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R&D investment strategies of firms: renewal or abandonment

A real options perspective

BY

Pingping Song

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree

Of

Doctor of Philosophy

In the Robinson College of Business

Of

Georgia State University

GEORGIA STATE UNIVERSITY
ROBINSON COLLEGE OF BUSINESS
2009

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ACCEPTANCE

This dissertation was prepared under the direction of the Pingping Song Dissertation Committee. It has been approved and accepted by all members of that committee, and it has been accepted in partial fulfillment of the requirements for the degree of Doctoral of Philosophy in Business Administration in the Robinson College of Business of Georgia State University.

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ABSTRACT

R&D investment strategies of firms: renewal or abandonment
A real options perspective

BY

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July, 2009

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Major Academic Unit: Managerial Sciences

This research develops a real options perspective framework for firms' valuation of strategic investments. I propose that a real options perspective can provide an effective means of re-examining and revising firms' strategic investment decisions in general, and of making individual, investment-level abandonment decisions in particular. The principal purposes of this research are to explore whether firms make abandonment decisions in accordance with real options theory, and the relative strength of the traditional economic theory, the behavioral theory of the firm and real options theory in explaining firms' abandonment decisions. I develop a set of hypotheses in the context of firms' R&D investment strategies in the world chemical industry. Using U.S. patent renewal data, I empirically test the hypotheses. The results from the empirical analyses suggest that, 1) firms' actual innovation abandonment decisions are consistent with the predictions made from real options theory; and 2) a real options perspective provides better explanation of firms' abandonment decisions than traditional economic theory and the behavioral theory of the firm. Therefore, taking such a perspective allows us to better predict abandonment than the other models. In investigating whether insights from real options theory enlighten firm's abandonment decisions, this research contributes to the strategic decision making literature, real options research, RBV and dynamic capability research and innovation literature.

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CHAPTER ONE

INTRODUCTION

Today many industries are characterized by rapid changes in technology, ambiguous consumer demands and heightened competition. These changes are persistent and can be competence destroying such that firms can no longer earn above average return for a meaningful period of time based on a single innovation or advantage (Bogner & Barr, 2000). In order to pursue competitive advantages and thus sustain superior performance, firms have to undertake various strategic actions to keep pace with environmental changes and exploit market opportunities (Eisenhardt, 1989), to seek risk and innovation (Bourgeois & Eisenhardt, 1988), and to create new spaces that are uniquely suited to the firms' strengths (Hamel & Prahalad, 2005).

Current strategy theory and research suggest that effective firms undertake a series of actions to gain and sustain competitive advantages, which are in turn, continually being undermined by changes in the environment (e.g., Ferrier, Smith, Grimm, 1999; Lee, Smith, Grimm, Schomburg, 2000; Makadok, 1998). Thus, firms exhibiting sustained competitive advantage are, in fact, constantly searching for new or improved basis for that competitive advantage. Theory and research also suggest that these firm actions need to be experimental-based, because it can be unclear what directions changes in the competitive environment will take (Weick, 1995). By taking such experimental actions a firm can learn more about the environment and the potential of these actions, and it can access a range of alternative opportunities to take in the future. These actions are consistent with action-based sense making, because when they are undertaken, managers have little knowledge *ex ante* about whether the actions will be

successful (Bogner & Barr, 2000). Such a series of experimental actions extend the firms' past investments and strengths into the future, and provide the firm with unique strategic positioning as compared to competitors employing different sense making schema (Bowman & Hurry, 1993; Brown & Eisenhardt, 1997).

The risky and explorative nature of experimental-based actions implies that a portfolio of these actions will be necessary over time. Because environmental changes can create new growth opportunities or erode the profitability potential of previously attractive investments, adjustments in this portfolio need to constantly be made. Thus, firms must act as adaptive learners, making timely adaptations and adjusting their capability sets to exploit current and future market opportunities. Further, firms are constrained by limited resources, and managers are unable to manage an unlimited number of investments or businesses. In practice, therefore, most firms are pursuing many more projects and ideas than they can successfully execute (MacMillan and McGrath, 2002). Thus, firms have to regularly re-examine and re-arrange their investment portfolios. And it follows that how effectively firms conduct this re-examination and re-arrangement of their portfolios will be a significant component on their ability to sustain competitive advantage in a dynamic environment.

