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WHY SOME FIRMS NEVER INVEST IN FORMAL R&D

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In this paper we study the frequency of formal R&D investments. We link real options theory to the knowledge-based view to explain how a firm's knowledge resources influence its frequency of investing in R&D to establish technological options. Specifically, we propose that a firm that lacks internal knowledge resources is more likely to never invest in R&D, a firm that has both internal and external knowledge resources is more likely to sometimes invest in R&D, while a firm that has internal knowledge resources but lacks external knowledge resources is more likely to always invest in R&D. Copyright © 2010 John Wiley & Sons, Ltd.

INTRODUCTION

Never investing in formal research and development (R&D) poses a challenge to theory, which has argued that a firm must invest in formal R&D continuously to develop its technological capabilities and ensure its future advantage. The technological capabilities of a firm are critical to its competitive advantage (Teece, 1986; Schumpeter, 1942). However, technological advances, competitors' efforts, and changes in customers' needs eventually render advantages obsolete (Helfat, 1997; Nagarajan and Mitchell, 1998; Teece, Pisano, and Shuen, 1997). As a result, the firm must invest in formal R&D to develop and renew its technological capabilities (Helfat, 1997). A firm that does not invest in formal R&D not only limits its ability to develop new technologies internally (Helfat, 1997, 2000) but also limits its ability to absorb external technologies (Cohen and Levinthal, 1989). However, empirical studies have found that some firms do not invest in R&D. For example, Cohen, Levin, and Mowery's (1987) study of large U.S. firms reported that 24 percent of the firms did not invest in formal R&D. Similarly, Bound *et al.*'s (1984) study indicated that 40 percent of U.S. firms did not report positive R&D expenditures, and Galende and Suarez's (1999) analysis of Spanish firms revealed that 71 percent of companies did not undertake formal R&D. Empirical studies analyze the amounts invested in R&D and tackle the anomaly of firms not investing in R&D by either restricting their samples to R&D-active firms (e.g., Galende and de la Fuente, 2003; Molero and Buesa, 1996) or by using a Tobit model that takes into account the existence of firms that do not invest in R&D when analyzing the amount invested in R&D (e.g., Helfat, 1997; Cohen *et al.*, 1987). However, even in such cases there is still no explanation for why a firm will never invest in R&D, a behavior that goes counter to theory.

Therefore, in this paper we explain why some firms never invest in formal R&D by analyzing the frequency of investments in formal R&D.

Keywords: R&D investments; real options theory; knowledge-based view; technological capabilities
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We build on real options theory and extend it with arguments from the knowledge-based view to provide an explanation of the frequency of R&D investments, becoming among the first to do so. Real options theory draws insights from financial options and applies them to the decision to invest in real assets (Myers, 1977; for reviews of the theory see Pindyck, 1991, and Tong and Reuer, 2007b, and the papers in Reuer and Tong, 2007b). It studies irreversible investments under uncertainty and analyzes the decision to invest, the amount and timing, and the value associated with such a decision in the face of uncertainty. In this theory, investments in formal R&D are viewed as part of a sequential option in which the firm first invests in R&D to create growth options that later can be exercised with additional investments, such as prototype development, production, and marketing (Pindyck, 1991; McGrath, 1997). This literature has mostly analyzed the valuation of the amount invested in R&D that ensures the availability of future technological options. We extend the theory by arguing that, unlike other real options, the frequency of R&D investments is important because the knowledge generated through R&D investments has ill-defined property rights and is subject to disappearance. As a result, a firm needs to maintain frequency in investments. However, we argue that this frequency depends on the existence of internal and external knowledge resources. Specifically, we propose that a firm is more likely to never invest in R&D when it lacks internal knowledge resources; a firm is more likely to sometimes invest in R&D when it has both internal and external knowledge resources; a firm is more likely to always invest in R&D when it has internal knowledge resources but lacks external knowledge resources.

These arguments extend theory by explaining how knowledge affects the options available to the firm. This complements previous studies of real options theory's boundaries (e.g., Adner and Levinthal, 2004; McGrath, 1997; Miller and Shapira, 2004) by identifying how the establishment of options on knowledge assets differs from the establishment of options on real assets. In the particular case of R&D investments, internal and external knowledge resources determine the frequency of investments and, thus, the possibility of establishing a technological option. Hence, the paper provides depth to the idea that capabilities determine a firm's options (Kogut and Kulatilaka, 2001). The arguments presented here have implications beyond R&D investments, as they can explain the challenge of establishing options on other knowledge assets in which sequential investments are needed.

The paper also contributes to studies of technology strategy (see a review in Fagerberg, Mowery, and Nelson, 2005) by being the first to analyze the frequency of investments in formal R&D the literature has concentrated on analyzing the amounts invested in R&D. We explain why some firms choose to never or sometimes invest in R&D rather than always invest as the literature assumes. The study highlights how the frequency of investment in R&D has different explanations and is affected by different factors than the amount invested in R&D. Additionally, the paper provides a new classification of firms into three types by the frequency of their investment behavior—invest in R&D, sometimes invest, and always invest—and shows that the determinants of each strategy differ. This classification extends previous studies that have only classified firms as either R&D-active or R&D-inactive.

REAL OPTIONS AND THE DECISION TO NEVER INVEST IN FORMAL R&D

Real options theory

Real options theory has recently emerged as a key explanation of investments under uncertainty and has been applied in a variety of fields, not only in strategic management (e.g., Bowman and Moskowitz, 2001; Kogut and Kulatilaka, 2001; Kumar, 2005; Folta, 1998; Folta and Miller, 2002) but also in technology (e.g., McGrath and Nerkar, 2004), international management (Chi, 2000; Tong and Reuer, 2007a), entrepreneurship (McGrath, 1999), human resources (e.g., Wang and Lim, 2008), and even as an explanation of the firm (e.g., Scherpereel, 2008).

The theory traces its origins to work on financial options, in which a firm that creates an option has the right, but not the obligation, to acquire or sell a financial asset at an agreed-upon price before or at a certain date. This idea was then applied to the analysis of investments in real assets, as an alternative to net present value analysis, to evaluate the appropriateness of the investment in the face of uncertainty (Myers, 1977; Dixit and Pindyck,

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1994). The logic behind the application is that, as in financial options, investments in real assets give the firm a right but not the obligation to a stream of future cash flows. The firm can wait until additional information emerges, giving it flexibility in the investment decision. Thus, a firm will undertake a small initial investment that provides it the vantage point from which to either increase the investment once the profit potential is revealed, continue waiting until the uncertainty is lifted, or sell the investment and limit its potential losses if the revealed profit potential is not appropriate.

The application of real options in strategic management has taken three main avenues (Tong and Reuer, 2007b): the analysis of investment decisions, the implementation of real options, and the performance implications of real options. Progress has been made in each of these areas (see Tong and Reuer, 2007b, and Li *et al.*, 2007 for recent reviews).

Boundaries of real options theory

Some theoretical developments have focused on establishing the boundaries of the theory. McGrath (1997) analyzes how different types of uncertainty affect the options a firm can take. Adner and Levinthal (2004) and Miller and Shapira (2004) discuss how managerial limitations influence the options of the firm.

