Clarifying the Effects of R&D on Performance: Evidence from the High Technology Industries

Chao-Hung Wang*

Department of Marketing and Logistics Management, Ling Tung University, Taiwan.

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Abstract

It has been assumed that there is a clear linear causal effect of research and development (R&D) on performance. However, recent empirical studies have shown both a positive relationship, which suggests an increase in R&D leading to improved performance, as well as a negative relationship, which suggests an increase in R&D resulting in poor performance. Therefore, the evidence for this assumption is not as clear-cut as might be expected, despite a number of efforts to validate it. This paper proposes a new unified nonlinear relationship that incorporates both effects (optimal and threshold) into the proposed model. In examining a panel data of high-technology industry, the relationship between R&D and performance could be graphically depicted as an inverse S-shaped nonlinearity. Our empirical findings also confirmed not only an optimal effect that a specific level of R&D corresponded to maximum performance, but also a threshold indicating that a minimum level of R&D is required in order for R&D to be effective.

Keywords: R&D, performance, optimal, threshold

1. Introduction

The surge of R&D activity has been associated with an increased interest in the rationale of firm performance. In the literature, the relationship between R&D activity and performance is mostly considered to be linear, and for the most part, R&D activity does have a positive effect on a firm’s performance (Morikawa, 2004; Fosfuri and Tribó, 2008). For example, using the empirical studies of the US and Japan enterprises, Ito and Rose (1999) argue that R&D investment improves firm performance. Lev et al. (2005) use data on US firms to show that past R&D expenditures have a significant positive effect on earnings. Eberhart et al. (2004) use a sample of US firms and also find that R&D has above average rates of return. Other evidence from the United Kingdom also demonstrates that R&D contributes to market performance (e.g. Al-Horani et al., 2003). These studies show that a positive linear fit confirms the basic proposal of R&D studies, which argue that a greater R&D investment leads to improved performance. However, from the risk viewpoint, there exists great uncertainty in the R&D process when the high-tech firms cannot precisely forecast the market demand or make a breakthrough in technology (Taggart and Blaxter, 1992). Some empirical studies show that R&D activity has negative effect on firm performance (e.g. Chan et al., 1990). Mank and Nystrom (2001) argue that R&D spending has a decreasing return in the computer industry, contradicting those previous findings. Hoskisson and Hitt (1988) find that R&D intensity and operational performance are negative for firms diversifying in business growth. Similar findings are reported by Billings et al. (1994).

* Corresponding author. Email: chw@mail.ltu.edu.tw
Previous studies have examined the relationship between R&D activity and firm performance. They revealed inconclusive findings and left some ambiguities concerning the interpretation of their results. The performance implications of R&D investment are far from conclusion. In particular, the linear or non-linear nature of the relationship has not yet been explored by researchers. Thus, a more thorough understanding of the relationship between R&D and performance calls for continued research. This study reviews related theoretical and empirical findings to demonstrate the derivation of its research hypotheses.

This study assesses R&D and performance in general for the Taiwan market. It also provides the first complete empirical investigation for the pattern of R&D investment across the whole spectrum of firms listed on the database of the Taiwan Economic Journal. In addition, in the process of assessing operating performance as a result of investment in R&D, the study assesses of the relation between R&D and returns of equity (ROE). These topics have already been examined in the larger industrial countries (e.g. the United States and the United Kingdom). Thus, in the process of expanding prior evidence on R&D and valuation by examining the impact of R&D on operating performance, our study replicates prior evidence found in other industrial countries as important markets within the global high-tech industry. It also represents a comprehensive assessment of operating performance, as well as the sustainability of the Taiwan market. One of main purposes of this empirical study is to report the major findings in the Taiwan context that relate to R&D, and what valuation implications these findings may have.

The primary objective of this study, which has not been discussed in previous empirical studies, is to reconcile the contradictory findings by determining how R&D activity actually affects a firm’s performance. There are several theories relevant to our work (Edwards and Gordon, 1984). In this study, the innovation process has three stages beginning with an idea, then proceeding with the development of an invention, and finally resulting in the introduction of a new product, process or service to the marketplace. Our theoretical background is developed from these three stages. The initial stage is rooted in exploring a firm’s performance in initial innovation activity. It is argued that to a certain extent the optimal level of performance will be a function of a firm’s innovative idea and invention capabilities. The second stage investigates whether the firm’s performance may decrease with continuous R&D expenditure invested in the introduction of new products. The final stage examines the threshold effect of R&D activity. A small amount of R&D investment has virtually no effect on performance, but as R&D investment increases, it pushes the response through a threshold, after which it enhances performance.