Timely abandonment of previously attractive investments is an important way to revise a firm's investment portfolio. In general, as Chang (1996) suggested, exit is a necessary component of a firm's search and learning process. It is a phenomenon that is common in dynamic competitive environment where exploration and innovation are critical, and effective entrepreneurship is highly valued. Helfat and Eisenhardt (2004) noted that it is not uncommon that firms abandon some markets and later enter related

markets to deploy their resources and capabilities. As all firm investments entail organizational resources and managerial attention, managing abandonment has important implications for firms. Firms need to terminate less attractive projects in a timely manner to limit the downside risk. In addition, timely abandonment is critical for firms to redirect valuable resources to those projects that can lead to greater return. Unsuccessful investments can comprise a significant proportion of all the investments that firms make. If firms are unable to effectively abandon less promising projects, they will be unable to focus their resources on the more promising investments. Thus, abandonment is not necessarily a rare and desperate management decision as it was regarded in the past. Rather, it can be a regular proactive choice linking resource allocation to superior performance.

Strategy research has noted the importance of abandonment. Dating back to the seminal work by Cyert and March (1963) and Nelson and Winter (1982), the behavioral theory of the firm and evolutionary economics suggest that firms follow particular routines and search processes to identify strategic assets and make investments to upgrade their strategic assets. By doing so, firms seek to improve their competitive positions. During this evolutionary process, when firms find that some strategic investments are less promising than expected, they should terminate such investments. In his widely cited article, Porter (1996) pointed out that the essence of firm strategy is choosing what not to do. The resource-based view of the firm (RBV), and especially the dynamic capability research, suggests that firms consistently seek, acquire, and exploit their resources to attain competitive advantages and pursue superior performance (Barney 1991; Teece, Pisano, Shuen 1997). While firms strive to develop and accumulate

valuable resources, it is also important for them to decide what not to do, including discontinuing some investments in which they have previously invested resources. For example, Eisenhardt and Martin (2000) noted that the key to firm effectiveness in dynamic markets is a firm's ability not only to decide which processes to incorporate into ongoing routines but also to decide which processes to leave out. Siggelkow (2002) also argued that when firms are confronted with evolving market conditions, asset trimming is one of the core processes that firms engage in to create and elaborate core organizational capabilities.

Although the literature has recognized the importance of abandonment, abandonment decision remains largely an unexplored area in the strategy literature. Staw (1993) noted that much of organizational theory can be reduced to two fundamental questions: how to get organizations moving, and how to get organizations stopped once they are moving. He suggested that while the vast majority of organizational studies focus on why and how organizations initiate action, more attention should be devoted to understanding of organizational termination decisions. Along these lines, Mahoney and Pandian (1992) pointed out that while the resource-based view predicts growth and diversification, a "resource-based theory of divestment is clearly lacking". Indeed, little empirical research has been conducted in this territory. The studies that did examine divestment mostly studied abandonment decisions in the context of divesture of entire business units or product segments such as corporate divestment decisions, which are often linked to previous diversification (e.g., Duhaime and Grant, 1984; Chang, 1996). Hence, as suggested by Lowe and Veloso (2004), more research at the more granular level is needed to examine firms' abandonment decisions. In this research I move from

the more common corporate-level strategic perspective and look primarily at the investment decisions that are components of business-level strategy.

While at the firm level we can say that abandonment decisions are important for firm performance and firms should make effective abandonment decisions, at the individual investment level abandonment decisions are not always wisely made. Despite the normative literature that suggests firms should make timely decisions to abandon certain investments and pursue those that entail higher growth potential, research shows that abandoning ongoing investments poses substantial challenges to firms. Guler (2007b) argued that while the signals of progress are relatively easy to interpret when the projects perform well, signals of failure are ambiguous and complex. Therefore, she suggested that firms usually can effectively decide to continue successful investments, but it is much more challenging for firms to identify and abandon investments that are no longer economically justified.

In addition, any decision that involves reversing a prior, public commitment involves cognitive biases that are not found in decisions to invest. Thus abandonment decisions take mechanics of distinctive traits when compared to investment decisions.