We contribute to this line of thinking that discusses theoretical boundaries by analyzing how the characteristics of the investments affect real options. Real options theory builds on three assumptions from financial options as to the characteristics of the investments that cannot always be made when analyzing investments in real assets: incrementality, immediacy, and availability. The literature discusses some solutions to the first two assumptions; this paper addresses the third assumption. Another assumption regarding investments, their irreversibility (i.e., investments are sunk), is a requirement for the application of options to real investments (Pindyck, 1991); if the investments are fully reversible, the firm will always invest because it will not suffer losses when uncertainty is lifted. Hence, this will not be discussed.

First, real options theory assumes that investments are incremental, that is, a firm can undertake a small investment to establish a foothold in an area and, once uncertainty regarding the future profitability of the investment is lifted, increase the investment to the needed scale to reap the benefits. This assumption comes from financial options, where an option can be established over another financial instrument and can always be incrementally scaled up or down by repeating the option or taking a fraction of the option. For example, an option on a share can always be multiplied to the desired number of shares or can be scaled down to a fraction of a share. Some theoretical analyses in real options assume that investments are incremental in nature (e.g., Pindyck, 1991). However, many real investments are not incremental in nature. Instead they are discrete investments with a minimum scale. For example, a new power plant has to be built at a certain scale not only for it to be economical but also for it to operate. Building half of a plant does not result in half of its productive capacity but in an unproductive building. Thus, a firm may not be able to limit the size of the initial investment in real assets or its associated exposure to a potential loss and may have to forfeit establishing a real option.

A solution to the challenge posed by discrete investments is the use of alliances to reduce the amount invested in the project by the firm. Instead of underwriting the full investment, the firm can share the cost with partners and wait for the uncertainty regarding the value of the investment to be lifted. At that point in time, the firm can buy out the partners, increase its investment, and internalize the value of the project (e.g., Folta and Miller, 2002). This strategy limits the initial investment of the firm in the project, but still necessitates an investment with a minimum scale, requiring the firm to find partners to share the investment. Moreover, acquiring the alliance partners will be done at a higher price than the one paid at the beginning because the value of the investment has been revealed. Nevertheless, this strategy limits the downside of having to write down the full amount of the investment if there is no profit potential, while providing the firm with the upside of its initial investment.

Second, real options theory assumes that the investments are immediate, that is, they will be instantly materialized once the decision to invest has been made. In financial options, a firm can design an option and trade it in the market immediately. Such assumption of immediate investments has been made in some theoretical models (e.g., Pindyck, 1991). However, many real investments

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take time to materialize, with a delay from the date the decision to invest is taken to the date when the investment is operational. For example, a new manufacturing plant takes time, in some cases years, to build and start production. Before reaching production, however, the uncertainty regarding the value of the investment may have been lifted, resulting in the need for a different plant design or size, or even resulting in an investment that is not economical. Hence, the firm may not consider such investment and forgo the option associated with it.

A solution to the lack of immediacy in investments is to purchase an ongoing operation as opposed to building the operation. The firm can purchase a plant that is already in operation or acquire a company that controls the desired plant. Therefore, the firm will not have to wait for the plant to be built and reach operational level (e.g., Gilroy and Lukas, 2006). Such a strategy is not perfect because it takes time to evaluate and negotiate the acquisition of a plant or firm, and the seller may obtain most of the potential value associated with the option. Moreover, purchasing an operation may not be available in new technological fields or new markets because there are no firms currently operating there.

Third, real options theory assumes that options are available to the firm, that is, the firm can undertake the investment once it has decided to do so. In financial options, the firm can invest in the option it needs once it designs it, paying the fee to the counterparty. In some cases the firm can reduce the fee paid, such as in naked options where a firm does not borrow a share before it establishes an option on it. However, investments in real options may not always be available to the firm, because the firm may not have the resources that support such investments.

We explore this assumption in the context of R&D investments to highlight the importance of resources on the availability of options. We propose that internal and external knowledge resources affect the ability of the firm to undertake R&D investments. As a result, a firm may not be able to establish a technological option even if it desires to do so. Moreover, unlike other real options, R&D investments generate knowledge that has ill-defined property rights and that is subject to disappearance, further complicating the availability of the technological option.

Real options and formal R&D investments

In real options theory, formal R&D investments are the initial step in a sequence of investments in technology. Initial investments in R&D provide the firm with an option to undertake additional investments in testing and prototyping, which in turn provide the firm with additional options over a future revenue stream from either licensing the resulting innovation or selling the product that embodies the innovation (McGrath, 1997).

This view of formal R&D investments as the first step in a sequence of technological options has a long tradition in real options theory. However, the majority of studies have focused on the valuation of the options that formal R&D investments provide, and have not studied the determinants of the frequency of R&D investments as we do here. Pindyck (1991), in his review of the use of options thinking to analyze investments in real assets, discusses R&D investments as part of a sequence of technological options. McGrath (1997) focuses on the study of options in technology investments, discussing how uncertainty affects the value of technological options. Pennings and Lint (1997) assess the value of R&D projects under an options approach. Perlitz, Peske, and Schrank (1999) also focus on the valuation of R&D projects following an options approach, providing an overview of the challenges of applying options thinking to value R&D projects. Huchzermeier and Loch (2001) discuss the influence of flexibility on the valuation of R&D under a real options approach. Weeds (2002) presents a model analyzing delay in R&D. Worner and Grupp (2003) discuss the interrelation among options within a portfolio of R&D projects. Lewis, Enke, and Spurlock (2004) use computer simulations to analyze the impact of deferral on the value of R&D. Newton, Paxson, and Widdicks (2004) review the literature on R&D under a real options approach. Cassimon *et al.* (2004) study the use of real options to value R&D by pharmaceutical firms. McGrath and Nerkar (2004) apply real options to the decision to undertake new R&D investments in the pharmaceutical industry. Schwartz (2004) presents a model analyzing R&D and patents from a real options perspective. Hartmann and Hassan (2006) apply real options to the valuation of R&D projects in pharmaceutical firms. Wu and Yen (2007) also analyze the valuation of R&D using options. Chan, Nickerson, and Owan (2007) analyze the relationships

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among R&D pipelines and the cospecialization of R&D and commercialization assets. Danneels (2008) discusses how R&D investments, a second-order competence, enable the firm to develop first-order technological competences that support its competitive advantage. Oriani and Sobrero (2008) discuss how market and technological uncertainty affect the valuation of R&D.

Under the real options approach that views technology and R&D as part of a series of sequential investments, we go back in the causality chain and analyze the determinants of the frequency of R&D investments. R&D investments differ from other investments in real assets on one key characteristic: they are investments in knowledge. This affects the ability of the firm to invest in R&D and establish a technological option, and highlights the importance of analyzing the frequency of R&D investments.

Knowledge and R&D investment frequency

Although real options theory has viewed R&D investments in similar terms as other investments in real assets, they differ in a significant way: they are investments in knowledge assets that have ill-defined property rights and that disappear over time. These two characteristics of R&D investments have been overlooked in previous literature, which has focused mostly on the challenges of valuing R&D investments rather than on their nature. However, they are important to analyze because the logic behind the creation of an option on a real asset does not fully apply to the creation of an option on a knowledge asset.

