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Technological Environments, R&D Investment, and Firm Survival

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Abstract

This paper is concerned with the impact of research and development (R&D) investment on the survival of firms, conditioned on their technological environments. Survival is the most fundamental aspect of firm performance, and is the minimal pre-requisite for all consequent (and more `noisy') aspects of performance, such as profitability, market share and growth. Building on the research literature on innovation, strategy and firm survival, we propose that the returns to firm-level R&D investment are contingent on the firm's technological environment, defined in terms of technological intensity of the sector in which the firm competes, and technological intensity of the region in which the firm is located. We develop a set of hypotheses about the relationship between R&D investment and firm survival in different technological environments, and test these using data on R&D active UK manufacturing firms for the period 1998 to 2005. We find that geographic knowledge spillovers play a significant role in determining the effect of R&D investment on survival.

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Keywords: R&D, Technological Environment, Knowledge spillover, Firm Survival, Cox Proportional Hazards Model.

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1 Introduction

Nations concerned with long run productivity growth are concerned with innovation. So are firms, given the widespread recognition that competitive advantage, and thus productivity and performance, all hinge on distinctiveness, which flow from firms' resources and capabilities (Amit and Schoemaker, 1993; Barney, 1991, 1997; Eisenhardt and Martin, 2000). Research in strategic management has highlighted the role of firm-level investments that take the form of "endogenous sunk costs" - fixed investments that can raise price-cost margin, and over the level of which firms have choice (Sutton, 1998). The primary endogenous sunk cost in a knowledge intensive industry is R&D investment. R&D investments are inputs into the innovation process, and are the first step in the innovation pathway. Their intended outputs are product, service and process innovations which support higher prices and/or reduced costs. These secure competitive advantage and improved firm performance.

However, uncertainty mediates between R&D investments and their outcomes to a greater extent than in the case of other sunk investments such as those in physical plant and equipment, for example. Spending on R&D translates only uncertainly into firms' innovative outputs and/or efficiency. R&D investment choices of firms are therefore necessarily conditioned on risks over anticipated benefits and costs. The point of departure for this paper is the fact that risks over benefits and costs of R&D investment depend on the firm's technological environment.

We focus on the most fundamental aspect of the firm performance, survival, and examine how this minimal basis for firm performance depends on the interaction between R&D investments undertaken by firms and their technological environments. As business environments, particularly in knowledge-intensive markets, grow more uncertain and difficult, research into the determinants of firm survival has become more important. The results will be useful in shaping policy support for enabling and encouraging innovation.

2 Literature

There is a large extant literature on firm survival, reviewed in Siegfried and Evans (1994) and Caves (1998). Some robust facts have been established. Firm exit rates decline with age and size, consistent with theoretical models of firm life-cycles with learning (Hopenhayn, 1992; Jovanovic, 1982; Dunne, Roberts, and Samuelson, 1989b). Firm exit are explained by proximate firm level factors reflected in financial ratios such as leverage, cashflow and profitability (Cuthbertson and Hudson, 1996; Lennox, 1999; Taffler, 1982). Macro-economic causes of exit include the phase of the economic cycle, macro-economic instability, and the interaction between the two (Bhattacharjee et al., 2009).

The particular focus in the recent literature has been on post-entry survival of new firms. For the UK, Disney, Haskel, and Heden (2003) estimated hazard models for new firm survival using the establishment (ARD) database of the Office of National Statistics for the period 1986-1991. About two-thirds of new entrants were observed to exit within five years. Exit and entry rates were found to correlate strongly, both across time and within industries. Exit rates decline steadily with firm age and size and there are significant differences between establishments that are singles and those that are part of a group. The quality of the data available for Portugal has generated considerable analysis of the Portuguese experience (Geroski, Mata, and Portugal, 2007; Mata and Portugal, 1994). A finding of this work is that post entry performance of new firms depends on the characteristics of the industry in which they operate. Mata, Portugal, and Guimarães (1995) found that firms entering expanding industries were more likely to survive, while Nunes and Sarmento (2010) found that industries with high entry rates were less favorable to firm survival.

2.1 Innovation, R&D and survival

Literature on the role of innovation in firm survival has begun to grow more recently, with some empirical studies finding a survival premium for firms that innovate that is independent of firm age and size (Banbury and Mitchell, 1995; Cefis and Marsili, 2005, 2006; Christensen, Suárez, and Utterback, 1998). A few studies have considered the impact of R&D investments, as inputs into the innovation process, on firm survival. Firms that invest in R&D activities have been found to have a lower probability of exit than those that do not (Esteve-Pérez, Sanchis-Llopis, and Sanchis-Llopis, 2004), while higher R&D expenditure intensity has also been found to positively influence the survival probability of firms (Hall, 1987).

Cohen and Levinthal (1989) have argued that the cost of utilising public domain knowledge fruitfully depends on whether firms have accumulated sufficient "technological capability" to absorb such knowledge. One obvious implication of this absorption view is that recipient firms need to undertake their own R&D investments in order to benefit from technological knowledge spillovers. The more prepared the recipient, the more beneficial, less costly and less risky is the knowledge transfer. In addition, knowledge creation and learning are both inputs and outputs of the innovation process, and therefore internal capabilities are path dependent and subject to cumulative causation: R&D benefits, costs and risk depend on the amount of R&D experience (see Cohen, 1995; Lee, 2002; Rothwell et al., 1974).

Another stream in the literature has considered the 'technological environment' in which the firm operates and its effect on the innovation process. A firm's technological environment can be defined in terms of the sector in which the firm competes and the geographic region in which the firm is located. These have been argued to play different roles.

2.2 Sector

In a knowledge intensive sector, firms can be expected to use R&D as an element of competitive strategy. There is evidence to suggest that increased competition, controlling for other factors, has a positive effect on R&D spending and, through this, on innovation. Blundell, Griffith, and Van Reenen (1999) analysed innovation output for a panel of manufacturing firms for the 1972-82 period and found an overall positive effect of competition on the number of industry innovations. The greater the degree of competition (however measured), the greater the R&D investment and innovation output. A more recent study has found evidence for an inverted-U relationship between competition and innovation (Aghion et al., 2005). The theoretical argument is that increasing competition initially results in firms innovating more in order to gain a competitive advantage over their rivals. After a point, increasing competition leads to less innovation effort. This is because firms that lag behind the leaders in a highly competitive industry are behind by a maximum of one innovation, assuming costless technology transfer of the innovation that has preceeded it, and thus have little incentive to innovate.