I propose in this dissertation that a real options perspective can provide an effective means of re-examining and revising firms' strategic investment decisions in general, and of making individual, investment-level abandonment decisions in particular. I argue that in these situations real options theory can provide a better lens for the examination of investment value than traditional economic models such as Net Present Value (NPV) and the behavioral theory of the firm alone. Although there are difficulties for firms in reversing what has been done, using the real option lens can help firms

overcome or reduce cognitive and behavioral biases and thus help them make abandonment decisions more effectively. In the remainder of this dissertation, I will examine firms' investment abandonment decisions using arguments based on economic logic, the behavioral theory of the firm and real options theory.

The main research questions to be explored in this dissertation are:

1. To what extent do firms make decisions to abandon or keep investments in accordance with the predictions and prescriptions made from real options theory?

2. What is the relative strength of the Net Present Value model, the behavioral theory of the firm, and real options theory in explaining firms' abandonment decisions?

Although real options theory is conceptually rooted in finance, I approach these questions from a strategic management perspective. I borrow from the resource-based view (RBV), knowledge-based view (KBV) and search literature to help build my arguments. According to RBV and KBV, firms differ in their resources including knowledge and capabilities, and these resource differences can explain performance differentials across firms. As a firm's strategic investments can be considered as options on growth opportunities, the knowledge utilized in such investments has implications for the value of such options. In addition, the firm's knowledge asset position has influence on the value the firm can appropriate from the strategic investments. Therefore, knowledge heterogeneity may also lead to differences across firms in the valuation of similar investments.

Real options theory in recent years has attracted increasing academic interest in the field of strategic management. Bowman and Hurry (1993) suggested that real options theory is an attractive framework to examine strategic decision making under uncertainty. Fruitful research using the real option lens has been conducted with respect to many types of strategic decisions, among which are joint ventures (Kogut, 1991; Kumar, 2005; Reuer & Tong, 2005), international entry (Reuer and Leiblein, 2000), equity partnerships (Folta and Miller, 2002), industry entry (Kim and Kogut, 1996; Folta and O'Brien, 2004), and R&D investments (McGrath, 1997; McGrath and Nerkar, 2004). Some scholars also use other terms to refer to the application of real options theory in management studies, such as ROA (real option approach or real option analysis) (Kumar and Shyam, 2005; Bowman and Moskowitz, 2001), ROR (real option reasoning) (McGrath and Nerkar, 2004), and ROL (real option logic) (Warner, Fairbank, and Steensma, 2006). Though the terms differ, they all refer to the same underlying conceptualization of strategic decision making being seen through a real option lens.

Most extant research applying real options theory in the field of strategic management has examined the adoption of new options, leaving the implementing of options under-studied. Even less research has been conducted on firms' abandonment decisions. Some scholars raise criticisms of this gap in the research and argue that abandonment is a critical aspect of real options perspective (Adner and Levinthal, 2004). They suggested that by not examining the abandonment decisions, the real option research does not offer a complete test of the theory and lacks persuading support in this vein. Importantly, because real options theory is being applied to managerial decision processes, its application to abandonment decisions is not merely applying the same

procedure as an initial investment, and deciding not to invest, as might be suggested by a financial options perspective. This dissertation responds to the call and seeks to examine whether real options theory can help us understand firms' investment abandonment decisions.

In this study I do not intend to explicitly calculate the value of specific options. Rather, I examine whether factors that impact option value are systematically related to the actual abandonment decisions in a manner consistent with predictions derived from real options theory. In doing so, I develop and empirically test a series of hypotheses in the context of R&D strategies, which represent a critical aspect of firms' strategic investment decisions.

In investigating whether insights from real options theory enlighten firm's abandonment decisions, this study seeks to make the following contributions to the literature.

First, it contributes broadly to the strategic decision making literature. The incorporation of a real options theory perspective into the strategic decision making literature in general, and abandonment decisions in particular, offers two important contributions. First, it allows for the development of a more complete model of decision making than that offered by either economic models or behavioral theory alone. Economic models, such as NPV, have served as good normative models for decision making, but, as will be noted in subsequent chapters, they do not accurately reflect actual decision making behavior. The behavioral theory of the firm recognizes the biased and cognitively constrained nature of decision making in practice and so comes closer to predicting actual decision outcomes. However, managers often make complex decisions

under conditions of uncertainty that have quite positive results, despite the biases and heuristics that behavioral theory claims should limit the effectiveness of decision making. This suggests that current models of decision making may be incomplete and that managers may use logics that help overcome cognitive limitations. I will argue that real options reasoning can provide that logic. If the findings from this study provide evidence that real options reasoning is used in abandonment decisions, along with economic and behavioral logics, then we will have moved one step closer to building a more comprehensive model of strategic decision making.