Before we discuss how these two characteristics of knowledge affect the investment in R&D and its frequency, we need to clarify the focus of the discussion. We center our attention on the R&D investment process before it becomes successful and generates knowledge that can be patented. When the R&D investment process has reached success and created an innovation, a patent can be requested that will provide the firm with property rights over knowledge from which it can exclude other companies. At this point, the firm can exploit the innovation by undertaking additional investments that would create a product that can be sold in the market or sell the innovation by granting the rights of exploitation to other companies in exchange for a royalty. This is the traditional view of R&D investments under an options approach. However, what is usually overlooked in this discussion is that before the R&D investments are successful, they generate knowledge that, unlike investments in real assets, has ill-defined property rights and disappears over time.

R&D investments generate knowledge with ill-defined property rights

First, R&D investments generate knowledge that has ill-defined property rights, unlike other investments in real assets. This requires the firm to continue investing in R&D to reach knowledge with well-defined property rights, that is, an innovation that can be patented.

Investments in real assets, such as purchasing a participation in a firm to enter a foreign country or purchasing multiuse machinery for a production line, provide the firm with a bundle of ownership rights over the real assets that are well defined and can be protected. The company has a registration of ownership on the asset and, in many cases, has the physical control that enables it to exclude others from using the assets without its consent. In this case, the challenge for the firm is to wait for the uncertainty over the value of the asset to be solved over time. Once the value is revealed, the firm can then exercise the option granted by the real asset and undertake additional investments to achieve the benefits or sell the asset. This is the traditional view of investments in real assets in real options theory.

In contrast, investments in R&D, before they reach success and an innovation that can be legally protected, have knowledge assets with ill-defined property rights, inducing the firm to continue investing in R&D to achieve patentable knowledge. Most of the knowledge generated with R&D investments cannot be legally protected because it does not conform to the requirement of novelty and usefulness that patents require (Cohen, Nelson, Walsh, 2000; Levin *et al.*, 1987). Most of the knowledge generated is merely knowledge of what does not work or knowledge of what may or may not work. This knowledge does not have well-defined property rights because the firm cannot legally exclude others without a patent or physically exclude others from use because knowledge is an intangible asset. Thus, if the firm reveals the outcome of the R&D investments before reaching success, other firms will benefit from such knowledge, but the firm cannot force them to pay

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for the knowledge once it is revealed or exclude them from using the knowledge (Bhattacharya and Guriev, 2006; Gans, Hsu, and Stern, 2008; Gill, 2008). Although other investments in real assets also generate knowledge, this knowledge has protected property rights indirectly through the control that the firm has over the real assets and the exclusion this affords. For example, when drilling for oil in an area, the exploration efforts may not be successful, but the information gained has value for the exploitation rights of the area, rights that are owned by the firm with the exploration license. These rights enable the firm to exclude others from acting on the information in the area upon which it has the rights. In contrast, in R&D projects, the firm cannot exclude others from using the information generated during the R&D process because there is no control over associated real assets. This lack of well-defined property rights provides the incentive to have a continued stream of R&D investments to build on previously created knowledge until success is achieved and knowledge can be granted a legal protection with a patent.

R&D investments generate knowledge that disappears over time

Second, R&D investments generate an asset—knowledge—that disappears over time, requiring a continued stream of investments to maintain it.

An investment in a real asset does not have a built-in rate of disappearance. A firm invests in a real asset and can wait for the uncertainty over the value to be resolved before investing more in the asset. Although its value may decrease or increase, the asset itself will not disappear over time. For example, the firm may invest in the stock of a firm to enter a foreign market. The value of the investment will vary over time as uncertainty regarding the prospects of the foreign market and the firm there is resolved, but the stock acquired will remain without the need for additional stock purchases.

In contrast, the knowledge generated with investments in R&D disappears over time, inducing the firm to continue investing in R&D to maintain the knowledge. This disappearance of knowledge over time is independent from the variations in the value of knowledge discussed before. It is also independent from the competitive obsolescence of knowledge by which competitors' actions and customers' change in preferences render the firm's offers uncompetitive as Schumpeter discussed under the idea of creative destruction. Instead, we argue that knowledge created at one point in time disappears if additional investments are not made. Knowledge, unlike real assets, does not have a physical medium of storage, but instead is tacit and is stored in the mind of individuals in the firm and in their interactions with other members of the company and society (Hayek, 1945; Tsoukas, 1996). This knowledge is subject to individual and organizational forgetting (Benkard, 2000; de Holan and Phillips, 2004). An individual forgets knowledge when she or he does not use it. A firm forgets knowledge when employees do not use it and when they leave the firm. This forgetting is particularly problematic in the case of knowledge generated in an R&D investment process. In this process, the knowledge that is being generated does not yet have a clear outcome that can be made explicit to facilitate its transmission. Although individuals may create logs to track the steps taken and prototypes to test the outcomes, the reason, thinking, and logic behind the logs and prototypes are in the minds of individuals. If the firm stops investing in R&D before it achieves success, the knowledge generated at that point in time would start disappearing. The expertise achieved by the individuals fades away as their intellectual effort becomes focused on other tasks and the connections with the expertise of other individuals are not renewed through continued interactions in the project. Moreover, the stoppage of investments may result in individuals leaving the firm with the subsequent loss of their knowledge. This disappearance of knowledge in R&D investments provides an incentive to the firm to continue the investment process.

Frequency of R&D investments

These two characteristics of knowledge highlight the importance of analyzing the frequency of investments in R&D and its determinants. This question has been overlooked in the literature, not only the R&D investment literature, which has mostly focused on the amount invested in R&D, but also the real options literature, which has mostly focused on the valuation of R&D investments.

In terms of the frequency of investments in R&D, a firm has three main strategies open to it: (1) always invest in R&D, which is the strategy

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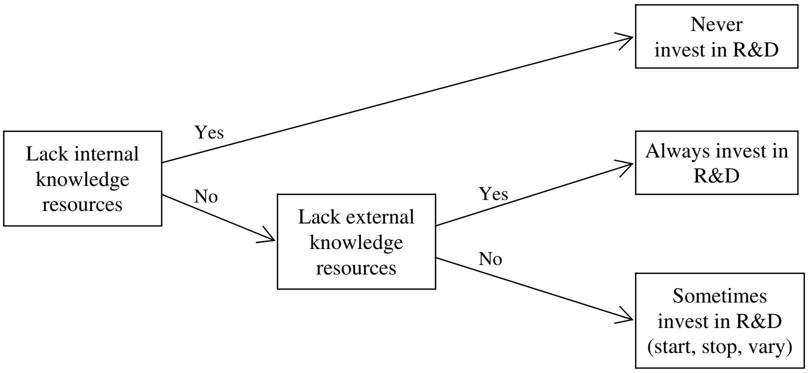

Figure 1. Knowledge resources and frequency of R&D investments

implicitly recommended in technology strategy studies of R&D investments and the real options view of R&D investments; (2) never invest in R&D, which is a strategy that defies recommendations and assumptions in the literature; and (3) sometimes invest in R&D, which questions the need for continuity in R&D investments discussed above. Moreover, within this third strategy of sometimes investing in R&D, a firm can follow several substrategies: (a) start investing, in which a firm that did not have R&D investments starts making them on a continuous basis; (b) stop investing, in which a firm that had continuous R&D investments stops investing; and (c) vary investing, in which a firm has R&D investments in some years, not in others, and yet again in others.