The greater are the opportunities arising from science in the firm's technology area, the lower are the expected costs of innovation (Cohen and Levinthal, 1989; Jaffe, 1986). Zietz and Fayissa (1992, 1994) find that more intense import competition (approximated by an appreciation of the real effective exchange rate) tends to raise R&D expenditures in high-technology, but not in low-technology US industries. The result also holds for domestic competition (proxied by unit labour costs). The magnitude of the domestic effect tends to be higher than in the international effect. To summarise, R&D investment appears to be a competitive strategy in high tech sectors more than in low-tech sectors.

2.3 Geographic region

There is a rich vein of discussion in terms of theory as well as empirics, on the extent to which firms can benefit from locational spillovers. The stylized theoretical view starts off with individual firms producing technological knowledge. Such knowledge, private to the firm to begin with, spills over to other firms to the extent it can be copied at low cost, and is useful. Thus technological knowledge acquired by individual firms has the potential to spill over and turn into social knowledge, enhancing productivity of all firms (Arrow, 1962; Grossman and Helpman, 1989; Romer, 1986).

Theories of localized knowledge spillovers emphasize the advantages that can arise from co-location of firms. Geographic proximity can reduce the cost of accessing and absorbing knowledge spillovers flowing from other firms' R&D. While basic research and new fundamental ideas are generally available through codified channels (such as scientific journals), a considerable portion of applicable research and resulting technical know-how is of tacit form, neither codifiable nor patentable. Technological knowledge capital of high-tech firms is substantially embodied in their employees. Such knowledge diffuses through informal contacts among workers including R&D personnel (industry conferences, talks and seminars) (Poyago-Theotoky, Beath, and Siegel, 2002). This made easier when firms (and individuals) are located in proximity and have low costs of participation in such activities. The cost of transferring this type of knowledge increases in geographic distance, and gives rise to localized externalities (Siegel, Westhead, and Wright, 2003). Localised spillovers may also be facilitated by workers' mobility between firms (Geroski, 1995; Møen, 2005). Firms located in agglomerations and spatial clusters are likely to have performance advantages over isolated counterparts due to the low cost of accessing external knowledge relative to producing it internally or of acquiring it externally over greater geographical distances (Harhoff, 2000).

These arguments also extend to the benefits firms obtain from geographic proximity to universities. Nelson (1986) found that university research fostered innovation in industries related to biological sciences. Jaffe (1989) found a large significant positive effect of university research on industry R&D spending within US states. Jaffe (1989), Acs, Audretsch, and Feldman (1992) and Jaffe, Trajtenberg, and Henderson (1993) all provide evidence that knowledge spillovers from university research to commercial innovation, as measured by the number of patents or recorded innovations increases with greater geographic proximity. The former two studies observe differences in the effects of university spillovers across different industry groups. Jaffe (1989), for example, finds a more significant and somewhat larger effect within technical industries such as drugs and chemicals than in the total across industries.

Knowledge flows and skilled labour exchange arising from regional proximity should reduce the costs of any firm's own R&D investments (Griliches, 1994; Jaffe, 1986). Irwin and Klenow (1996) found that amongst firms who participated in Sematech, a joint R&D consortium of US semiconductor producers, there was a drop in the total level of R&D expenditure, supporting the 'sharing' hypothesis. Information flows thus appear to help reduce duplicative R&D, allowing members to spend less on R&D than before.

To summarize, firms operating in high-technology regions have been found to benefit from knowledge spillovers from co-located firms, thus reducing the amount of R&D expenditure that they must undertake in order to produce innovations.

3 Conceptual Framework and Hypotheses

3.1 R&D investment and firm survival

In a competitive industry firms gain competitive advantage through exploiting resources that are valuable, rare, inimitable and non-substitutable (Barney, 1991). The innovation efforts of firms are aimed at creating these kinds of resources - whether they be technologically superior new product varieties which can be sold more profitably in the market, or new production processes that reduce the cost of production. To represent this relationship in a very simple way, consider both the price (p) and the unit cost (k) of firm output to be related to the firm's ability to produce economically useful innovations ($innov$):

$$p = f(innov^{+})$$

$$k = f(innov^{-})$$

R&D investment is the input into the generation of innovations. But there is no guarantee that R&D investment will produce innovations that are economically useful to the firm. This is partly due to the inherently unpredictable nature of the innovation process, but also in part due to some of a firm's R&D investment going towards building up the firm's absorptive capacity. Any firm requires some level of absorptive capacity in order to fully analyse innovations introduced by its competitors, and to make decisions on the kinds of innovations it can develop in response. The expected return to R&D investment ($R\&D$) in terms of useful innovation output ($\mathrm{E}[innov]$) is therefore zero until some threshold level (T) necessary to develop the required absoptive capacity, and positive in expectation thereafter:

$$\mathrm{E}[innov] = f(R\&D^{+}) \qquad \begin{array}{lll} > 0 & if & R\&D \geq T \\ = 0 & if & R\&D < T \end{array}$$

In a competitive environment firms that can sell better quality goods at lower prices than their competitors can be expected to outperform them in terms of sales, profit and market share. Firms that fail to keep up with the innovations introduced by their competitors will face shrinking sales, profits and market share. If these lagging firms cannot replicate innovations introduced by their competitors, and fail to generate their own innovations which would allow them to match competitors in terms of output quality and cost, they will face continued reduction in turnover, profitability and market share. As survival is contingent on the firm being able to generate sufficient sales revenue to cover the costs of production and any debt service payments, consistently falling turnover increases the probability that the firm in question will not meet this survival condition and hence will exit. Noting that R&D investment is a cost that the firm must cover, in a reduced form sense, the probability of firm exit ($Pr(exit)$) is a function of R&D investment, *ceteris paribus*:

$$Pr(exit) = f(R\&D < T^{+}; R\&D \geq T^{-})$$

To summarize, the probability of firm exit will increase in its R&D investment below an absorptive capacity threshold, as the firm is incurrs costs but has little or no prospect of generating useful innovative output. Above the threshold, exit probability decreases as the probability of innovations that allow the firm to sell at a higher price or produce at a lower cost increases. We can thus expect an inverted-U shaped relationship between the probability of firm exit and its R&D expenditure.

We now turn to how the firm's technological environment, as defined by the technological intensity of the region and of the sector in which it operates, affects the the relationship between R&D, innovation and firm survival as sketched out above.

3.2 Sectoral effects

Technological competition is more fierce in high-technology sectors than in low-technology ones. Firms operating in a high-technology sector (S_H) must develop and maintain a large technological knowledge base in order to compete effectively with rivals. On the other hand, firms operating in a low-technology sector (S_L) can invest less and yet keep abreast of technological developments in their industry. In other words the absorptive capacity threshold of R&D expenditure which must be reached before R&D investment becomes productive will be higher for S_H firms than for S_L firms. We expect the threshold after which R&D investment begins to reduce the probability of firm exit to be higher for firms operating in S_H than for firms operating in S_L. In terms of the inverted-U relationship between R&D expenditure and the probability of firm exit hypothesized above we expect the turning point after which R&D investment becomes negatively associated with firm exit to occur at a higher level of R&D for S_H firms than for S_L firms.