Based on these arguments, three hypotheses on the relationship between the R&D activity and firm performance are developed. The hypotheses are tested using a panel dataset comprised of 40 integrated circuit (IC) manufacturers from 2001 to 2008. Having controlled for firm size, firm age, and leverage, we isolate the effect of R&D on firm performance. The remainder of this paper is organized as follows. In Section 2, we review related theories and develop the research hypotheses. Section 3 describes the dataset and the methodology employed. Statistical results are presented in Section 4 and their implications are discussed in Section 5. Conclusions drawn from the analysis are included in Section 6.

2. Theoretical background and hypotheses development

2.1 Initial stage: Optimal effect of R&D on performance

This argument is anchored in the resource-based view (RBV) (Williamson, 1975). The RBV theory suggests that firms with rare, valuable, non-substitutable, and difficult-to-imitate resources and capabilities will achieve a sustained competitive advantage over other firms (Barney, 1991). Collins and Montgomery (1997) argue that organizations, in order to adapt
and survive in a fiercely competitive environment, need to allocate their limited intangible assets efficiently (e.g. technology and innovation). Numerous studies also confirmed that the (dis)advantages of firms are often linked to the (dis)advantage of the firm’s idiosyncratic assets (e.g. Dhanaraj and Parkhe, 2006). Accordingly, the RBV paradigm tends to view investment in valuable resources, especially innovation and R&D, as a competing for a firm’s critical resources.

Due to the large amount of R&D expenditures, high-tech firms adopting an innovative strategy face more risks and rising costs in the initial stage. Developing new ideas or processes from a scientific breakthrough and transferring these ideas to a new product is a long and costly process with no guarantee of commercial success (Greve, 2007). These uncertainties are associated with spending millions of dollars on R&D activity. However, when the growth of firm-specific resources and the accumulated internal capability of innovation exceed the growth rate of R&D expenditure, the benefits might well outweigh the cost (Kotabe et al., 2002).

We expect that the optimal level of performance will be a function of a firm’s heterogeneous resources (i.e. R&D activity) and invention capabilities. Sher and Yang (2005) argue that innovative ability can be employed as a means for improving performance and of avoiding the inertia in the developing stage of the high-tech industry. That is, in the initial stage, the performance of a high-tech firm might outweigh the R&D costs. On the other hand, once the performance exceeds an optimal equilibrium, the costs incurred by the R&D activity might outweigh the benefits. For instance, successful innovative ideas have not often created a tremendous effect initially, but there eventually become “firm-specific assets” (Christensen, 1997). Along these lines, increased R&D activity is likely to result in better performance up to an optimal equilibrium, beyond which the R&D expenditure might outweigh its benefits. Bounded rationality supports the rationale of this behaviour that firms have limits on their rationality. Bounded rationality simply means that certain physical limits exist on the human ability to process information. Decision makers are intentionally rational, but within limits. Firms face a disadvantageous situation for R&D investment at this stage and should intend to act rationally (e.g. terminating the R&D investment). However, this intention may be circumscribed by constraints on their ability to process information. Thus, firms continue to invest in R&D activities. We posit the following:

**H1: In the initial stage, R&D activity is positively associated with firm performance, which increases up to an optimal equilibrium.**

2.2 Middle stage: Negative effect of R&D on performance

Although previous research has accepted the positive relationship between innovative activity and firm performance (Zhao and Li, 1997), firms with higher R&D expenditure are expected to reap more than those that do not. However, recent empirical evidence does not fully demonstrate a positive relationship. This line of argument is anchored in transaction cost theory (Williamson, 1975; 1994). Under these conditions and rather reasonable assumptions of bounded rationality, high-tech firms will invest in in-house R&D rather than out-sourcing R&D because technological innovation and market expansion are subject to the opportunistic behaviour of the parties involved. In general, R&D involves a high degree of uncertainty with respect to the nature (McCutchen et al., 2004) and the timing of the research outputs (Arrow, 1962). Taggart and Blaxter (1992) examine the uncertainty of R&D that is determined by two sets of actors in technology and the market. Technological uncertainty means that the R&D activity does not absolutely result in greater output; while market uncertainty means that demand is fluctuating and competition means that R&D investment cannot be recouped. Therefore, R&D activity often requires transaction-
specific investments in assets that are not easily redeployed (e.g. physical- or human capital-specificity).