Knowledge resources and the frequency of R&D investments

Extending real options theory with ideas from the knowledge-based view, we explain the determinants of the frequency of R&D investments. We propose that previous investments in knowledge resources in the firm determine the firm's frequency of investing in R&D, which in turn facilitates the creation of a technological option. As such, we go back in the causality chain of the technological option, establishing a link between real options thinking and the knowledge-based view. This provides depth to the argument that a firm's resources determine the options available to the firm, which in turn determine the resources of the company (Kogut and Kulatilaka, 2001). Different from previous literature, we discuss how knowledge resources affect the frequency of investment in the creation of options. Specifically, we propose that the lack of internal knowledge resources limits the frequency of R&D investments and the creation of technological options. In contrast, the lack of external knowledge resources increases the frequency of R&D investments and the creation of technological options. The interaction between these two sets of resources determines whether a firm never, always, or sometimes invests in R&D. Figure 1 illustrates the predictions we discuss now.

Internal knowledge resources

We argue that a firm that lacks internal knowledge resources has a limitation on its ability to invest in R&D to create a technological option. As a result, such a firm may be more likely to never invest in R&D than to always or sometimes invest. To be able to invest in R&D, a firm has to have internal knowledge resources in the form of qualified personnel that can undertake the R&D and generate new knowledge. It also needs money to be able to undertake the investments. These resources complement each other in the sense that a firm with money but without qualified personnel may not be able to do the research, while a firm with qualified personnel but no money may not be able to undertake the investment.

First, a firm needs to have qualified personnel to undertake the research and development side of R&D investments. The firm's employees are the ones who actually undertake the R&D. To do this, they need skills to be able to understand not only how to use the technology but also why to use it (Leiponen, 2005). This applies both to externally and internally developed technologies. Thus, even if the firm is willing to invest in formal R&D to develop new technologies, it may not be able to do so unless it has employees with the necessary

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education, such as scientists and technicians with the appropriate training in advanced technology development (Galende and Suarez, 1999; Galende and de la Fuente, 2003). Thus, a firm that lacks skilled employees will be more likely to never invest in formal R&D because its employees are not able to develop new technologies (research) or adapt external technologies for the use of the firm (develop). This supports the following hypothesis:

Hypothesis 1a: A firm that lacks skilled employees is more likely to never invest in R&D than to sometimes or always invest in R&D.

Second, a firm needs funds to undertake R&D investments. To be able to invest in formal R&D, a firm needs to have financial resources in excess of those needed for current operations (Fazzari, Hubbard, Petersen, 1988; Hubbard, 1998). In contrast to other investments in real assets that can be funded with debt, such as those in plants and machinery, R&D investments tend to be funded with free cash flow. There are four reasons for this. First, there are asymmetries of information that limit the ability of the firm to explain the project to potential investors and obtain external funds (Myers and Majluf, 1984; Stiglitz and Weiss, 1981). Second, the firm may be unwilling to discuss its proprietary technologies with external fund providers because these technologies may leak to its competitors (Teece, 1980). Third, the technology is specific to the firm and thus external providers of funds would be reluctant to fund a resource that has a reduced secondary value (Vicente-Lorente, 2001). Fourth, R&D investments do not have collateral value and thus cannot be given as a guarantee of repayment to debt holders (Hart, 1995). Thus, a firm that has limited free cash flow does not have discretionary funds to invest in R&D and will be more likely to never invest. Hence, we hypothesize that:

Hypothesis 1b: A firm that lacks free cash flow is more likely to never invest in R&D than to sometimes or always invest in R&D.

External knowledge resources

In contrast to internal knowledge resources, we propose that a firm that lacks external knowledge resources limits its ability to rely on valuable external knowledge to establish a technological option. As a result, it is more likely to always invest in R&D than sometimes or never. We are not arguing that the firm will purchase external technologies to substitute for internal R&D investments (e.g., Pisano, 1990; Poppo and Zenger, 1998; Nagarajan and Mitchell, 1998; Robertson and Gatignon, 1998; White, 2000); this would be merely a type of R&D investment. Instead, we argue that a firm with tight relationships with other companies may obtain useful knowledge to create innovations without having to pay for this knowledge. The tight relationships are needed to facilitate building the trust and incentives that support knowledge transfer (Szulanski, 1996). Tight relationships with customers provide the firm with ideas on the needs of customers as well as where and how it can innovate its products; tight relationships with suppliers give the firm ideas on the development and integration of inputs into updated processes and new products; tight relationships with parent companies provide the firm with ideas on new technologies. These relationships enable the firm to obtain useful knowledge and, thus, it may not have to continuously invest to develop it.

First, a firm that has tight relationships with customers can obtain useful knowledge on the needs of customers and better guide its R&D investments, reducing its need to continuously invest in R&D. The tight relationships with the customer can help the firm obtain detailed information on what the specific needs of the customers are and ideas on how to best fulfill such needs (Un and Cuervo-Cazurra, 2006). Thus, companies that work together with lead users benefit from the development of new ideas on innovative products that solve unmet needs of customers. The firms that maintain the tight relationship are able to appropriate the ideas and use their manufacturing capabilities to bring the innovative products to the market (Baldwin, Hienerth, and von Hippel, 2006; Thomke and von Hippel, 2002). A tight relationship with the customer is needed to facilitate the development of trust and exchange of information. As a result of the tight relationship, the firm may be able to better target its R&D investments and only undertake those that deal with specific needs of the customer, allowing it to be continuously innovating without continuously investing in R&D. In contrast, a firm that lacks tight relationships with customers may not obtain the detailed knowledge needed to address specific unmet needs

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of customers. It may have to maintain a continuous stream of investments that generate a variety of new ideas, some of which may address the needs of customers. As a result, the firm with limited customer relationships would have to always invest in R&D. Hence, we hypothesize that:

Hypothesis 2a: A firm that lacks a tight relationship with customers is more likely to always invest in R&D than sometimes or never invest in R&D.

Second, a firm that has tight relationships with suppliers may obtain technology indirectly from the suppliers and incorporate it in its products, reducing the need to continuously invest in formal R&D to develop its own technologies. The inputs that the firm purchases have technological development embedded in them (Carlile, 2002). The firm that has a tight relationship with suppliers can develop the trusting relationships that facilitate the transfer not only of inputs but also of the technology and knowledge associated with these inputs. A firm that is already dependent on few suppliers for its inputs has solved transaction problems associated with such dependence, such as in the relationships established by Toyota and its lead suppliers (Dyer and Nobeoka, 2000; Kotabe, Martin, and Domoto, 2003; Takeishi, 2001). Thus, the firm can obtain knowledge useful for improving the products and reduce its need to continuously invest in R&D to generate such knowledge. In contrast, a firm that lacks tight relationships with suppliers would not benefit from the transfer of knowledge about advances in input technology and processes. Instead, it would have to rely on its own continuous R&D investments to generate new process innovation or identify new product features, giving suppliers the specifications for such innovations. Thus, we hypothesize that:

Hypothesis 2b: A firm that lacks a tight relationship with suppliers is more likely to always invest in R&D than sometimes or never invest in R&D.

