible, and it contributes, along with the latter, to the performance of the firms. This clearly suggests that the performance of the firms are positively affected by a proper combination of internal R&D investments and external technological relationships, thereby providing new evidence in favour of the view that corporate strategies should take external technological opportunities seriously. The importance of external technological assets is confirmed by more traditional approaches based on total factor productivity measures. Particularly, we find that the growth of the technological network capital affects the growth of the real outputs of the firms even beyond the growth of the R&D and patent stocks, and that of the classical inputs like physical capital and labour.

Apart from the mere recognition of the importance of external technological linkages, our results have additional implications for business strategy and public policy which are worth mentioning. For

mean value of the error of the equation. This does not affect our estimation of the other parameters, as discussed above, example, publicly-funded R&D (e.g. to support joint R&D) is motivated by the imperfections in the market for knowledge. These imperfections reduce the economic value of R&D investment and therefore weaken the private incentives to innovation. Most theoretical literature has noted that strategic alliances in high tech sectors can be viewed as organisational arrangements that allow the firms to share the costs and the risks associated with R&D, and to absorb external knowledge in the presence of imperfections in the market for technology. This points to the existence of cost reducing effects of inter-firms alliances. But inter-firm networks also represent a way to exchange knowledge. From this perspective, the network of linkages affect firm growth and expected profits by affecting the expected revenues from the use of in-house knowledge on a larger scale. Whatever the line of argument that one may desire to pursue, this paper suggested that the rising attention that business practitioners and policy maker are paying to innovation networks is indeed justified by the evidence of the effects of such network on the long-run performance of the firms.

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APPENDIX – Description of variables

Sales
This is gross sales reduced by cash discounts, trade discounts, returned sales, excise taxes, and value-added taxes and allowances for which credit is given to customers. Data in local currency were converted in US dollars. Data sources: Compustat, Worldscope and Fortune 500 (various issues).

Employees
This is the number of company workers as reported to shareholders. It is reported by some companies as an average number of employees and by others as the number of employees at the end of the year. Data sources: Computast, Worldscope and Fortune 500 do not distinguish between these two different reporting methods.

Net Property, Plants and Equipment
This is net cost or valuation of tangible fixed property used in the production of revenue, and it is obtained as the sum of gross fixed Assets less depreciation, depletion, and amortisation (accumulated), investment grants and other deductions. We divided the nominal value of the variable that we obtained from Compustat or Worldscope by the firms' home country GDP deflator to obtain NPPE in real terms. Data sources: Compustat, Worldscope.

R&D Expenditures
This includes amortisation of software costs, company-sponsored research and development, software expenses. Real R&D expenditures were obtained by deflating the current R&D by the GDP deflator of the country of the company. Data sources: Compustat, Business Week R&D Scoreboard, Financial Times scoreboard.

Real R&D Stock
This was obtained using a declining balance formula and the past history of R&D spending. $KRD_t = R\&D_t + (1-\delta)KRD_{t-1}$, where δ is the depreciation rate. Our starting R&D stock was calculated for 1990 as $KRD = RD/\delta$. We computed different measures of the R&D stock using various depreciation rate (15%, 25%, 50% and 75%). The results presented in the paper are based on a 15 per cent depreciation rate. Data sources: Compustat, Business Week R&D Scoreboard, Financial Times scoreboard.

Patent Stock
This was constructed by the same method as the R&D stock. Our starting Patent stock is the average number of patents between 1976 and 1984. The stock was obtained by aggregating the counts of patent applications filed with the US Patent Office between 1970 and 1996. These counts were grouped into 34 technological classes. Data sources: SPRU.

Market Value
Following Hall et al. (1998) and Hall (1999) this variable was calculated by summing up the following items:

a. The Close Price multiplied by Common Shares Outstanding at the end of the last month of each fiscal year;
b. The value of preferred stocks, which represents the stated value of all redeemable and nonredeemable preferred/preference shares issued. This item excludes the subsidiary shares, while includes savings shares (Italy), and priority shares (Netherlands);

c. The value of the short-term debt (it is also referred to as debt in current liabilities). This item represents all debt obligations due within the next operating cycle of the company. It includes the current portion of long-term debt (when a breakout is available);
d. The value of the long-term debt. This item includes all financial obligations due after the current operating cycle. It includes the current portion of long-term borrowings (when no breakout is available).

The market value was deflated by an index of annual average stock prices of the firm's home country. Data sources: Computat, Worldscope.

Technological Linkages
We obtained the number of minority participations, received licenses, cross-licenses, strategic alliances and joint-ventures with predominant technological content by the firms in our sample. Each event is quoted several times in our information sources. We collected information (title, abstract or full text etc.) from the most comprehensive and detailed article reporting each event. Moreover, the database includes only events that are reported to have actually occurred (e.g., 'after a negotiation IBM acquired the company X', not 'IBM plans to acquire X'). As noted in the text we attributed a dollar value to these alliances using a different data base (SDC, 1998). Data sources: ARGO data base constructed at Cattaneo University (LIUC) and CESIT, University of Urbino, using Information Access Company's Insite Promt Database (http://www.insitepro.com).