In combination with the high demand uncertainty and a large investment cost, R&D activity may not lead to expected performance. Furthermore, if innovation activities in high-tech industry do not lead to successful products and market success, they can but fail or, in the worst case, put firms at the risk of bankruptcy. R&D activities accompanied by risks are expected to affect the performance negatively, as the firm faces a higher probability of failure. However, innovation is a key driving force for high-tech industry and therefore an innovative firm may achieve higher profit. There might well be an internal optimum, meaning that some R&D is useful, while too much R&D may not maximize performance. This innovation process is filled with risk and high uncertainty; any risk should be of negative value except for the market success of R&D.

H2: In the middle stage, R&D activity is negatively associated with firm performance.

2.3 Final stage: Threshold effect of R&D on performance

The dilemma of how R&D affects performance must be considered differently once the possibility of innovation activity through the threshold effect is accounted for. Omta et al. (1994) investigated the innovation effectiveness of pharmaceutical industry in Europe and America and showed that a minimum level (about 100 million dollars) of investment is required to maintain innovative capability. The threshold perspective in the final stage is taking a particular interpretation of the organization learning theory (Cook and Yanow, 1993). In fact, there is evidence supporting the view that for an entrepreneur who intends to enhance the marketing of a new technology or product, organizational learning is the critical driving force (Argyris and Schon, 1978). Organizational learning refers to a process by which a firm acquires information, knowledge, understanding, know-how that lead to changes in its routines (Mavondo et al., 2005). R&D activity is one of major sources of organizational learning (Mowery, 1981). However, the innovation process nearly reaches the decay stage, which implies innovation activity may have difficulty making a technological breakthrough. A larger the R&D expenditure accumulated over a long time period has a lower probability of creating radical innovation in the final stage of the innovation process (Henderson and Clark, 1990).

The above discussion suggests that the performance of a high-tech firm may be weakened with increased R&D investment up to a certain level, beyond which the firm will be better off. This is the threshold effect. We posit the importance of the threshold effect of R&D investment on performance in the final stage in H3.

H3: In the final stage, if R&D activity exceeds a certain threshold level, then there will be a positive relationship between R&D activity and firm performance.

3. Methods

3.1 Data and sample

High-tech industries are identified according to the classification suggested by Hall (1994) and Chandler (1994) according to the research intensity of the industries and an informal assessment of those industries that are likely to grow faster. Therefore, this study examines the integrated circuit (IC) design industries in Taiwan which are a high-tech industry. The top firms, ranked by company assets, were extracted from 2001 to 2008. The original observations of 56 firms were matched with firm-level data from the Taiwan Economic Journal (TEJ), which contains data about firms’ annual financial reports. However, many firms did not report the type of information we sought for in this study, and those with firm-
level information missing from the database were eliminated from the sample. A total of 16 firms were omitted, leaving 40 IC firms in our final sample.

3.2 The nonlinear model

As discussed in the introduction, this study investigates the relationship between R&D activities and our measure of outcome of these activities, the firm performance. Clearly, some prior studies have examined this relationship according to the assumption of linearity, leading to inconsistent findings. Through there is no standard approach to measure a nonlinear relationship, we incorporate the square- and cubic- R&D intensity into the proposed nonlinear regression model based on prior studies (Foster, 1986; Mckee, 1992). The models used in this study can be written in the following forms.