3.3 Regional effects

Firms operating in a high-technology region (R_H) can benefit from the R&D efforts of other firms in the region through knowledge spillovers, increasing the effectiveness of their own R&D investments in producing useful innovation output. This can be a result of lower costs of R&D and/or increased demand (and therefore price) for the innovation output of R&D. The costs of doing R&D in a high-technology region may be lower due spill-over benefits from the R&D investments of co-located firms. Further, the demand for the firm's innovation output from firms operating in other industries may be greater within a high-technology region due to the diffusion of information about new products and services which may find (unexpected) uses in other industries. Firms operating in a low-technology region (R_L) cannot be expected to benefit as much from these spillover effects. If they are to produce the same innovation output (in expectation) as R_H firms, they will need to invest more in their own R&D. The return to R&D in terms of reducing the probability of exit will thus be greater for R_H firms than for R_L firms. In terms of the inverted-U relationship between R&D expenditure and the probability of firm exit, we expect the slope of the curve to be steeper for firms operating in high-technology regions than for firms operating in low-technology regions.

3.4 Hypotheses

To bring together the strands in the argument we have developed so far: firm survival, as a fundamental aspect of firm performance, is determined by innovation outputs, and these in turn are determined somewhat 'noisily' by R&D investment as an innovation input. The performance impact of R&D investment depends on the firm's technological environment, defined by both its sector and its region. Within each technological environment so defined, an inverted-U shaped relationship between R&D investment and the probability of firm exit can be expected. We can add precision to this hypotheses by comparing the inverted-U relationships in the different technological environments.

We take as the base the technology environment defined as high-technology sector, high-technology region. In this environment the competition in sector requires high levels of own R&D investment in absorptive capacity before the relationship between R&D investment and probability of exit becomes negative (high T). However, being located in a high-technology region, firms can benefit from spillovers of the R&D of other firms in the region. Thus there are greater returns to R&D investment in terms of decline in probability of exit, once R&D investment is greater than T.

1. Relative to the benchmark, S_H, R_L firms will need to spend more on R&D (in order to develop the required absorptive capacity), and will gain less survival advantage from R&D expenditure above this higher threshold (as they cannot benefit as much from the R&D efforts of other firms in the region).

2. Again, relative to benchmark, S_L, R_H firms will need to do less own R&D (to attain the required absorptive capacity, as the R&D competition thresholds of their sectors are lower).

Further ordering relations are straightforward:

3. Relative to S_L, R_H firms, S_L, R_L firms will need to invest more in R&D to attain the required absorptive capacity, and will gain less of a survival advantage from R&D expenditure above this higher threshold as they can benefit less from the R&D of others.

4. Relative to S_H, R_L firms, S_L, R_L firms will need to invest less in own R&D before they can experience its positive impact on their survival prospects. (This is because their sectors have lower R&D competition, and thus are characterised by lower absorptive capacity thresholds).

5. Relative to S_L, R_H firms, S_H, R_L firms will need to do more own R&D to develop their absorptive capacity, as their sectors have higher R&D competition; but at the same time they gain less of a survival advantage from R&D expenditure above this threshold (as they cannot expect to benefit as much from other firms' R&D).

6. Relative to S_H, R_H firms, firms in low-technology sectors and regions (S_L, R_L) will face a lower absorptive capacity threshold beyond which R&D investment becomes negatively related to their probability of exit (as their sectors are not as technologically intense). However, these firms will also face lower returns to R&D investment above the threshold value in terms of a survival premium as they will not be able to benefit from regional R&D spillovers.

Having defined the technological environments and developed hypotheses about the way relationship between R&D investment and firm survival differ between these, we now turn to empirical analysis.

4 Empirical Strategy

We are interested in understanding how survival of firms is conditional on their past R&D investments in different technological environments. We follow firms in their different technological environments over the period 1998 to 2005. If T is the number of years that a firm has survived till 2005, the cumulative distribution function for duration T is: $F(t) = Pr(T \leq t)$, where the value of t ranges between 0 and 8 years as 1998 marks the start of our observation period. $F(t)$ gives the probability that duration T is less than or equal to t; i.e., the probability that the firm exits before t years after 1998. The survival function gives the probability that a firm survives t years from 1995: $S(t) = 1 - F(t) = Pr(T > t)$.

The counterpart to the survival function is the hazard rate - the limiting probability that failure occurs in a given interval, conditional on the firm having survived to the beginning of that interval:

$$\lambda(t) = \begin{matrix} lim \\ \triangle t \rightarrow 0 \end{matrix} \frac{Pr(t + \triangle t > T > t | T > t)}{\triangle t} = \frac{\partial F(t)/\partial(t)}{S(t)}$$

Our focus is on the effect of covariates on the hazard rate and on the probability of firm survival. We estimate the semi-parametric Cox proportional hazards model, a popular and well-understood technique in toolkit of researchers interested in understanding the determinants of firm survival (Cox, 1972). According to this model, any given firm faces a hazard rate that is a function of a baseline hazard rate $\lambda_0(t)$ which all firms face, transformed by a set of explanatory variables $\mathbf{z}$, through a vector of parameters, $\boldsymbol{\beta}$. The relationship between the hazard rate at duration t and the covariates $\mathbf{z}$ (explanatory factors other than the duration variable), is modelled as:

$$\lambda(t|s, \mathbf{z}) = \lambda_0(t) \exp(\boldsymbol{\beta}' \mathbf{z})$$

Under this model, changes in the covariates induce only a multiplicative shift in the hazard function. In other words, the hazard functions for different values of the covariates are proportional to each other and have the same shape as the baseline hazard function. This is a strong assumption and we test whether it holds in all of our specifications. That said, the Cox model allows the shape of the hazard function to be flexible after conditioning on explanatory factors other than duration time so the nature of duration dependence is unrestricted. The model thus provides a very convenient representation of the relationship between the hazard rate at a given duration time conditional on the values of the covariates.

The models we estimate will consider how hazard rates depend on the interaction between R&D investment and the technological environment, and specifically, if there are any non-linearities in this relationship.