Third, a firm that has a tight relationship with a parent company can obtain technologies from the parent company without having to pay for them. As a result, the firm may sometimes not invest in R&D but still be innovative. A firm that belongs to another company can rely on the parent firm for resources, not only managerial and financial (Chandler, 1962; Williamson, 1985) but also technological. The parent company can be more efficient in undertaking formal R&D in a centralized unit and achieve economies of scale and scope in technology development. This technology is then transferred to the subsidiaries for their use in production. This applies not only to domestic parents but also to foreign ones. A foreign firm can concentrate its R&D facilities in countries where it can obtain access to the best technological capabilities and transfer them to its subsidiaries around the world (Kuemmerle, 1999; Penner-Hahn, 1998; Un and Cuervo-Cazurra, 2008). This enables the local subsidiary to reduce the frequency of its investments in formal R&D. The subsidiary can concentrate on production and marketing activities in the foreign country and undertake sporadic R&D investments when it needs to adapt the innovations from the parent to the local conditions. In contrast, a firm that does not have a tight relationship with a parent firm does not benefit from the technologies developed by the parent firm and would have to instead develop all its own technologies and innovations through continuous investments in R&D. Therefore, we hypothesize that:

Hypothesis 2c: A firm that lacks a tight relationship with a parent firm is more likely to always invest in R&D than sometimes or never invest in R&D.

RESEARCH DESIGN

We use a sample of manufacturing firms to test the hypotheses. Data come from a survey of industrial firms conducted by the Ministry of Industry and Technology of Spain and the Public Enterprise Foundation (SEPI) between 1990 and 2002. The sample includes 785 firms for which information was available across the 12 years. All firms are in industrial sectors, Standard Industrial Classification (SIC) codes 2 and 3. The sample is widely representative of the underlying population of firms in industrial sectors in Spain since it was randomly drawn from manufacturing firms with more than 10 employees throughout the country. The average firm has €51.7 million in sales and 216 employees.

Analyses using this database have studied firm diversification (e.g., Merino and Rodriguez, 1997), internationalization (e.g., Salomon and Shaver,

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2005), R&D Collaborations (Un, Cuervo-Cazurra, and Asakawa, 2010), and R&D investments (e.g., Cuervo-Cazurra and Un, 2007). Other studies of R&D in the country have focused on studying firms in specific regions (e.g., Galende and Suarez, 1999; Molero and Buesa, 1996) or have been restricted to the analysis of firms that are R&D active (e.g. Galende and de la Fuente, 2003; Molero and Buesa, 1996). However, none of these studies have analyzed the frequency of formal R&D investments.

Variables and measures

Table 1 summarizes the variables and measures. The dependent variable is the frequency of R&D investments. This frequency of R&D investments is measured via a classification of firms by the frequency of their R&D expenditures during the period for which we have data, 1990–2002. As we discussed before, we have five possible types of R&D investment strategies. We have two extremes, those firms that never invest in R&D and those that always do. Firms are classified as never investing in R&D when they do not have positive R&D expenditures in the period 1990–2002. Firms are classified as always investing in R&D when they have positive R&D expenditures for every year in the period 1990–2002. In between the extremes of always and never investing in R&D, we have firms that sometimes invest in R&D, that is, that in some years have positive expenditures and in

Table 1. Variables and measures

Constructs	Variables	Measures	Values
R&D investments	Frequency of R&D investments (never, start, stop, vary, or always invest)	(1) Never: the firm has zero expenditures in R&D in all the years analyzed. (2) Start: the firm has zero expenditures in R&D some years at the beginning of the period analyzed and then positive for other years until the end of the period analyzed. (3) Stop: the firm has positive expenditures in R&D some years at the beginning of the period analyzed and then zero for other years until the end of the period analyzed. (4) Vary: the firm has positive expenditures in R&D some years, zero others, and positive again other years, and so on. (5) Always: the firm has positive expenditures in R&D in all the years analyzed.	1, 2, 3, 4, or 5
	Amount of R&D investments	Total R&D expenditures divided by sales and multiplied by 1,000	Positive
Internal knowledge resources	Skilled employees	Employees with more than a secondary education divided by total number of employees multiplied by 100	0 to 100
	Free cash flow	Natural logarithm of the free cash flow	Positive
External knowledge resources	Tight relationship with customers	Percentage of the sales to the three main customers over total sales	0 to 100
	Tight relationship with suppliers	Percentage of the purchases from the three main suppliers over total purchases	0 to 100
	Tight relationship with parent firm	Percentage of stock of the firm that is owned by another firm	0 to 100
Controls	Age	Age of the firm in years	Positive
	Size	Natural logarithm of the value of sales	Positive
	Diversification	Indicator that the main product of the firm accounts for more than 70% of sales	1 or 0
	Competition	Market share of the largest four competitors	0 to 100
	Industry	Industry of the main product of the firm at the two-digit CNAE level (21 industries)	1 or 0
	Year	Year of analysis (13 years)	1 or 0

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other years have zero expenditures. Moreover, there are three possible types of behavior among firms that sometimes invest in R&D, which may be influenced by different determinants. Some firms stop investing in R&D, that is, have positive R&D expenditures continuously at the beginning of the period but then have zero expenditures until the end of the period. Other firms start investing in R&D, that is, have zero R&D expenditures at the beginning of the period but then have positive R&D expenditures continuously until the end of the period. A final type is firms that vary investing in R&D, that is, have positive R&D expenditures in some years, zero expenditures in others, again positive expenditures, and so on. The outcome of this classification is five types of firms by frequency of R&D investments, types that are mutually exclusive and include all possible R&D investment frequency strategies: never invest, always invest, start investing, stop investing, and vary investing. We assign numbers to each category and analyze the selection among categories. The numbers assigned are not relevant, because there is no order among the five types of firms. What is relevant is that they represent mutually exclusive categories.

In our sample, in the period 1990–2002, 35.6 percent of the firms never invested in formal R&D, 15.9 percent always invested, 7.38 percent started investing, 4.5 percent stopped investing, and 36.4 percent varied their R&D investments. The length of time in the data, 12 years, increases the confidence that the firms are correctly classified by their frequency of investment. Unfortunately, although there is the possibility that some firms may have started investing before the period or stopped investing after the period, we are unable to observe firms' investments before 1990 or after 2002 because the database disguises the identity of the firms to ensure confidentiality. The classification of firms by their investment pattern is not affected by changes in the measurement method because the question used to capture R&D investments in the questionnaire is the same throughout the period.

To provide a comparison with previous analyses of the amount invested in R&D, we also measure this variable and explore the impact of the determinants used in our study. We measure the amount of R&D with an indicator of the expenditures in R&D divided by sales and multiplied by 1,000, in line with previous literature on R&D investment.

Table 1 provides detailed descriptions of the measures for the independent variables. We study two types of internal knowledge resources: skilled employees, which is measured as the percentage of employees with more than a secondary education; and free cash flow, which is measured by the natural logarithm of free cash flow. We also study three types of external knowledge resources: a tight relationship with customers, which is measured by the percentage of sales sold to the top three customers; a tight relationship with suppliers, which is measured by the percentage of inputs purchased from the top three suppliers; and a tight relationship with a parent firm, which is measured by the percentage of a firm's capital that is owned by another local or foreign company.