\[
ROE_{it} = \beta_0 + \beta_1(LR)_{it} + \beta_2(FS)_{it} + \beta_3(FA)_{it} + \beta_4(RDI)_{it} + \epsilon_{it}, \quad (1)
\]

\[
ROE_{it} = \hat{\beta}_0 + \hat{\beta}_1(LR)_{it} + \hat{\beta}_2(FS)_{it} + \hat{\beta}_3(FA)_{it} + \hat{\beta}_4(RDI)_{it} + \hat{\beta}_5(RDI)^2_{it} + \epsilon_{it}, \quad (2)
\]

\[
ROE_{it} = \tilde{\beta}_0 + \tilde{\beta}_1(LR)_{it} + \tilde{\beta}_2(FS)_{it} + \tilde{\beta}_3(FA)_{it} + \tilde{\beta}_4(RDI)_{it} + \tilde{\beta}_5(RDI)^2_{it} + \tilde{\beta}_6(RDI)^3_{it} + \epsilon_{it}. \quad (3)
\]

The subscript \(i=1, 2, \ldots, 40\), stands for individual companies, while \(t=1, 2, \ldots, 8\) stands for the years 2001-2008. \(LR\) is leverage, \(FS\) is firm size, \(FA\) is firm age, and \(RDI\) is R&D intensity.

More specifically, \(RDI\), \(RDI^2\), and \(RDI^3\) are highly correlated. When an explanatory variable exhibits little variation, it is difficult to isolate its impact. In response to this problem, Aiken and West (1991) recommend mean centering of \(RDI\), \(RDI^2\), and \(RDI^3\) as an approach to alleviating concerns relating to collinearity. Mean centering (2) and (3) are given as follows.

\[
ROE_{it} = \tilde{\beta}_0 + \tilde{\beta}_1(LR)_{it} + \tilde{\beta}_2(FS)_{it} + \tilde{\beta}_3(FA)_{it} + \tilde{\beta}_4(RDI)_{it} + \tilde{\beta}_5(RDI - \overline{RDI})_{it}^2 + \hat{\epsilon}_{it}, \quad (4)
\]

\[
ROE_{it} = \hat{\beta}_0 + \hat{\beta}_1(LR)_{it} + \hat{\beta}_2(FS)_{it} + \hat{\beta}_3(FA)_{it} + \hat{\beta}_4(RDI - \overline{RDI})_{it} + \hat{\beta}_5(RDI - \overline{RDI})^2 + \hat{\beta}_6(RDI - \overline{RDI})^3 + \hat{\epsilon}_{it}. \quad (5)
\]

3.3 Model specification

R&D intensity

The RBV theory suggests that innovation capability generates higher competency than that of other resources in high-tech industry. The innovative profile of a firm is examined according to its R&D inputs proxied by R&D intensity, R&D outputs proxied by the number of successful patent applications (Blonigen and Taylor, 2000), and the stock of accumulated knowledge generated by past R&D efforts. However, because the distribution of the value of a patented innovation is extremely skewed in studies on market value (Chauvin and Hirschey, 1993), scholars usually measure the knowledge stock calculated by R&D through the perpetual inventory method from a time series of annual expenditures. But in this study, we do not have the necessary information to do so. Thus, we only consider current R&D intensity (Wang et al., 2008).

Investments in R&D have generally been shown to be very dependent upon industry and competitive issues. R&D intensive firms represent a rapid growth sector of the economy, and the high-tech industry as a whole is viewed as the primary means of regaining competitive advantage. R&D intensity is defined as the ratio of R&D expenditures of a firm to its total sales.

For the purposes of this study, we use the R&D expense taken from the income statement. Although Taiwan allows the conditional capitalization of R&D costs because of their ability to generate future cash flows, the dominant practice in Taiwan is for R&D to be immediately expensed. Thus, R&D expenditures in Taiwan are usually expensed because their link to future benefits is uncertain. Previous studies on R&D have also relied solely on the R&D expenses that appear on the income statement (e.g. Green et al., 1996; Al-Horani et al., 2003;
Anagnostopoulou and Levis, 2008), and therefore the methodology that we use also permits comparability of our study with previous works.

We do not make use of R&D capital calculation since this would require the use of lagged R&D values, and our sample period starts in 2001 and only covers eight years. Therefore we have applied the methodology first used by Al-Horani et al. (2003). By estimating the Pearson coefficients that we obtain, it is assumed that yearly R&D expense is a good proxy for R&D activity and, therefore, we do not use calculated R&D capital.