5 Data

To test our hypotheses regarding the relationship between R&D investment and firm survival in different technological environments we put together a dataset containing information on firm R&D investments and survival, using two datasets maintained by the UK Office for National Statistics (ONS): the Business Structure Database (BSD) and the Business Enterprise Research and Development (BERD). As the sample coverage of R&D activities of manufacturing firms is substantially greater than that of firms in the service sector, we focus our analysis on firms in manufacturing industries - SIC 2-digit sector codes ranging from 15 to 37. We describe these two datasets below before proceeding to define the variables that we use in our analysis.

5.1 BSD

The BSD provides annual coverage accounting for nearly 99% of UK economic activity. The database is constructed from the ONS' Inter Departmental Business Register and contains information on 2.5 - 3 million UK enterprises from 1997 to the present, of which just over 2.1 million are currently active. The sources of these data are Value Added Tax (VAT) data, covering ~1.7 million UK traders, and Pay As You Earn (PAYE) data, covering ~1.1 million UK employers, both of which are provided by Her Majesty's Revenue and Customs (HMRC), the former on a daily basis and the latter every quarter. The BSD contains information at both enterprise and local unit level.

We conduct our analysis at the enterprise level as decisions regarding investment in R&D are likely to be made at this level, rather than at the level of the local unit. We use the period between 1998 and 2005 for our analysis, thereby discarding data from the first and latest available years due to its reduced accuracy. While BSD covers nearly all economically active enterprises in the UK the information about enterprise characteristics that it provides is rather limited. The variables available in the data are whether or not the enterprise is still active, and for active enterprises, their postcode, industry (at SIC 5-digit level), employment, turnover, number of active local units, enterprise group links and country of ownership, and legal status.

Table 1 on the following page present some summary statistics for the BSD population of firms between 1998 and 2005, and for the manufacturing sector within BSD. It is to be noted that fewer than 10% of British firms operate in the manufacturing sector and that their number shrank by close to 27,000 in the time period of our study, while the overall number of active enterprises in the economy increased by more than 150,000. Firms in the manufacturing subsample are on average older and larger, in terms of employment, turnover and their number of active local units, than the average firm in the BSD.

Table 1: The BSD population

Year	Age	Employees	Turnover (000 GBP)	Live Local Units	Number
All Enterprises					
1998	8.99	12.47	2,092	1.55	2,047,023
1999	9.30	12.37	2,048	1.53	2,073,414
2000	9.65	12.59	2,049	1.52	2,064,409
2001	9.91	12.56	1,824	1.54	2,095,466
2002	10.13	12.81	1,756	1.54	2,107,352
2003	10.28	12.93	1,574	1.54	2,109,542
2004	10.24	12.60	1,784	1.54	2,155,956
2005	10.31	12.56	1,798	1.53	2,201,357
Manufacturing Enterprises					
1998	10.12	23.50	2,395	1.66	189,379
1999	10.65	23.55	2,467	1.65	185,980
2000	11.27	23.97	2,673	1.64	177,789
2001	11.60	23.36	2,769	1.63	177,138
2002	11.95	23.33	2,653	1.62	174,554
2003	12.29	22.16	2,631	1.60	170,280
2004	12.53	21.65	2,740	1.60	166,433
2005	12.89	21.11	2,854	1.60	162,474

5.2 BERD

The BERD is a panel dataset of the R&D investments and other innovation inputs of UK firms that engage in R&D activity. The panel started in 1997 and was updated annually. We extracted data on enterprise R&D expenditures for the period between 1998 and 2005 and merged it with the BSD dataset. The merged dataset consists of observations on around 4,000 manufacturing firms every year. These firms are on average older and much larger than the average manufacturing firm in the population: the average age of firms in our dataset is 18 years and they employed 321 persons on average. Given this we do not make any claims about the generalizability of our results to all manufacturing firms. We limit the scope of our analysis to investigating the relationship between R&D expenditure and survival for those firms who do choose to invest in R&D.

5.3 Variables

As described in section 4, we use the hazard rate of firm exit in analysis period t as our dependent variable. We use analysis time rather than age as our duration variable because the enterprises in our sample vary significantly in age at the start of our analysis period.

Our main independent variable is a measure of firm level intramural R&D expenditure (all expenditures for R&D performed within the enterprise). Annual R&D expenditure is volatile due to the lumpy nature of R&D investments. Further, the relationship between R&D expenditure and innovation output is time lagged and uncertain. For these reasons we follow examples from previous studies in taking average R&D expenditure undertaken by the firm in the 3 years prior to the year of observation as our measure of firm investment in R&D. To take into account the possibility that firms within the same sectors may be operating at different scales, we divide our lagged 3-year average R&D investment by the firm's average turnover

Table 2: High Technology Sectors

Pharmaceuticals - SIC 24.4
Computers, Office Machinery - SIC 30
Electronics-Communications - SIC 32
Aerospace - SIC 35.3
Scientific Instruments - SIC 33
Motor Vehicles - SIC 34
Electrical Machinery - SIC 31
Chemicals - SIC 24, excluding 24.4
Other Transport Equipment - SIC 35.2, 35.4, 35.5
Non-electrical Machinery - SIC 29

over that 3-year period to generate a variable (RDT) that can be interpreted as the average percentage of turnover that a firm invests in R&D. We also include the square of our R&D variable in the regression specifications in order to capture any non-linearities in the relationship between R&D expenditure and firm survival.

To classify sectors as high- or low-technology (S_H or S_L) we follow the OECD classification of industry technological intensity. Specifically, we take sectors classified as being of high or medium-high technology by the OECD as our high-technology sectors. Table 2 lists these sectors, along with their SIC codes. The rest of the manufacturing industries in our sample are classified as being relatively low-tech.

For the classification of the technological intensity of regions, we use data on regional R&D expenditure from Eurostat. The largest amount of R&D spending occurs in the South East and East Anglia regions, followed by the North West and London. The rest of the UK's regions lag far behind in R&D expenditure terms. Table 3 on the following page lists the high and low technology regions (R_H and R_L) based on this classification.

In order to test hypotheses regarding the relationship between R&D expenditure and firm survival and how this is affected by a firm's technological environment, we create 4 region×sector dummy variables: $S_H R_H$ (equal to one for firms operating in high-technology sectors and regions, and zero otherwise), $S_H R_L$ (equal to

Table 3: High and Low Technology Regions

High Technology Regions	Low Technology Regions
South East	North East
East Anglia	Yorkshire and Humberside
North West	East Midlands
London	West Midlands
	South West
	Wales
	Scotland
	Northern Ireland

one for firms operating in high-technology sectors and low-technology regions, and zero otherwise), $S_L R_H$ (equal to one for firms operating in low-technology sectors and high-technology regions, and zero otherwise), and $S_L R_L$ (equal to one for firms operating in low-technology sectors and regions, and zero otherwise). We interact these dummy variables with our measure of a firm's past R&D expenditure, and its square to capture any non-linearities.