The second contribution to the strategic decision making literature concerns avenues for future research. If the results suggest that there is a significant relationship between the variables that determine option value and abandonment decisions, it raises the question of whether real options logic truly improves decision making. Thus, my findings would open up an important new avenue of research that would seek to determine the relationship between real options reasoning and decision outcomes. If such a link is found, it would move the role of real options logics in decision making from purely descriptive to a more prescriptive role.

This study also seeks to advance the development of real option research by empirically testing the application of real options theory in the implementation of firms' investment options. Although real options theory has attracted significant interest in the field of strategic management and considerable progress has been made, many scholars agree that empirical studies that validate the propositions of real options theory are still sparse. The implementing of real option abandonment decisions remains under-researched, although it is a critical aspect of real options in general.

Third, it contributes to innovation literature as I develop and test the hypotheses that emerge from real options theory in the setting of R&D investment decisions. In spite of widespread attention to firm innovations in the form of patents, little is known about how firms manage their innovation portfolio through the abandonment of patents and the research trajectory that they represent. The use of real options theory provides new insights into the valuation of firms' R&D investments and patent abandonment decisions.

The remainder of this dissertation is organized as follows. In the next chapter I present the theory background and develop a set of propositions about investment valuation and thus abandonment. Chapter Three develops a series of hypotheses on firms' R&D investment abandonment decisions. Then Chapter Four presents the research methods, explaining my use of logistic analysis to empirically test the hypotheses in the context of the world chemical industry using U.S. patent data. Chapter Five reports the hypotheses test results. In Chapter Six I present the discussion, implications, limitations and future research.

CHAPTER TWO

THEORY DEVELOPMENT

In this chapter, I will compare the arguments about investment valuation derived from traditional economic logic, behavioral theory of the firm, and real options theory. Then a series of propositions will be developed.

II. 1. Economic logic

Traditional economic theory assumes that managers are fully rational and make optimal decisions. The most popular traditional approach to valuating investments is the net present value (NPV) calculation, which is based on discounted cash flow (DCF). The reasoning is that an investment creates value for shareholders if the present value of the expected cash inflow exceeds that of the expected cash outflow. Namely, an investment should be made when the net present value is positive. NPV models assume that investment decisions are based on managers' rational valuation of the investments. The NPV valuation technique offers an economic rationale for investments and is widely applied.

However, this neoclassical investment model has both conceptual and implementation problems (Slater, Reddy, Zwirlein, 1998). Conceptually, the NPV approach gives limited consideration to uncertainty and does not adequately consider the value of embedded growth opportunities, thus it tends to devalue those investments that do not produce clear, measurable cash flow streams. In addition, the NPV approach takes a static view and fails to consider management's ability to revise their decisions in response to subsequent unanticipated market developments, which can cause cash flows to deviate from original expectations (Ross, 1995; Trigeorgis, 1993). As a result, the NPV approach tends to under-value explorative projects and long-term strategic investments (Haley and Goldberg, 1995; Kogut and Kulatilaka, 1994; Stein, 1996).

In addition to these conceptual problems, implementation problems with the NPV approach include inaccuracy and bias in forecasts of cash flow, and the use of an inappropriate discount rate. As managers are only boundedly rational and have limited

information processing ability (March and Simon, 1958), the calculation of net present value will often be meaningfully inaccurate because of the inappropriate inputs.