Although the accounting treatment of R&D is broadly similar in Taiwan and United States, R&D spending appears more pervasive in the United States. For example, only about 30% of Taiwan firms report R&D expenses in comparison to about 40% in the United States (Chambers et al., 2002). Furthermore, R&D expending in Taiwan is concentrated mainly in larger enterprises compared to United States firms. However, corporate R&D activity in Taiwan significantly increased in importance during the time period examined in this study, starting with a total value of firm R&D expense for our sample firms of Taiwan Dollar (TWD) 49,831.148 million in 2001, to more than double that amount TWD 105,959.258 million in 2008. The observation of this time period could reflect the interactions of R&D activity and operating performance. Although the period of 2001-2008 may be not perceived to be enough long to measure operating performance, it still may account for the R&D activity.

**Performance**

Simons (1990) observes that performance measurement should track the implementation of business strategy by comparing actual results against strategic goals. Neely (1998) suggests that performance measurement is “the process of quantifying past action”. Performance must be measured in order to analyze strategies, since performance is the result of an activity (Porter and Millar, 1985). The firm’s performance is proxied by three variables. First, added value is proxied by firm growth (i.e. annual growth of total assets). Second, economic value is proxied by profitability (i.e. the ratio of earnings before interest taxation to total assets). Third, accounting-based earnings are proxied by return of assets (ROA), return of equity (ROE), and return of sales (ROS). Previous studies have adopted the accounting nature of performance, such as ROA (Hitt et al., 1997), ROS (Geringer et al., 2000), and ROE (Grant, 1987). ROA and ROE are two of the most common accounting-based performance measures in prior research. Although some researchers (Jacobson and Aaker, 1987) have criticized the accounting-based measures of performance, most scholars have asserted these financial indexes are acceptable. Since ROE is defined as net income divided by average common stockholders' equity is the ratio often employed to measure innovative effectiveness (Han et al., 1998), and it usually shows a high degree of multicollinearity with ROA ($r = 0.76$), ROE was selected over alternative criteria, such as added value and market value because it is seen to be more sensitive to capital structure, which reflects the firm’s R&D investment. We present only empirical findings obtained by the ROE measure based on a panel dataset comprising data on R&D intensity and ROE data collected from the Taiwan Economic Journal Database for 40 high-tech firms over the period 2001-2008.

**Control variables**

Although our primary interest is the performance of these firms, it is investigated in the light of their innovation activity. This is because R&D inputs are likely to influence their performance. However, the performance may be affected by other factors besides innovativeness. Furthermore, we have chosen this specific size measure, because it has the best coverage among all the alternatives considered (sales, number of employees, and net assets). Recent studies employing a similar size proxy include Chiao et al. (2006) and Thornhill (2006). Firm size is particularly important in our context because larger firms are thought to have above-average resources and capability for innovation. Firm size is measured
as a logarithmic function of the number of employees. The variable is maintained constant so that we can better assess the effect of R&D input upon performance revealed in the innovation process. Leverage, which is employed as a proxy of a firm’s capital structure, reflects the financial risk faced by a firm which might limit managers’ ability to allocate resources to R&D activity (Smith and Warner, 1979). The study also controlled for a firm’s age because younger high-tech firms might have pursued more innovations than older firms (Rosen, 1991; Zahra, 1999). Age was measured by the number of years the firms had been in existence.

4. Results

In Table 1, we report the descriptive statistics and correlation matrix of the variables during the period 2001-2008 on panel data.

Table 1. Descriptive statistics and correlation matrix for the theoretical constructs.

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>S.D.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.ROE</td>
<td>-0.996</td>
<td>0.940</td>
<td>0.077</td>
<td>0.258</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.LR</td>
<td>0.069</td>
<td>2.700</td>
<td>0.309</td>
<td>0.218</td>
<td>-0.326**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.FS</td>
<td>1.477</td>
<td>4.305</td>
<td>2.809</td>
<td>0.721</td>
<td>0.017</td>
<td>0.192**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.FA</td>
<td>3</td>
<td>39</td>
<td>15.050</td>
<td>7.737</td>
<td>-0.076</td>
<td>0.140*</td>
<td>0.320**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.RDI</td>
<td>0.000</td>
<td>0.901</td>
<td>0.472</td>
<td>0.255</td>
<td>0.173**</td>
<td>-0.318**</td>
<td>-0.112</td>
<td>-0.478**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.(RDI)²</td>
<td>0.000</td>
<td>0.811</td>
<td>0.286</td>
<td>0.222</td>
<td>0.153*</td>
<td>-0.278**</td>
<td>-0.093</td>
<td>-0.439**</td>
<td>0.971**</td>
<td></td>
</tr>
<tr>
<td>7.(RDI)³</td>
<td>0.000</td>
<td>0.731</td>
<td>0.184</td>
<td>0.178</td>
<td>0.145*</td>
<td>-0.245**</td>
<td>-0.082</td>
<td>-0.408**</td>
<td>0.922**</td>
<td>0.986**</td>
</tr>
</tbody>
</table>