Age and size as measured by firm employment are standard controls in survival analysis. The number of local units operated by the business is a dimension of size as well as diversification. These also serve as proxies for collateral which determines the ability of a firm to access sources of finance. Whether the business is part of an enterprise group is a useful control, following Dunne, Roberts, and Samuelson (1989a). We also control for labour productivity, the level of turbulence (sum of entry and exit rates) in the industry in which the firm operates and the size concentration in the firm's sector as measured by the Herfindahl index. We control for other sectoral differences by including sectoral dummy variables. It is a plausible to conjecture that subsidiaries of foreign firms rely upon parents for inventions and innovative ideas. Related to this is the tendency for R&D branches of firms to be located close to head office (Leahy and Pavelin, 2004). We control for foreign ownership, distinguishing between parent companies from the US, EU, South and East Asia and the Rest of the World.

5.4 Summary statistics

Table 4 on the next page presents the summary statistics for firms operating in different technological environments in our sample. As can be seen, the different technological environments are comparably populated, though firms in high-technology sectors and low-technology regions are more than twice as numerous as those in low-technology sectors but high-technology regions.

The magnitudes of the R&D to Turnover ratios in different technological environments can be rationalized in terms of the hypotheses we presented. Relative to the 8.6% RDT in the $\mathrm{S}_H\mathrm{R}_H$ environment, RDT in the $\mathrm{S}_L\mathrm{R}_H$ environment is lower at 3%, and in the $\mathrm{S}_H\mathrm{R}_L$ environment is higher at 12.5% . These patterns are consistent with more intense R&D competition in high-technology sectors and greater effect of R&D expenditures high-technology regions due to spillovers. The R&D intensity of firms in the $\mathrm{S}_L\mathrm{R}_L$ environment is 6.5%, which is also consistent with our ranking hypotheses.

In terms of average labour productivity, we note that holding the technological intensity of the sector constant, firms in high-technology regions exhibit greater labour productivity than firms in low-technology regions. Employees of firms in high-technology sectors also appear to be more productive than those of firms in low-technology sectors for a given technological intensity of their region. For completeness, we also include the summary statistics of the dummy variables for enterprise group membership and foreign ownership. These do not differ much between the different environments. Around 30% of firms in our sample are members of enterprise groups and around 17-18% are foreign-owned.

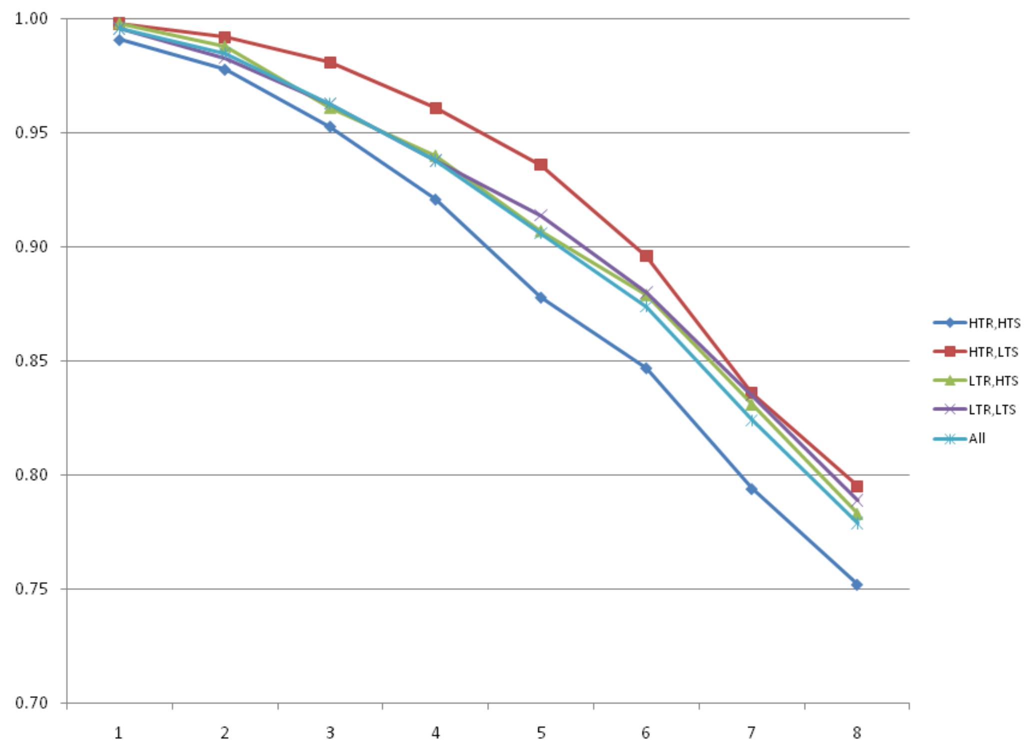
Coming to firm survival, Figure 1 on page 22 shows the survival probabilities of firms operating in different technological environments in our sample over the analysis period. It can be seen that among R_H firms, unconditional survival probabilities are uniformly greater for any time horizon for low-technology sector firms than for

Table 4: Summary Statistics by Technological Environment (1998-2005)

Sector / Region	No. Observations	Age	Employees	R&D/ Turnover 3-yr Av.	Average Labour Productivity	Ent. Group Membership	Foreign Ownership
S_H, R_H	7,803	17.9	310.1	8.6%	117.6	0.32	0.19
S_H, R_L	10,719	17.6	309.1	12.5%	105.4	0.31	0.18
S_L, R_H	5,066	18.8	333.9	3.0%	101.4	0.28	0.17
S_L, R_L	8,708	18.3	337.1	6.5%	97	0.3	0.15

high-technology ones. There does not appear to be a clear difference of the above type in unconditional survival probabilities for firms operating in sectors of differing technological intensity in low-technology regions. Among S_L firms, those in high-technology regions generally have unconditional survival probabilities that dominate those of firms in low-technology regions. Finally, firms in high-technology sectors and low-technology regions appear to have higher unconditional survival probabilities than $S_H R_H$ firms. This pattern does not appear at first glance to be consistent with our hypotheses; but it is worth noting that these survival probabilities are unconditional. It is only upon inclusion of firm-level R&D investment as well as our other control variables that a fuller understanding of the factors driving variation in the probabilities of firm exit will be forthcoming.

Figure 1: Survival Probabilities



6 Results

Table 5 below presents the results of three different specifications of our Cox Proportional Hazards regression. The first specification includes all our variables and is estimated using robust standard errors clustered at 2-digit industry level. The second specification excludes the turbulence and Herfindahl index control variables, while the third specification includes all variables but allows for different baseline hazards in different SIC 2-digit industries (industry dummy variables are excluded). The null hypothesis of the Proportional Hazards assumption holding is not rejected for any of the specifications estimated.