In light of the above, it is not surprising that many observed managerial behaviors are inconsistent with the expectations that come from a pure NPV model (Dixit, 1992). Firms that solely rely on NPV models may abandon investments that entail valuable opportunities. As a result, NPV models do not provide satisfactory prescriptive or descriptive models for explaining firms' abandonment decisions. Bettis and Hitt (1995) pointed out that when the environment is competitive and changing, reliance on such an approach is like a corporate ritual rather than an appropriate decision technique. In particular, NPV models tend to undervalue longer-term strategic investments and ignore the embedded growth opportunities. This is because strategic investments are usually characterized by exploration to a certain extent and are frequently confronted with significant uncertainties. Thus, firms using NPV models to evaluate strategic investments are inclined not to invest in projects that are of negative NPV but can be promising in the future. Even firms that have been successful in the past may fail to adapt or adopt new technology that will meet customers' unstated or future needs and will eventually fall behind (Christensen, 1997). Therefore, firms tend to prematurely terminate investments that might otherwise be profitable. This is analogous to type II error in research (Guler, 2007b).

Proposition 1:

Traditional NPV models can undervalue strategic investments and lead firms to abandon such investments too early.

II. 2. Behavioral theory of the firm

The behavioral theory of the firm emphasizes the actual process of decision making. Behavioral theory of the firm scholars criticize the neoclassical economic theory for assuming profit maximization and internal efficiency, and ignoring the most significant features of the organizational process, i.e., the process of actually managing the factors of production (Simon, 1982). The analytic assumptions of perfect rationality are not just incomplete, but are misleading as they are contrary to the actual processes that firm managers use to make decisions in complex business situations.

The behavioral theory of the firm is consistent with economics logic in the sense that the behaviors of organizations are considered as actions performed by coordinated agents to achieve their goals, but it insists on coming to terms with cognitive limits (Mahoney, 2006). In contrast to neoclassical models such as NPV that assume decision maker rationality and optimal decision making, the behavioral theory of the firm suggests that managers are only boundedly rational with limitations in information processing and that they make satisficing decisions (March and Simon, 1958; Cyert and March, 1963; Tversky and Kahneman, 1974). As pointed out by Bromiley (2005), while the traditional capital investment literature frames the investment problem as selecting among well-defined projects, real projects are rarely clearly defined and there are no cash flow forecasts attached. Therefore actual managerial evaluations of investments are not strictly made from the economics models. Greve (2003) showed that firms' R&D expenses and innovation launches are influenced by firm performance and slack resources, consistent with predictions derived from the behavioral theory of the firm. Sometimes firms can even do the opposite of what the economics literature suggests (Bromiley, 2005).

The bounded rationality and limited information processing capacity assumptions are more realistic and can better describe organizational behaviors compared to the neoclassical theory in which decision makers are regarded as fully rational. However, managers' decision biases impact their investment evaluations and can lead to decisions that are irrational in an economic sense. It can be hard for firms to identify investments that are no longer justified and decide to terminate such investments, although the ability to do so is critical for a firm to pursue investments with significant growth potential. Scholars have come to the observation that the challenges associated with abandoning investments can be even greater than those associated with initiating investments (Garud and Van de Ven, 1992; Adner and Levinthal, 2004).

The behavioral theory of the firm suggests that organizational factors lead firms to develop inertia and thus firms tend to continue doing what they have been doing (March and Simon, 1958). Because of internal organizational factors, firms are inclined to keep those investments that have been initiated by making follow-on investments. A prominent manifestation of organizational inertia is the observation that "exploitation drives out exploration" (March, 1991). This will lead to learning traps that favor specialization and inhibit experimentation (March, 1991; Levinthal and March, 1993), competency traps that impede an organization from accumulating adequate experience with a newer and eventually superior procedure (Levitt and March, 1988), and obsolescence in knowledge development (Sorenson and Stuart, 2000). As the result, the firm's competitiveness in the long run is harmed.

All the above dysfunctional outcomes can result from decision biases. In the following sub-sections I develop in further detail two types of biases that influence firms'

valuation of strategic investments and, in particular, can bias decisions to abandon investments: escalation of commitment and uncertainty avoidance.

II. 2. 1. Escalation of commitment

Escalation of commitment is a decision bias that has attracted sustained attention in organizational theory. Strategic investments are typically courses of actions associated with a series of decisions rather than isolated decisions. There are times when a decision maker has invested in a project or course of action and the project goes poorly. The literature shows that there are many instances in which decision makers in these circumstances become locked into a losing course of action. They may commit more efforts and resources even when the additional investment is not expected to pay off, or persist in the course of action despite the signal of failure. Such a situation is referred to as escalation of commitment. There may be a tendency for decision makers to become locked into losing situations so that they are "throwing good money after bad" (Staw, 1981).