Notes: ** Correlation is significant at the 0.01 level (2-tailed), * Correlation is significant at the 0.05 level (2-tailed).

Given the cross-sectional and time-series nature of our dataset, panel data estimation methods have the advantage that they allow us to account for some unobserved heterogeneity across firms (Hsiao, 1986). With respect to the choice between fixed and random effects, we conclude that the fixed effect is the most appropriate model for this study after using F-test, Lagrange multiplier (LM) test, and Hausman test, respectively. The choice criteria of the most optimal model are processed as follows. First, we judge which is better between fixed effect and Least Square (LS) using F-test; then we judge which is better between random effect and LS using Lagrange multiplier. Finally, if both fixed and random effects are better than LS, then we decide the choice which is better between fixed effects and random effect using the Hausman test. Table 2 compares the results of these two models obtained by the above three tests.

Table 2. The inspected results of fixed and random effect.

<table>
<thead>
<tr>
<th>Effects Test</th>
<th>Quadratic model</th>
<th>Cubic model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section F Statistic</td>
<td>9.4157***</td>
<td>9.4091***</td>
</tr>
<tr>
<td>LM Test</td>
<td>5290.35***</td>
<td>5238.05***</td>
</tr>
<tr>
<td>Hausman Test (Chi-Sq. Statistic)</td>
<td>15.1269***</td>
<td>21.8512***</td>
</tr>
</tbody>
</table>

Notes: ** p-value < 0.05, *** p-value < 0.01.

The estimation results are presented in Table 3. Surprisingly, the unexpected finding is that the firm sizes have negative significant effect on performance in first-order model and second-order model, respectively. What is less clear-cut is whether performance increases more or less proportionately with firm size. The possible explanation might be large firms’
scale of economic disadvantage, but there might also be the specific phenomena of Taiwan high-tech firm. Nevertheless, the size effect is not our primary concern; we only introduce a nonlinear term.

As in the first-order model, we find that R&D has a positive impact ($\beta_4 = 0.5348$; $t$-statistic = 2.113) on performance in the initial stage. This result is in accordance with the finding of previous studies (Ettlie, 1998). It is also in line with the findings of studies on innovation-intensive industries. Bean (1995) found a significantly positive relationship between R&D intensity and growth in market share for 15 drug companies. The increase in market value is attributed to the improved performance because firms spend more on R&D. In addition, R&D investment in the initial innovation process is directly related to performance. Aw (2002) also demonstrated the positive impact of R&D on the performance of export activities. Moreover, Hall and Oriani (2006) found that R&D expenditures were positively related to a firm’s current operational performance, but the strength of the association varied across countries and samples.

Table 3. Empirical results of nonlinearity regression.

<table>
<thead>
<tr>
<th></th>
<th>First-order model</th>
<th>Quadratic model</th>
<th>Cubic model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>t-statistic</td>
<td>Coefficient</td>
</tr>
<tr>
<td>Constant</td>
<td>-0.3068**</td>
<td>-2.0233</td>
<td>-0.4528***</td>
</tr>
<tr>
<td>LR</td>
<td>-0.2104**</td>
<td>-2.2357</td>
<td>-0.1504</td>
</tr>
<tr>
<td>FS</td>
<td>-0.1264*</td>
<td>-1.9108</td>
<td>-0.1890***</td>
</tr>
<tr>
<td>FA</td>
<td>0.0062</td>
<td>1.4278</td>
<td>0.0031</td>
</tr>
<tr>
<td>RDI (H1)</td>
<td>0.5348**</td>
<td>2.1130</td>
<td>0.7255***</td>
</tr>
<tr>
<td>(RDI)$^2$ (H2)</td>
<td>0.8985***</td>
<td>-3.5800</td>
<td>2.9839***</td>
</tr>
<tr>
<td>(RDI)$^3$ (H3)</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Notes: * p-value < 0.1, ** p-value < 0.05, *** p-value < 0.01.