Table 5: Cox Proportional Hazards Model Estimates

	Full model	No turbulence, Herfindahl	Stratified by Sector (SIC 2 digit)
$S_H R_H * RDT$	0.742**	0.767**	0.793*
	[0.298]	[0.329]	[0.407]
$S_H R_L * RDT$	0.374**	0.376**	0.408**
	[0.181]	[0.183]	[0.184]
$S_L R_H * RDT$	8.800***	8.318***	8.481**
	[3.107]	[3.106]	[4.282]
$S_L R_L * RDT$	2.551**	2.423**	2.776
	[1.197]	[1.208]	[2.044]
$S_H R_H * RDT^2$	-0.152	-0.159	-0.16
	[0.099]	[0.108]	[0.119]
$S_H R_L * RDT^2$	-0.029*	-0.029*	-0.031**
	[0.015]	[0.016]	[0.016]
$S_L R_H * RDT^2$	-21.28***	-20.18***	-20.20**
	[6.174]	[6.020]	[9.765]
$S_L R_L * RDT^2$	-2.709*	-2.603*	-3.002
	[1.519]	[1.520]	[1.857]
$S_H R_H$	0.044	0.116	0.019
	[0.350]	[0.328]	[0.267]
$S_H R_L$	-0.091	-0.021	-0.115
	[0.364]	[0.339]	[0.263]
$S_L R_H$	-0.072	-0.073	-0.06
	[0.123]	[0.123]	[0.163]
Turbulence	3.339***		3.292***
	[0.924]		[1.072]
Herfindahl	-2.507		-2.905
	[2.113]		[1.933]
Log(Age)	-0.268***	-0.270***	-0.259***
	[0.075]	[0.077]	[0.079]
Log(Emp)	0.005	0	0.011
	[0.030]	[0.030]	[0.037]
Log(Av. Labour Prod.)	-0.121**	-0.125**	-0.114*
	[0.057]	[0.057]	[0.059]
Log(Live Local Units)	-0.144**	-0.144**	-0.154*
	[0.070]	[0.071]	[0.089]
Enterprise Group	0.430***	0.432***	0.426***
	[0.083]	[0.082]	[0.086]

Foreign Owned - US	0.179*	0.193*	0.152
	[0.108]	[0.110]	[0.142]
Foreign Owned - EU	0.376**	0.386**	0.363***
	[0.151]	[0.153]	[0.121]
Foreign Owned - SEA	-0.264	-0.201	-0.256
	[0.409]	[0.353]	[0.509]
Foreign Owned - Other	0.24	0.23	0.237
	[0.219]	[0.221]	[0.243]
Industry (2 digit) effects	Yes	Yes	No
Observations	11813	11836	11813

Robust standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

In order to present the results relating to the relationship between R&D expenditure and firm survival in different technological environments as clearly as possible, we apply the estimated coefficients on the interaction of RDT and RDT^2 with the technological environment dummy variables to plot the estimated change in hazard, conditioned on different values of RDT. Though the coefficient on $\mathrm{S}_H\mathrm{R}_H{*}RDT^2$ is just outside significance at the 10% level, the joint hypothesis ($\mathrm{S}_H\mathrm{R}_H{*}RDT = 0$; $\mathrm{S}_H\mathrm{R}_H{*}RDT^2 = 0$) is convincingly rejected at 5% level of signficance.

Table 6: Non-linearity of Exit Hazard with respect to R&D/Turnover

Joint Hypotheses	$\chi^2(2)$
$\mathrm{S}_H\mathrm{R}_H{*}RDT{=}0$; $\mathrm{S}_H\mathrm{R}_H{*}RDT^2{=}0$	6.37**
$\mathrm{S}_H\mathrm{R}_L{*}RDT{=}0$; $\mathrm{S}_H\mathrm{R}_L{*}RDT^2{=}0$	4.84*
$\mathrm{S}_L\mathrm{R}_H{*}RDT{=}0$; $\mathrm{S}_L\mathrm{R}_H{*}RDT^2{=}0$	12.42***
$\mathrm{S}_L\mathrm{R}_L{*}RDT{=}0$; $\mathrm{S}_L\mathrm{R}_L{*}RDT^2{=}0$	5.04*

* significant at 10%; ** significant at 5%; *** significant at 1%

What is to be noted is the ordering of the different technological environments in terms of the values of RDT at which the respective hazard functions reach their maxima.

The plots of the estimated quadratic relationships between R&D expenditure and exit hazards for firms in different technological environments are presented in