We control for other variables that may influence the frequency of formal R&D investments. First, we control for the firm's age because older firms may need to invest in R&D more often to compensate for the obsolescence of their initial advantages. We measure age by the number of years since the firm's creation. Second, we control for firm size because larger firms may have to undertake R&D investments more frequently to generate innovations that address the needs of a larger and more diverse customer base, achieving economies of scale in R&D (Schumpeter, 1942). We measure size with the natural logarithm of sales. Third, we control for the firm's diversification because diversified firms may need to undertake more frequent R&D investments to address the needs of a wider business basis (Baysinger and Hoskisson, 1989; Hoskisson and Hitt, 1988). We measure diversification with an indicator that the main product of the firm accounts for less than 70 percent of its sales (Rumelt, 1974). Fourth, we control for the concentration of competition because this puts pressure on firms to invest in R&D to develop distinct technologies (Kamien and Schwartz, 1982; Schumpeter, 1942). We measure this with an indicator of the percentage of the market controlled by the largest four competitors. Fifth, we control for industry, because appropriability and technological opportunities in the industry may influence the firm's frequency of R&D investments (Levin, Cohen, and Mowery, 1985; Levin *et al.*, 1987). We measure industry with indicators for each industry at the two-digit Clasificación Nacional de Actividades Económicas (CNAE) level, which is a Spanish equivalent of the SIC codes. Sixth, we control for year to take into account temporal variations.

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We use indicators for each of the years. Finally, we control for other unobserved firm characteristics by clustering the error terms by firm.[1] Clustering is a technique for obtaining robust error terms by indicating that the observations are independent across clusters (firms in our case), but not within clusters.

Method of analysis

Since the dependent variable represents discrete categories, we cannot use traditional least square regression techniques. Instead, we use a multinomial logit method because the dependent variable takes discrete values that are not ordered. In this analysis, the specific numbers associated with each type of formal R&D investment behavior are not relevant; the only relevant information is that they represent mutually exclusive strategies (Greene, 2000). All the independent variables are lagged one year because previous characteristics are likely to affect later decisions. The general model specification is the following:

$$
\begin{aligned}
&Frequency\ of\ investment\ in\ formal\ R\&D\\
&\quad (never,\ always,\ start,\ stop,\ vary)\\
&\quad = \beta_0 + \beta_1 \times skilled\\
&employees + \beta_2 \times free\ cashflow + \beta_3\\
&\quad \times tight\ relationship\ withcustomers\\
&\quad + \beta_4 \times tight\\
&relationship\ with\ suppliers\ + \beta_5\\
&\quad \times tight\ relationship\ with\ parent\ company\\
&\quad + \beta_6 \times age + \beta_7 \times\\
&size + \beta_8 \times diversification\\
&\quad + \beta_9 \times competition + \beta_i \times industry_i\\
&\quad + \beta_j \times year_j + \varepsilon
\end{aligned}
$$

The coefficients need to be interpreted in relationship to the baseline category, which in the analysis is the category of always investing in R&D. We chose this category because it is the assumed behavior of most R&D investment analyses. The hypotheses are supported under the following conditions. Hypotheses 1a and 1b are supported if β_1 and β_2 are negative and statistically significant, respectively. Hypotheses 2a, 2b, and 2c are supported if β_3, β_4, and β_5 are positive and statistically significant, respectively.

RESULTS

Table 2 presents the descriptive statistics and correlation matrix. Although some of the independent variables show statistically significant correlations, the correlations are not large, with the exception of those between size and free cash flow, between a tight relationship with a parent firm and free cash flow, and between size and a tight relationship with a parent firm. We explored potential multicolinearity problems by running analyses that excluded each of the potentially problematic variables. We found that the sign and significance of the coefficients of the other variables do not change, indicating that these correlations do not pose a problem in the analyses (Greene, 2000).

Frequency of formal R&D investments

Table 3 presents the results. Model 3a provides the results of a multinomial logit analysis of the determinants of the frequency of R&D investments. The baseline category is firms that always invest in R&D. Hence, the coefficients are interpreted in comparison to this category, with submodels 3a1, 3a2, 3a3, and 3a4 presenting the results of the comparison of firms that never, start, stop, and vary their R&D investments in comparison to firms that always invest in R&D, respectively.

Model 3a1 provides the results of the comparison of firms that never invest in R&D to those that always invest in R&D. These results support Hypotheses 1a and 1b. The coefficients of skilled employees and of free cash flow are negative and statistically significant as expected. Firms that have fewer skilled employees and less free cash flow are more likely to never invest in R&D. These results are also in line with Hypothesis 2b, but do not support Hypotheses 2a and 2c. The coefficient of tight relationships with suppliers is positive and statistically significant, while the coefficients of tight relationships with customers and tight relationships with the parent firm are not statistically different

[1] A very different analytical technique that has the same name is cluster analysis. Cluster analysis is an exploratory data analysis technique in which the researcher tries to identify the natural groupings (or clusters) of observations. See Everitt, Landau, and Leese (2001) and Kaufman and Rousseeuw (2005) for descriptions of cluster analysis. An alternative to control for unobserved firm heterogeneity is to use fixed- or random-effects models. Unfortunately, this procedure is not available for the multinomial logit method we use to test the hypotheses.

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Table 2. Summary statistics and correlation matrix

	Mean	Std dev	1	2	3	4	5	6	7	8	9	10	11
1. Frequency of R&D investments	2.896	1.578	1										
2. Amount of R&D investments	6.952	22.778	0.269***	1									
3. Skilled employees	8.785	10.265	0.285***	0.252***	1								
4. Free cash flow	11.961	2.129	0.521***	0.180***	0.301***	1							
5. Tight relationship with customers	39.213	27.064	0.004	0.029**	−0.036***	−0.068***	1						
6. Tight relationship with suppliers	45.427	22.778	−0.235***	−0.098***	−0.104***	−0.201***	0.189***	1					
7. Tight relationship with parent firm	27.078	40.726	0.328***	0.087***	0.219***	0.548***	0.092***	−0.062***	1				
8. Size	14.007	2.008	0.517***	0.180***	0.310***	0.910***	−0.040***	−0.204***	0.573***	1			
9. Age	27.988	21.684	0.238***	0.074***	0.135***	0.393***	−0.066***	−0.122***	0.236***	0.395***	1		
10. Diversification	0.526	0.499	−0.166***	−0.005	−0.126***	−0.210***	0.159***	0.104***	−0.124***	−0.211***	−0.112***	1	
11. Competition	18.896	27.094	0.138***	0.050***	0.078***	0.161***	−0.070***	0.010	0.147***	0.154***	0.060***	−0.044***	1

Two-tailed correlation.
Significance levels: + $p < 0.10$, * $p < 0.5$, ** $p < 0.01$, *** $p < 0.001$.

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Table 3. Analysis of the determinants of the frequency of formal R&D investments and of the amount invested in R&D