The quadratic model seen in Figure 1 shows a decreasing effect in performance with increasing R&D intensity. As can be seen, R&D has a concave impact on firm performance in the middle stage of the innovative process. This relationship is bell-shaped and the curve peak at 0.4 of R&D intensity shows that first-order R&D intensity is positively ($\beta_4 = 0.7255$; $t$-statistic = 3.1477) associated with firm performance at the initial stage. Thus, Hypothesis 1 is supported by the results of both first-order model and quadratic model. After R&D intensity reaches an optimal level, the quadratic R&D intensity has a significantly negative ($\beta_5 = -0.8985$; $t$-statistic = -3.58) impact on performance, thus supporting $H2$.

Figure 1. The graph of quadratic regression.
A further examination of the estimated cubic regression coefficient reveals that the quadratic R&D intensity negatively \( (\beta_5 = -4.9643; \ t\text{-statistic} = -2.8521) \) impacts performance, while the cubic R&D intensity shows a positive effect \( (\beta_6 = 2.9839; \ t\text{-statistic} = 2.4262) \). The above results illustrate the threshold effect \( (0.81) \) for R&D activities, thus supporting Hypothesis 3. More specifically, in order to obtain the benefits of R&D activities in the final innovation stage, high-tech firms should invest heavily on R&D, at least exceeding the threshold level. Figure 2 shows that the sigmoid curve conforms to all the three stages. Any R&D expenditure under the threshold level is wasteful for firms; in other words, if a firm attempts to achieve the desired effectiveness, it must invest a minimum amount of R&D. This threshold effect is also observed in previous studies (e.g. Kotabe et al., 2002).

![Figure 2. The graph of cubic regression.](image)

In conclusion, adjusted \( R \)-square reveals that the proposed models are improved when the quadratic variable \( (\text{adj}-R^2 = 0.6039) \) is added to the linear model \( (\text{adj}-R^2 = 0.3884) \) and when the cubic variable \( (\text{adj}-R^2 = 0.6122) \) is added to the second-order model \( (\text{adj}-R^2 = 0.6039) \). Moreover, using an \( F \)-test, we can accept that all three models are significant. This result suggests the existence of the nonlinearity relationship between R&D intensity and performance.

**5. Discussion and implications**

R&D investment plays a pivotal role in firm performance, representing future growth opportunities. The first-order, quadratic, and cubic R&D intensity in respective model require detailed comments. The first-order R&D intensity has a positive coefficient in the first-order model, a positive slope similar to that found in the quadratic model. To interpret this situation, perhaps the strongest argument supporting the positive R&D-performance connection in the initial stage is the first-mover advantage theory (Foster, 1986). Firms that are the first to market product improvements have to distinguish these new products from existing ones, usually requiring innovation features and technology breakthrough. The high-quality product of large R&D investment in the initial stage is reflected in the increasing performance, which, after reaching an optimal point, shows diminishing and negative returns in the middle stage.

Another possible explanation for this finding is that most high-tech firms of Taiwan are predominately composed of original-equipment manufacturing (OEM) firms. The innovation process in OEM firms focus mostly on manufacturing process innovation rather than new product innovation. It should be noted as well that not all OEM firms attempt to take ideas from the process research stage to market new products in the middle stage of the innovation
process. It results in the new products losing competitiveness in the market and showing poor performance in the middle stage.

In addition, the finding of the optimal point offers two important managerial implications. First, the theory of the technological life cycle (TLC) (Ford and Ryan, 1988) provides the underlying rationale. Even the innovation process is in the initial stage, the technology easily reaches technological maturity leading to production standardization and comparison disadvantage of new products. Owing to the short TLC of high-tech industry, managers of high-tech firms need to extend the strategy from manufacturing process innovation to new product innovation in the middle stage to improve the slow down profit. In general, the results do not diverge from the findings of previous studies (Betz, 1993).