Technological Network Capital
The Technological Network Capital by the same method used to compute the R&D and Patent stocks from the computed values of the annual flows (with a 0.33 depreciations rates, which assumes that the value of these investments disappears in 3 years). As noted in the text, other depreciation rates were also used in the estimation with no significant change in the results. The initial value of the stock was obtained by dividing the given investment value in 1993 by the depreciation rate.

1992 subsidiaries
Number count of the subsidiaries that belonged to each sample firms in 1992. Data sources: Dun&Bradstreet's Who Owns Whom.

Table A. The sample firms by sector and by country

Electronics	Country
ABB	CH
Alcatel Alsthom (CGE)	F
Alps	J
AMP	USA
Emerson	USA
GEC	GB
General Electric	USA
Harris	USA
Hitachi	J
Intel	USA
Kyocera	J
Litton	USA
Matsushita	J
Mitsubishi	J
Motorola	USA
NEC	J
Oki	J
Omron	J
Philips	NL
Pioneer	J
Racal	GB
Raytheon	USA
Rockwell	USA
Sanyo	J
Schneider	F
Sharp	J
Siemens	DE
Sony	J
TDK	J
Teledyne	USA
Texas Ins.	USA
Thomson S.A.	F
Thorn EMI Plc	GB
Toshiba	J
Unisys	USA
Westinghouse	USA
Xerox	USA
Zenith	USA
Telecomunications	
AT&T	USA
BCE	CA
Ericsson	SE
Nokia	FIN
Nortel (Northern Telecom, BCE)	CAN
Computers	
Apple	USA
Bull	F
Canon	J
Compaq	USA
Control Data Corporation	USA
DEC	USA
Fujitsu	J
Hewlett-Packard	USA
Honeywell	USA
IBM	USA
ICL (Fujitsu)	GB
NCR	USA
Nixdorf (Siemens)	DE
Olivetti	I
Pitney	USA
Ricoh	J
Trw Inc	USA
Wang lab	USA
Chemicals	

Akzo Nobel N.v.	NL
BASF	DE
Bayer	DE
Dow Chemical	USA
E.I. du Pont de Nemours	USA
Hoechst	DE
Imperial Chemical Industries	GB
Mitsubishi Chemical Corporation	J
Norsk Hydro ASA	NOR
Rhone-Poulenc	FR
Petroleum refining	
Amoco Corporation	USA
Atlantic Richfield Company	USA
British Petroleum plc	GB
Chevron Corporation	USA
Elf Aquitaine	FR
ENI Spa	IT
Exxon Corporation	USA
Idemitsu Kosan Co.	J
Japan Energy Corporation	J
Mobil Corporation	USA
Nippon Oil Co. Ltd.	J
PetroFina S.A.	BE
Phillips Petroleum Company	USA
Repsol S.A.	SPA
Royal Dutch/Shell Group	UK/NL
Texaco Inc.	USA
Total	FR
USX Corporation	USA

Pharmaceuticals	
American Home Product Corp.	USA
Bristol-Myers Squibb Co.	USA
Glaxo Wellcome PLC	GB
Johnson & Johnson	USA
Merck & Co. Inc.	USA
Novartis Group (a Sandoz and Ciba Geigy merger)	CH
Roche Holding Ltd.	CH
Smithkline Beecham plc	GB
Rubber and plastic products	
Bridgestone Corporation	J
Co. Generale Michelin	FR
Goodyear Tire & Rubber Co.	USA

Soaps, cosmetics	
Procter & Gamble Company	USA

Notes:

1. Glaxo-Wellcome resulted from the merger of Glaxo and Wellcome occurred 1995. The data of these firms for the years 1995 to 1997 were consolidated.
2. Novartis resulted from the merger of Sandoz and Ciba Geigy in 1996. The data for these two firms for 1996 and 1997 were consolidated

Table B. SPRU technological classes

Class	**Technological Name**
1	Inorganic Chemicals
2	Organic Chemicals
3	Agricultural Chemicals
4	Chemical Processes
5	Hydrocarbons, mineral oils, fuels and igniting devices
6	Bleaching Dyeing and Disinfecting
7	Drugs and Bioengineering
8	Plastic and rubber products
9	Materials (inc glass and ceramics)
10	Food and Tobacco (processes and products)
11	Metallurgical and Metal Treatment processes
12	Apparatus for chemicals, food, glass etc.
13	General Non-electrical Industrial Equipment
14	General Electrical Industrial Apparatus
15	Non-electrical specialized industrial equipment
16	Metallurgical and metal working equipment
17	Assembling and material handling apparatus
18	Induced Nuclear Reactions: systems and elements
19	Power Plants
20	Road vehicles and engines
21	Other transport equipment (exc. aircraft)
22	Aircraft
23	Mining and wells machinery and processes
24	Telecommunications
25	Semiconductors
26	Electrical devices and systems
27	Calculators, computers, and other office equipment
28	Image and sound equipment
29	Photography and photocopy
30	Instruments and controls
31	Miscellaneous metal products
32	Textile, clothing, leather, wood products
33	Dentistry and Surgery
34	Other - (Ammunitions and weapons, etc.)