	Dependent variable: frequency of R&D investments: never, start, stop, vary, or always invest in R&D				Dependent variable: amount of R&D investments	
	All firms				All firms	R&D-active firms
	Multinomial logit analysis				Tobit analysis	Regression analysis
	Model 3a				Model 3.b	Model 3.c
	Submodel 3.a.1	Submodel 3.a.2	Submodel 3.a.3	Submodel 3.a.4		
	Never compared to always	Start compared to always	Stop compared to always	Vary compared to always		
Skilled employees	−0.053 (0.01)***	−0.011 (0.02)	0.002 (0.01)	−0.010 (0.01)	0.771 (0.15)***	0.501 (0.16)***
Free cash flow	−0.351 (0.12)**	−0.048 (0.14)	−0.078 (0.17)	−0.128 (0.11)	2.168 (1.24)+	0.579 (1.37)
Tight relationship with customers	−0.005 (0.00)	−0.005 (0.01)	0.005 (0.01)	−0.001 (0.00)	0.024 (0.04)	0.021 (0.04)
Tight relationship with suppliers	0.026 (0.01)***	0.016 (0.01)*	0.006 (0.01)	0.012 (0.00)*	−0.206 (0.05)***	−0.031 (0.06)
Tight relationship with parent firm	0.003 (0.00)	0.000 (0.00)	0.013 (0.01)**	0.000 (0.00)	−0.057 (0.03)*	−0.048 (0.02)*
Age	−0.009 (0.01)	−0.017 (0.01)*	−0.019 (0.01)*	−0.010 (0.01)+	0.048 (0.06)	−0.039 (0.05)
Size	−0.965 (0.16)***	−0.242 (0.19)	−0.622 (0.26)*	−0.409 (0.14)**	6.654 (1.65)***	−1.476 (1.43)
Diversification	−0.008 (0.22)	0.498 (0.26)+	0.216 (0.32)	−0.128 (0.20)	0.331 (2.26)	3.861 (2.58)
Competition	−0.009 (0.00)*	−0.002 (0.01)	−0.003 (0.01)	−0.007 (0.00)*	0.083 (0.04)*	0.005 (0.04)
Industry	Included	Included	Included	Included	Included	Included
Year	Included	Included	Included	Included	Included	Included
Constant	19.392 (1.99)***	3.538 (2.40)	9.430 (3.13)**	9.225 (1.71)***	−89.78 (19.36)***	51.941 (18.67)**
Number of observations	9420				9420	4560
Number of firms	785				785	380
X2 or F statistic	8546.970				5.24***	6.95***
Log likelihood	−8347.123				−17946	n/a

White-Huber heteroskedasticity-consistent standard errors appear in parentheses. Errors are clustered by firm. The models control for industry and year, but the coefficients are not presented in the table. n/a = not applicable.
Significance levels: + $p < 0.10$, * $p < 0.5$, ** $p < 0.01$, *** $p < 0.001$.

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from zero. In other words, firms whose relationships with suppliers are less tight are more likely to always invest in R&D. These results indicate that, all else being equal, an increase of one employee with more than a secondary education decreases the probability that the firm will never invest in R&D, instead of always invest, by 5.3 percent; an increase in the natural logarithm of free cash flow by one unit decreases the probability that the firm will never invest in R&D, instead of always invest, by 35.1 percent; while an increase of one percent in the purchases that the firm makes from the top three suppliers will increase the probability that the firm will never invest in R&D, instead of always invest, by 2.6 percent.

Models 3a2, 3a3, and 3a4 provide the results of the comparison of firms that start, stop, and vary in their investments in R&D to those that always invest in R&D. These provide additional support for Hypothesis 2b in the case of firms that start and vary in their R&D investments and for Hypothesis 2c in the case of firms that stop R&D investments, but do not support Hypothesis 2a in all three cases. In other words, firms that have tight relationships with their suppliers are more likely to start or vary their R&D investments over time, while firms that have tight relationships with their parent firm are more likely to stop investing. Thus, these results indicate that, all else being equal, an increase in one percent in the purchases that the firm makes from the top three suppliers will increase the probability that the firm will start investing in R&D, instead of always invest, by 1.6 percent; an increase of one percent in the percentage of stock controlled by the parent firm will increase the probability that the firm will stop investing in R&D, instead of always invest, by 1.3 percent; while an increase of one percent in the purchases that the firm makes from the top three suppliers will increase the probability that the firm will vary investing in R&D, instead of always invest, by 1.2 percent.

The difference in determinants between firms that start or vary R&D investments and firms that stop R&D investments is important. Whereas the first two are affected by tight relationships with suppliers, the last one is affected by tight relationships with a parent firm. This points to the possibility that it is the parent company rather than the firm deciding when to stop investing in R&D, whereas in the other cases it may be the firm making the decision on the frequency of R&D investments and using its access to the technologies of suppliers to start or vary the R&D investment projects. This tight relationship with suppliers also has an influence on the firm deciding never to invest in R&D. As such, it appears that tight relationships with suppliers are an important source of knowledge and innovation with a large impact on the frequency of R&D investments; this is a novel finding that has not been analyzed in the literature of R&D investments in detail.

All in all, results of these analyses are novel and important. First, the results are novel because they explain the frequency of R&D investment, which has not been analyzed before. Previous studies at most have distinguished between R&D-active and R&D-inactive firms. By separating firms in terms of their R&D investment frequency strategy, we show that the strategies are, in fact, distinct as they are influenced by different determinants.

Second, the results are important because they indicate that the establishment of a technological option through R&D investments is not only affected by the knowledge resources of the firm, but also that different knowledge resources affect different R&D investment strategies. A firm is more likely to never invest in R&D rather than always when it lacks internal knowledge resources and has external knowledge resources. In contrast, a firm is more likely to sometimes invest in R&D rather than always when it has external knowledge resources, but it is not influenced by internal knowledge resources. This points to internal knowledge resources acting as a constraint on R&D investments. A firm that lacks such resources would not be able to invest in R&D. However, external knowledge resources appear to act as substitutes of R&D investments. They have a negative influence on R&D investments, with a firm that has external knowledge resources being more likely to never or sometimes invest in R&D rather than always. As such, the general argument that knowledge resources determine R&D investments needs to be more nuanced. Internal knowledge resources act as enablers of R&D investments, allowing the firm to invest. In contrast, external knowledge resources act as substitutes for R&D investments, allowing the firm not to always invest in R&D.

These findings and the arguments underlying them are an important contribution to real options theory. They show how knowledge resources in the firm affect the ability and frequency of R&D investments and thus the ability of the firm to

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generate future technological options. These arguments and findings contribute to real options theory by providing a nuanced explanation of how resources affect options (Kogut and Kulatilaka, 2001). They also establish another boundary on the application of the theory. In addition to boundaries on the impact of uncertainty (McGrath, 1997) and of managerial behavior (Adner and Levinthal, 2004; Miller and Shapira, 2004), real options theory has boundaries regarding the assumptions made on the characteristics of the investment (incrementality, immediacy, and availability). In this paper we focus on the assumption of availability of investments and show that not all firms have the option of investing in R&D, which would provide them with options for additional technological investments.

The arguments and findings also contribute to studies of technology strategy that have identified that some firms do not invest in formal R&D but have not explained this behavior; instead, they have controlled for it. However, not investing in R&D goes counter to the arguments that firms need to invest in formal R&D to develop technologies (e.g., Helfat, 1997) and to use externally generated technologies (e.g., Cohen and Levinthal, 1989). Rather than taking this behavior as an exception and controlling for it, we focus on explaining it. Thus, we analyze the frequency of R&D investments and discuss how prescriptions on R&D investments need to be modified to take into account the variety of knowledge in firms and their ability to establish a continuous R&D investment process.

Amount invested in formal R&D

Finally, to establish that the results are, in fact, novel and different from previous studies, we analyze the amount invested in formal R&D, which has been the dependent variable analyzed in other studies of R&D investments. To facilitate comparisons with previous studies, we run two different analyses. First, we include in the same analysis firms that have no R&D expenditures and firms with positive R&D expenditures as is done in some studies (e.g., Cohen *et al*., 1987; Helfat, 1997). We use a Tobit model to take into account that some firms do not invest in R&D whereas others have positive expenditures. Second, we include only R&D-active firms, or firms with positive R&D expenditures, as done in other studies (e.g., Galende and de la Fuente, 2003; Molero and Buesa, 1996). Following the literature, we use a regression model, because all firms have positive expenditures. In both analyses, we control for unobserved firm effects by clustering the error terms by firm to facilitate comparisons with the results discussed in the previous sections.