Both individual and organizational decision makers exhibit undesirable decision commitment and face difficulties in terminating investments or courses of action. Early research on escalation of commitment research mostly concerned individuals and most of the evidence was collected through laboratory studies (e.g., Brockner, Rubin, and Lang, 1981; Corlon and Garland, 1993). Organizational scholars, however, have also found evidence of commitment escalation in organizational decision making (e.g., Staw, 1976; Staw and Hoang, 1995; McNamara, Moon, and Bromiley, 2002). For example, Garud and Van de Ven (1992) suggest that managers focused on a particular project may see

greater potential in the pursuit of the project and become dedicated to the initiative. In a series of research studies, Staw and his colleagues found that decision makers may become over committed to a course of action as they seek to recoup their losses and justify their previous decisions (Staw, 1976; Staw and Fox, 1977; Staw and Ross, 1978) or to conform to the norms of consistency (Staw and Ross, 1980). McGrath (1999) also suggested that managers can become over committed because they are unwilling to admit error or failure.

Therefore, although traditional economic theory suggests that investments should be continued if future benefits are greater than future costs and otherwise be abandoned, escalation of commitment leads decision makers to keep an investment open even though it is "throwing good money after bad". By doing so, firms are likely to commit type I errors (Guler, 2007b), as they may fail to terminate investments that are no longer economically justified.

Proposition 2:

The behavioral theory of the firm suggests that escalation of commitment often leads firms to fail to abandon investments in a timely manner.

II. 2. 2. Uncertainty avoidance

The behavioral theory of the firm literature suggests that both individual and organizational decisions may be biased toward uncertainty avoidance, in the sense that the decision makers tend to choose alternatives with foreseeable outcomes. Ellsberg's experiments (1961) showed that people generally avoid ambiguous choices. Curley, Yates, and Abrams (1986) found that if decision makers anticipate that others will

evaluate their decisions, the decision makers tend to choose clear alternatives and avoid ambiguous alternatives because they believe that such alternatives are less justifiable than clear ones. At the organization level, Cyert and March (1963) argued that organizations typically exhibit uncertainty avoidance in the actual process of organizational decision making: organizational goal, expectation, choice and control. They suggested that uncertainty avoidance is a basic principle of firms' general choice procedures. Organizations try to avoid the need to anticipate events in the distant future. They tend to use decision rules emphasizing short-run actions and short-run effects, rather than anticipating long-run uncertain events.

Strategic investments have effects on performance in the long run and are often characterized by significant uncertainty. As a matter of fact, strategy is largely about resource allocation when the resulting impact on performance is not clear. The uncertainty avoidance bias, therefore, tends to make firms reluctant to allocate resources to longer-term strategic investments. Consequently, firms inadequately initiate long-term and explorative strategic investments, and tend to be biased toward projects with lower uncertainty when valuating ongoing investments. Thus the decision makers are more inclined to continue those investments with clear and certain payoffs. As a result, they may commit type II error, terminating explorative investments that are of higher uncertainty, even though they may be rewarding in the future. This leads to the following proposition and it is going to be contrasted with real options perspective later.

Proposition 3a:

The behavioral theory of the firm suggests that firms are overly inclined to abandon investments with higher uncertainty.

Bounded rationality as well as cognitive and behavioral biases constrain and shape organizational decisions (e.g., March and Simon, 1958; Cyert and March, 1963). These behavioral and cognitive biases may lead to decisions that are irrational in an economic sense. The decision errors in investment termination can be either type I error (failing to abandon investments which are no longer economically justified and should be terminated in a timely manner), or type II error (abandoning investments which are of high potential and should be kept). From a normative perspective, however, organizations should avoid such biases and decision errors. Organizational decision makers are experts in their fields and thus should use their expertise and experience to strive to avoid such decision errors. Also, as the survival of firms depends on effective business decisions, those firms that repeatedly exhibit decision errors should be selected out of the environment in the long run (Knez, Smith, and William, 1985; Smith, 1989). Thus, firms need to look for ways to avoid strategic decision errors and improve the efficacy of their decision making.