Figure 2: Regression Results: R&D/Turnover and Exit Hazard

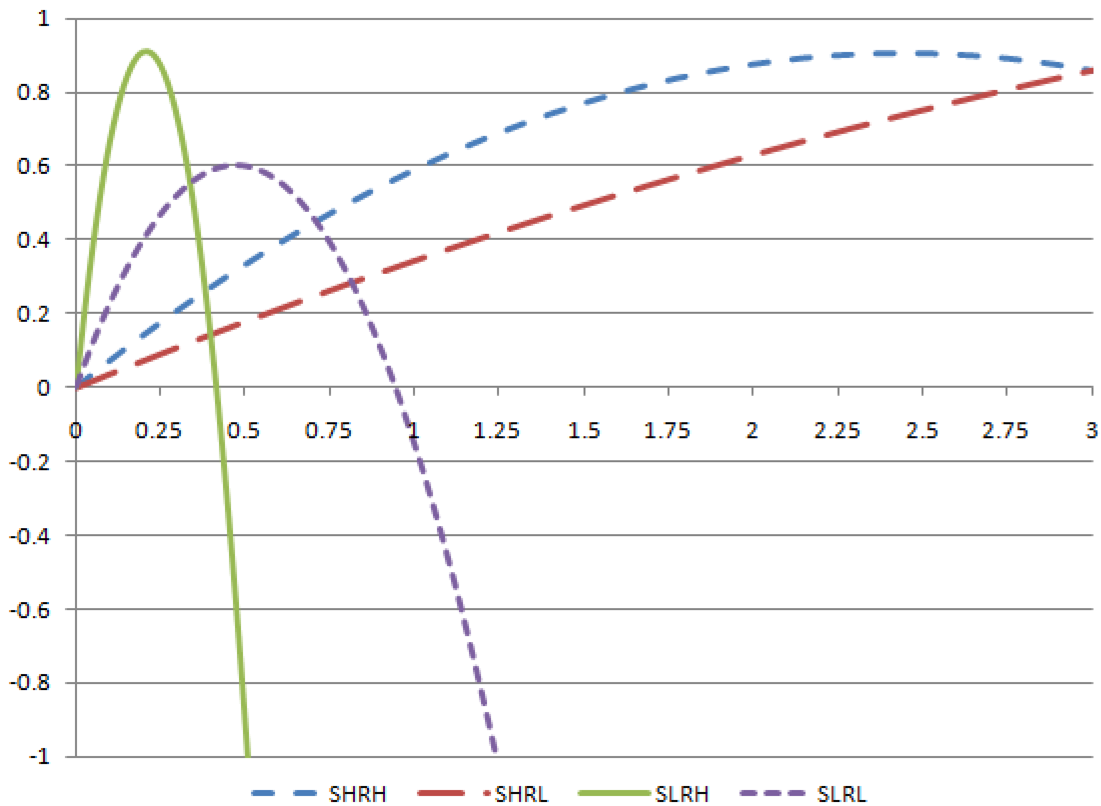


Figure 2 on the previous page. Given the thresholds for *RDT* required in different technological environments to build up absorptive capacity, we hypothesized that relative to firms in $S_H R_H$ environment, firms in $S_H R_L$ environment would need a higher value of *RDT* in order to begin to realize survival benefits from their R&D investments. High technology sectors would generally require higher levels of R&D to meet firm level competition, and to the extent that high technology sector firms located in low technology regions cannot benefit from geographical spillovers, their own R&D investments need to be larger.

The effectiveness of R&D as a strategy for survival is reflected in the slope of the hazard function with respect to *RDT* (symmetric about the maximum in our specification). The fact that this slope is relatively small for technological environments containing high technology sector firms would seem to reflect the intensity of R&D competition there. In addition, high technology sector firms in high technology regions arguably have some R&D cost advantage due to knowledge spillovers from co-located firms over high technology sector firms in low technology regions, and this can explain why the slope of the hazard function is smaller in the $S_H R_L$ environment than in the $S_H R_H$ environment.

As hypothesiszed, we find evidence that relative to firms in the $S_L R_L$ environment, firms in the $S_L R_H$ environment need a lower value of *RDT* in order to begin to realize survival benefits from their R&D investments. We also find that the slope of the hazard function is smaller in the $S_L R_L$ environment than in the $S_L R_H$ environment, supporting our conjecture that firms in high technology regions benefit from R&D cost advantage over firms in low-technology regions due to knowledge spillovers from co-located firms. It is also to be noted that the turning points (reflecting R&D thresholds) of both hazard functions for firms in low-technology sectors are lower than those for firms in high-technology sectors, as expected. To summarize, these empirical results are consistent with all of our hypotheses.

In terms of the control variables, as expected the effect of age on the hazard of firm exit is negative, the effect of size is positive though not significant, which is not surprising considering that the sample consists of firms that are in general fairly large. Firms in more turbulent industries are more likely to exit, a result that is consistent with findings for Portugal (Nunes and Sarmento, 2010), while the degree of competition as measured by the Herfindahl index does not appear to significantly affect exit hazards. Average labour productivity and the number of local units operated by the enterprise have negative effects on the probability of exit as expected. Interestingly, being a member of an enterprise group, as well as being owned by corporate parents based in the US or continental Europe increases the probability of firm exit, ceteris paribus. This can be interpreted in terms of a more activist and strategic business portfolio policy followed by corporate parents whether in the UK, US or in continental Europe.

As a robustness check we estimated parametric hazard models incorporating a number of different distributional assumptions. The results from these models broadly support the above findings.

7 Conclusions

Our focus in this paper was on the impact of research and development, conditioned on the firm's technological environment, on its survival. We found that the returns to firm-level R&D investments in terms of survival are contingent on the firm's technological environment, comprising both the sector and the region of the firm. The technological intensity of the sector in which the firm competes determines the amount of R&D expenditure required to build and maintain absorptive capacity required for competing effectively and survival. The technological intensity of the region in which the firm is located determines the R&D costs of generating innovation outputs. These principles lead to a set of hypotheses in the form of an ordering relationship over the threshold R&D expenditures beyond which firm survival probabilities increase in the different technological environments, and the rates at which they do so. We tested these hypotheses using firm level data on the R&D expenditures and survival of UK manufacturing firms between 1998 and 2005. Our hypotheses are substantially supported by the empirical analysis. These results highlight the importance of knowledge spillovers in high-technology regions and of technological competition in high-technology sectors in determining the effect of firm level R&D investments on firm survival.

References

Acs, Zoltan J., Audretsch, David B., and Feldman, Maryann P., 1992. "Real Effects of Academic Research: Comment." *American Economic Review* 82:363–367.

Aghion, Philippe, Bloom, Nick, Blundell, Richard, Griffith, Rachel, and Howitt, Peter, 2005. "Competition and Innovation: An Inverted-U Relationship." *Quarterly Journal of Economics* 120:701–728.

Amit, Raphael, and Schoemaker, Paul J.H., 1993. "Strategic Assets and Organizational Rent." *Strategic Management Journal* 14:33–46.

Arrow, Kenneth, 1962. *The Rate and Direction of Inventive Activity: Economic and Social Factors*, chap. Economic Welfare and the Allocation of Resources for Inventions, 609–626. Princeton, NJ: Princeton University Press.

Banbury, Catherine M., and Mitchell, Will, 1995. "The Effect of Introducing Important Incremental Innovations on Market Share and Business Survival." *Strategic Management Journal* 16:161–182.

Barney, Jay B., 1991. "Firm Resources and Sustained Competitive Advantage." *Journal of Management* 17:99–120.

Barney, Jay B., 1997. *Gaining and Sustaining Competitive Advantage*. Reading, MA: Addison-Wesley.

Bhattacharjee, Arnab, Higson, Chris, Holly, Sean, and Kattuman, Paul, 2009. "Macroeconomic Instability and Business Exit: Determinants of Failures and Acquisitions of UK Firms." *Economica* 76:108–131.

Blundell, Richard, Griffith, Rachel, and Van Reenen, John, 1999. "Market Share, Market Value and Innovation in a Panel of British Manufacturing Firms." *Review of Economic Studies* 66:529–554.

Caves, Richard E., 1998. "Industrial Organization and New Findings on the Turnover and Mobility of Firms." *Journal of Economic Literature* 36:1947–1982.

Cefis, Elena, and Marsili, Orietta, 2005. "A Matter of Life and Death: Innovation and Firm Survival." *Industrial and Corporate Change* 14:1167–1192.

Cefis, Elena, and Marsili, Orietta, 2006. "Survivor: The Role of Innovation in Firms' Survival." *Research Policy* 35:626–641.