Model 3b presents the results of the Tobit analysis of the amount invested in R&D for all firms, while Model 3c provides the results of the regression analysis of the amount invested in R&D for R&D-active firms. The results of these analyses show that the determinants of the amount invested in R&D and of the frequency of R&D investments are, in fact, different. Specifically, the analysis of the amount invested in R&D by all firms presented in Model 3b shows that the coefficient of skilled employees is positive and statistically significant, while the coefficients of tight relationship with suppliers and tight relationship with the parent firm are negative and statistically significant. In other words, firms that have more skilled employees and have weaker relationships with suppliers and the parent firm invest more in R&D. These factors differ from those that determine the frequency of R&D investments that we discussed earlier.

Similarly, the analysis of the amount invested in R&D by R&D-active firms also shows different determinants, not only in comparison to the frequency of R&D investments but also in comparison to the amount invested in R&D by all firms. Specifically, the results of Model 3c indicate that the coefficient of skilled employees is positive and statistically significant, while the coefficient of a tight relationship with the parent firm is negative and statistically significant. In other words, among those firms that invest in R&D, firms that have more skilled employees and that have weaker relationship with a parent firm are likely to invest more in R&D.

These two comparisons are important to clarify the novelty of our study and to show that the implications of the analysis of frequency of R&D investments differ from those derived from analyzing the amount invested in R&D, which has been the traditional dependent variable in other studies. Although the decisions are related in that both analyze R&D investments, they answer different questions and have different determinants. Analyzing the frequency of R&D investments does not generate the same insights as analyzing the

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decision as to how much to invest in R&D. Thus, arguments used to explain and conclusions drawn from studying one type of R&D investment behavior may not directly translate as explanations of a related but different behavior.

Robustness tests[2]

We ran additional analyses to check for the robustness of the results of the analysis of the frequency of R&D investments. These results, not presented here, indicate that the results are robust and support conclusions similar to the ones discussed before. First, we ran analyses with additional time lags to analyze the robustness of the results across time. The results are surprisingly robust over time. Analyses with two, three, four, five, and six years of time lag support the same conclusions presented here. Second, we use different periods of time to analyze whether the results hold across time and are not an artifact of the time frame. We divide the sample into three four-year periods (1991–1994, 1995–1998, and 1999–2002) and find that the results of these studies support similar conclusions to the ones discussed before.

CONCLUSIONS

In this paper we study the frequency of R&D investments. R&D investments are seen in theory as necessary for the firm to generate technologies that support its competitive advantage and to absorb externally developed technologies. However, despite these theoretical arguments, some firms never invest in formal R&D. Analyzing this strategy helps us not only explain this contradictory behavior but also extend theory.

We built on real options theory and the knowledge-based view to analyze the frequency of R&D investments. In real options theory, R&D investments are the first stage of a multistage technological option. We reviewed how assumptions about the characteristics of investments (incrementality, immediacy, availability) limit the applicability of financial options thinking to the analysis of investments in real assets. We focused on the assumption that investments are always available to the firm to establish an option and argued that this is not always the case in real assets, especially those that are based on knowledge, because knowledge has ill-defined property rights and disappears over time. Thus, we analyzed the determinants of the frequency of R&D investments as the initial step toward the creation of a technological option, identifying five strategies (never, always, start, stop, and vary investing in R&D) and analyzed how they have different determinants, and how the determinants also differ from those that explain the amount invested in R&D. The arguments and findings highlight the novelty and importance of the present study.

The paper contributes to options theory (for a review see Reuer and Tong, 2007b) by discussing in detail one of the boundary conditions of the application of the arguments from financial options to real options. We proposed that whereas in financial options the firm is not limited in the availability of resources for establishing options, in real options the firm is affected by the availability of resources needed for establishing options. Moreover, we discussed how the creation of a real option on knowledge assets differs from the creation of a real option on real assets, requiring the adaptation and extension of arguments from real options with insights from the knowledge-based view. Thus, the paper complements previous studies that have established theoretical boundaries regarding uncertainty (McGrath, 1997) and implementation (Adner and Levinthal, 2004; Miller and Shapira, 2004) by explaining another theoretical boundary and by extending the theory to address it. Hence, future research on real options needs to take into account these and other theoretical boundaries when applying options thinking to investments in real assets, especially those that are based on knowledge.

Additionally, the arguments contribute to the technology strategy literature (for a review see Fagerberg *et al*., 2005) by explaining the frequency of R&D investments. This is a research question that has not been studied before, but is nevertheless important because it implicitly contradicts the traditional argument that firms need to invest in formal R&D not only to develop new technologies internally but also to use technologies purchased externally. The paper explains how internal and external knowledge resources affect the frequency of R&D investments. Moreover, the current study goes beyond the traditional distinction between R&D-active and R&D-inactive firms discussed in

[2] We thank one of the anonymous referees for suggesting some of these analyses.

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the literature. Instead, it separates firms into five groups: those that never invest in formal R&D, those that always invest in formal R&D, and those that sometimes invest in formal R&D, further separating the last type into three subtypes: those that start, stop, or vary their R&D investments. Empirically, the study shows that the determinants of each of the behaviors differ and that the determinants of the frequency of R&D investments also differ from the determinants of the amount invested in R&D, which has been the traditional variable of interest in previous studies. These arguments and findings highlight the need for future studies to be careful in extrapolating conclusions from analyses that study one type of R&D investment strategy into studies that analyze a related but different R&D investment strategy because they may not be applicable. Moreover, the paper identifies a new line of research on R&D investments in the form of the frequency of investments and explains why it is important to study the frequency and not only the amount invested in R&D.

The paper has some limitations that can be dealt with in future research. First, the paper has focused on understanding the frequency of investments in formal R&D to develop technological capabilities. Future studies can analyze the frequency of investments in the development of other resources and capabilities, such as organizational, financial, or marketing capabilities, which have different characteristics. This will allow us to generate a better understanding of the determinants of the development of resources in the firm and of the theoretical boundaries of real options theory. Second, in the present study we focused on industrial firms. This was appropriate for testing the arguments because formal R&D is a key process in developing technological capabilities in manufacturing firms. Future studies can adapt the theoretical framework to study service firms. Although they are less likely to formally invest in R&D to develop technology (Dougherty, 2004; Thomke, 2003), examination of these firms could nonetheless yield important insights into resource development (e.g., Poppo and Zenger, 1998).

Managers can also benefit from the arguments presented here. The paper explains some of the boundaries they need to take into account when applying options thinking to the investment in real assets and how investments in knowledge differ from investments in real assets when establishing a real option. Thus, managers trained in financial options need to use caution when applying this line of thinking to investments in real assets, especially those that are based on knowledge. The characteristics of the investment in terms of incrementality, immediacy, and availability, as well as the characteristics of knowledge will affect such options and will require a different frequency in investments.

Real options theory has made much progress in recent years, but it is in need of additional studies, especially empirical ones that can help it advance further (Reuer and Tong, 2007a). The present paper contributes to this by helping to understand some of the boundaries of the theory and, in the process, identifying new areas of research on R&D investment.

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