Although the behavioral theory of the firm explains some variance between observed managerial decisions and economically rational ones, it is descriptive and does not offer decision making approaches for overcoming these biases through the institution of alternative decision processes or routines. Therefore, by itself the behavioral theory of the firm has limited prescriptive insight and cannot be relied on to prescribe what decisions managers should make or how they should make them. Further, while subsequent research that takes a behavioral theory prescriptive has offered some methods

to improve decision making, they have focused primarily on the decisions to invest and have not addressed investment termination.

These observations lead naturally to the question: How can managers ensure sound decision making and improve their effectiveness in making decisions, while also reducing such biases and errors? In the following, I propose that real options theory can be used to improve managerial decision making prescriptions by overcoming the weaknesses of both the NPV perspective and the behavioral theory of the firm, and, in turn, may be a better predictor of organizational decisions.

II. 3. Real options theory

Recent research suggests that a real option lens might usefully complement the traditional approaches to evaluate firms' strategic investment decisions (Mitchell and Hamilton, 1988; Kogut, 1991; Bowman and Hurry, 1993; Trigeorgis, 1996; McGrath, 1997; Slater, Reddy, Zwirlein, 1998). Originating in the finance literature, real options theory presumes information asymmetries, path dependence and uncertainty (Miller, 1998). Dixit and Pindyck (1994) in their book, *Investment under Uncertainty*, offer an excellent survey of how real options theory advances the understanding of evaluation of explorative and risky projects relative to the traditional approaches. Unlike an NPV model that sets investment thresholds (i.e., at NPVs=0) ahead of the investment, real options theory accommodates the process of retrospective sense making and the management's ability to revise their investment decisions. In contrast to the static view of NPV, real options theory takes a more flexible and dynamic view because it values the ability to preserve management decision options in the future. Further, it provides a set of

decision rules that managers can utilize to avoid biases. Therefore, real options theory may reveal valuable insights that traditional approaches fail to provide for managerial decision making.

In the following, I will give a brief introduction to financial option theory and the use of option theory in strategy research, and then apply real options theory to investment valuation.

II. 3. 1. Financial option theory

Originating in finance, an option originally referred to special contractual arrangement that conveys the right, but not the obligation to purchase (call option) or sell (put option) an underlying asset at a preset price (exercise price, or striking price) in the future. As uncertainty exists about the price of the underlying asset, there is the possibility that the asset price may exceed the preset price so the call option is of positive value. Similarly, a put option is valuable as the price of the underlying asset may possibly fall below the preset price. There is phenomenal growth in option trading on organized exchanges since April 1973, when the Chicago Board of Options Exchange (CBOE) became the first organized exchange for trading standardized option contracts. The option traded volume in 2006 at this Exchange surpassed 674.7 million contracts (CBOE website).

Option theory has become a significant component in the field of finance. It plays a major role in shaping the thinking in finance today because of its ability to assume the existence of considerable uncertainty and value flexibility. While the most common options traded on exchanges are options on stocks or bonds, many other financial

instruments have some option features. Indeed, much of corporate financial theory can be presented in option terms. In this view, common stock can be viewed as a call option on the underlying assets of a leveraged firm; risky debt, convertible debt, insurance, warrants, almost every issue of bonds and stocks may be thought of as options. Even the capital structure of the firm, capital budgeting, investment policy, mergers and acquisitions, spin-offs and dividend policy, can all be viewed in terms of options (Cox, Ross, Rubinstein, 1979; Copeland and Weston, 1992).

Option pricing theory, therefore, is relevant to almost every area of finance (Cox, Ross, Rubinstein, 1979). Applications of option pricing theory in finance include but are not limited to dividend policy, spin-offs, divestitures, convertible debt and warrants, exit decisions, capital asset pricing, and arbitrage pricing (Copeland and Weston, 1992). While organized option markets have developed fast in the past few decades, option pricing theory also has undergone rapid advances in recent years. The most widely used and well-accepted option-pricing models are the Black-Sholes model (Black-Sholes, 1973) and the binomial model. The Black-Sholes formula is considered one of the most important contributions in finance. It presents the price (thus the value) of an option as a function of five factors: the price of the underlying asset, the variance of the underlying asset, the time to expiration date, the exercise price, and the risk-free rate of return. Table 1 gives a simple description of the predicted relationships.