Christensen, Clayton M., Suárez, Fernando F., and Utterback, James M., 1998. "Strategies for Survival in Fast-Changing Industries." *Management Science* 44:S207–S220.

Cohen, Wesley M., 1995. *Handbook of the Economics of Innovation and Technical Change*, chap. Empirical Studies of Innovative Activity, 182–264. Cambridge, MA: Blackwell.

Cohen, Wesley M., and Levinthal, Daniel A., 1989. "Innovation and Learning: The Two Faces of R&D." *Economic Journal* 99:569–596.

Cox, D. R., 1972. "Regression Models and Life-Tables." *Journal of the Royal Statistical Society, Series B* 34:187–220.

Cuthbertson, Keith, and Hudson, John, 1996. "The Determinants of Compulsory Liquidations in the U.K." *Manchester School* 64:298–308.

Disney, Richard, Haskel, Jonathan, and Heden, Ylva, 2003. "Entry, Exit and Establishment Survival in UK Manufacturing." *Journal of Industrial Economics* 51:91–112.

Dunne, Timothy, Roberts, Mark J., and Samuelson, Larry, 1989a. "Firm Entry and Postentry Performance in the U. S. Chemical Industries." *Journal of Law and Economics* 32:S233–S271.

Dunne, Timothy, Roberts, Mark J., and Samuelson, Larry, 1989b. "The Growth and Failure of U. S. Manufacturing Plants." *The Quarterly Journal of Economics* 104:671–698.

Eisenhardt, Kathleen M., and Martin, Jeffrey A., 2000. "Dynamic Capabilities: What Are They?" *Strategic Management Journal* 21:1105–1121.

Esteve-Pérez, Silviano, Sanchis-Llopis, Amparo, and Sanchis-Llopis, Juan Alberto, 2004. "The Determinants of Survival of Spanish Manufacturing Firms." *Review of Industrial Organization* 25:251–273.

Geroski, P.A., 1995. "What Do We Know about Entry?" *International Journal of Industrial Organization* 13:421–440.

Geroski, P.A., Mata, José, and Portugal, Pedro, 2007. "Founding Conditions and the Survival of New Firms." *DRUID Working Paper Series* 07-11:1–38.

Griliches, Zvi, 1994. "Productivity, R&D, and the Data Constraint." *American Economic Review* 84:1–23.

Grossman, Gene M., and Helpman, Elhanan, 1989. "Product Development and International Trade." *Journal of Political Economy* 97:1261–1283.

Hall, Bronwyn H., 1987. "The Relationship between Firm Size and Firm Growth in the US Manufacturing Sector." *Journal of Industrial Economics* 35:583–606.

Harhoff, Dietmar, 2000. "R&D Spillovers, Technological Proximity, and Productivity Growth - Evidence from German Panel Data." *Schmalenbach Business Review* 52:238–260.

Hopenhayn, Hugo A., 1992. "Entry, Exit, and firm Dynamics in Long Run Equilibrium." *Econometrica* 60:1127–1150.

Irwin, Douglas A., and Klenow, Peter J., 1996. "High-tech R&D Subsidies: Estimating the Effects of Sematech." *Journal of International Economics* 40:323–344.

Jaffe, Adam B., 1986. "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value." *American Economic Review* 76:984–1001.

Jaffe, Adam B., 1989. "Real Effects of Academic Research." *American Economic Review* 79:957–970.

Jaffe, Adam B., Trajtenberg, Manuel, and Henderson, Rebecca, 1993. "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations." *Quarterly Journal of Economics* 108:577–598.

Jovanovic, Boyan, 1982. "Selection and the Evolution of Industry." *Econometrica* 50:649–670.

Leahy, Dermot, and Pavelin, Stephen, 2004. "Divide and Rule: Geographical Diversification and the Multinational Firm." *Open Economies Review* 15:363–374.

Lee, Chang-Yang, 2002. "A Simple Model of R&D: An Extension of the Dorfman-Steiner Theorem." *Applied Economics Letters* 9:449–452.

Lennox, Clive, 1999. "Identifying Failing Companies: A Reevaluation of the Logit, Probit and DA Approaches." *Journal of Economics and Business* 51:347–364.

Mata, José, and Portugal, Pedro, 1994. "Life Duration of New Firms." *Journal of Industrial Economics* 42:227–245.

Mata, José, Portugal, Pedro, and Guimarães, Paulo, 1995. "The Survival of New Plants: Start-up Conditions and Post-entry Evolution." *International Journal of Industrial Organization* 13:459–481.

Møen, Jarle, 2005. "Is Mobility of Technical Personnel a Source of R&D Spillovers?" *Journal of Labor Economics* 23:81–114.

Nelson, Richard R., 1986. "Institutions Supporting Technical Advance in Industry." *American Economic Review* 76:186–189.

Nunes, Alcina, and Sarmento, Elsa de Morais, 2010. "Business Demography Dynamics in Portugal: A Semi-Parametric Survival Analysis." *GEMF Working Papers* 2010-10:1–23.

Poyago-Theotoky, Joanna, Beath, John, and Siegel, Donald S., 2002. "Universities and Fundamental Research: Reflections on the Growth of University-Industry Partnerships." *Oxford Review of Economic Policy* 18:10–21.

Romer, Paul M., 1986. "Increasing Returns and Long-Run Growth." *Journal of Political Economy* 94:1002–1037.

Rothwell, R., Freeman, C., Horsley, A., Jervis, V. T. P., Robertson, A. B., and Townsend, J., 1974. "SAPPHO Updated - Project SAPPHO Phase II." *Research Policy* 3:258–291.

Siegel, Donald S., Westhead, Paul, and Wright, Mike, 2003. "Assessing the Impact of University Science Parks on Research Productivity: Exploratory Firm-level Evidencefrom the United Kingdom." *International Journal of Industrial Organization* 21:1357–1369.

Siegfried, John J., and Evans, Laurie Beth, 1994. "Empirical Studies of Entry and Exit: A Survey of the Evidence." *Review of Industrial Organization* 9:121–155.

Sutton, John, 1998. *Technology and Market Structure: Theory and History.* Cambridge, MA: MIT Press.

Taffler, R.J., 1982. "Forecasting Company Failure in the UK Using Discriminant Analysis and Financial Ratio Data." *Journal of the Royal Statistical Society, Series A* 145:342–358.

Zietz, Joachim, and Fayissa, Bichaka, 1992. "R&D Expenditures and Import Competition: Some Evidence for the U.S." *Review of World Economics* 128:52–66.

Zietz, Joachim, and Fayissa, Bichaka, 1994. "The Impact of Exchange Rate Changes on Investment in Research and Development." *Quarterly Review of Economics and Finance* 34:195–211.