Second, the plateau effect of the learning curve also provides the rationale for the optimal effect (Carlson, 1973). Organizational progress makes the learning curve become smooth; namely, the plateau effect. The occurrence of the plateau effect means that there may sometimes by no technological breakthrough even after investing a large amount of resources. Therefore, the judicious use of limited resources is crucial to the success of the middle stage of the innovation process.

In the second stage, the empirical results obtained from Taiwan’s high-tech industry show that R&D investment has a threshold effect on performance. According to prior argument, the concept of lag time of organizational learning on innovation activity can provide a reasonable explanation. The research plan is executed from the initial stage to marketing of the new product. It needs a long time, which is known as lag time innovation. Cooper and Schendel (1976) posited that technological innovation cannot be immediately reflected in performance because R&D activities can be divided into many stages including basic research, applied research and development. Furthermore, for Taiwan’s high-tech industry classified under OEM, process innovation may be relatively more important than other types of innovation (e.g., product innovation). Process innovation requires many more assets invested in the manufacturing process than product innovation. Such investment may become sunk cost before market success is realized.

As noted above, one of the possible interpretations is that lag time between the R&D activity and its impact on performance. This finding is consistent with previous results. Lev and Sougiannis (1996) used data on US firms and showed that past R&D expenditures have a positive effect on performance. More importantly, their data suggested that R&D investment of up to nine years can still have an impact. Other scholars have provided similar arguments, noting that the complexity of R&D activity is unable to immediately reflect on current performance (Boer, 1999), and then the threshold effect of innovation process might occur (Bosworth and Rogers, 2001). The possible existence of the above lag time of innovation learning and threshold effect suggests that the R&D activity does not drive the performance, except beyond the minimum threshold level. The central issue highlighted in this paper is that it is unlikely that R&D activity improve the performance in the final stage because of the threshold effect.

6. Conclusions

Identifying a theoretical gap concerning the nonlinearity relationship between R&D and performance, this study makes a contribution to the literature by investigating the respective optimal and threshold effects. The study adds insight in the following aspects. (a) It tests the relationship between R&D and performance in the initial innovation process. (b) Extensions are made to the cubic regression model to enhance the explanatory power, thus providing suggestions for measuring performance at different stages. (c) It discusses the optimal and threshold effects of R&D activity based on the agency theory and technological life cycle.
theory. (d) It graphically depicts the inverse “S-shaped” relationship between R&D and performance in the entire innovation process.

The first topic under consideration is whether the relationship between R&D and performance is positive or negative. The literature contains conflicting arguments. The contribution of this study is providing an optimal equilibrium according to the RBV theory. To this end, developing this relationship process to be really valuable in the initial innovation process and ensuring its performance. The second topic concerns the nonlinearity relationship between R&D and performance. Whether R&D activities have nonlinearity impact on performance is one of the key issues and has to be answered. Our theoretical analysis shows that firm performance in the context of innovation process varies with quadratic and cubic R&D intensities. The development of nonlinear regression solves the problem. A more important contribution of this study is the finding concerning how R&D is developed to the optimal level in the initial stage and, also how R&D must be increased beyond the minimum threshold level in the final stage to enhance firm performance. This study has explored the issue of performance as the result of both optimal and threshold effects. The result of the analysis is that the inverse “S-shaped” relationship can comprehensively depict the nonlinearity relationship between R&D and performance.

Our study has limitations that, nonetheless, may be tackled in future research. One first limitation is the industry-specific sample (IC design firms) which may pose constraints on our ability to generalize findings. Thus, future research needs to be conducted an examining the findings of this study in other innovation intensities industry. The second limitation is that the regression analysis on performance has been conducted separately in the three stages of the innovation process. A weakness of such analysis is that no long-term time-series data are available to examine the dynamic changes over time. In order to gain further insights into this issue, incorporating the long-term time-series sample sets should adequately capture the dynamic nature of the innovation process.

The final limitation comes from the nature of firm-level data. As can be seen in our dataset, the firms were matched with firm level data from the database. These firms are ranked by company assets other than R&D investment. This may cause the firms with the poorest return on R&D to be cut off from the sample, hence this study have the possibility of selection bias in analysis. We encourage future researchers to improve their efforts by collecting more reliable and valid measures of R&D and examining the performance implication.
References