Table 1

Relationships predicted by Black-Sholes Model

	Impact on option price
the price of the underlying asset	+
the variance of the underlying asset	+
the time to expiration date	+
the exercise price	-
the risk-free rate of return	+

The binomial option pricing approach uses binomial distributions and was independently derived by Cox, Ross and Rubinstein (1979) and Rendleman and Bartter (1979). It usually involves numerical calculations that can be facilitated with computer simulation. The binomial option pricing approach predicts relationships between the impacting factors and the option price that are similar to the Black-Sholes model. As a matter of fact, the Black-Sholes model can be regarded as a limiting case of the binomial option pricing approach (Copeland and Weston, 1992).

II. 3. 2. From financial option to real option

Although options have an origin in finance, option features are not limited to financial instruments. Almost all assets are really certain types of contingent claims because most investment decisions entail ongoing uncertainty, incomplete available information, and the possibility of exercising future managerial discretion (Dixit, 1992). Thus, option features are pervasive in many managerial decisions. Almost all projects have option-like characteristics and can be thought of as options—they are referred to as "real" options, because they are options on operating assets as opposed to financial assets that are tradable on market. Flexibility and embedded growth opportunities are inherent

in many investment proposals, making options an important aspect of the decision. Option valuation is therefore relevant to many strategic decisions of firms. Ross (1995) actually suggests that all investment decisions should be treated as option valuation problems. By incorporating the value of such real options, decision makers of firms can facilitate many of their decisions such as business entry, strategic alliances, and R&D investments etc.

There are important differences between financial options and real options so financial option-pricing models cannot be directly applied to real options problems. For example, finance theories are based on assumptions of market efficiency and equilibrium, hence market prices are evaluated to exactly reflect the value of the asset, and these prices are readily observable on market. Thus, using the option-pricing model, the value of options on stocks and bonds can be calculated explicitly. However, real options cannot be easily evaluated in such concrete numbers, and the use of this financial option pricing methodology for real options is limited by various difficulties.

First, real options lack some of the explicit features of exchange-traded options, so the financial models can be problematic. One important concern is that financial options and real options differ in their assumptions about the distribution of the future prices (return) of the underlying asset (Bowman and Moskowitz, 2001). Option pricing models are based on different assumptions about the distribution of the underlying asset price. The Black-Sholes model, for example, assumes that the stock price follows a lognormal distribution with a constant level of volatility. Such assumptions about distribution, however, may be inappropriate for real options as the distribution of return can be quite lopsided.

Second, firm specific resources and capabilities are commonly involved in real managerial decisions. These factors are not incorporated in the standard financial option valuation models. However, firm specific resources and capabilities can significantly impact the value the firm can realize through its strategic investments. For example, whether a firm has independently held complementary resources to expand in a target market affects the firm's valuation of a joint venture and accordingly the decision to acquire or divest (Kogut, 1991; Chi, 2000)

Third, like other quantitative models, there are a number of implementation problems related with quantitatively using the standard financial option pricing models to evaluate strategic real options (Lander and Pinches, 1998). Determining the value of inputs is challenging. The underlying asset of a real option is usually not publicly traded on active market; the asset price is thus not readily observable like a stock or bond price. Similarly, the future cash flow and the volatility of future return are difficult to predict; the risk-free rate of return may vary over the option's lifetime; the exercise prices for real options may not be known ahead of time. As a result, if the inputs are not calculated right, the valuation outcome derived from the option-pricing model is misleading.

In addition, the standard financial option pricing models cannot be directly applied to a strategic real option without complicated customization of modeling. The mathematical solution of the customized pricing algorithm can be overly sophisticated for most corporate managers and thus limit its use in many firms. Furthermore, real projects often are collections of embedded options, making the explicit pricing almost impossible. Consequently, real managers rarely explicitly employ advanced real option pricing models in strategic decision making (Copeland and Keenan, 1998). Rather, firms most

likely use the real options perspective qualitatively to facilitate their strategic decision making. Along with other scholars in strategy, I am not proposing that the real options perspective be used as a substitute for traditional valuation methods. Rather, I argue that the real options perspective can be a useful complement to the traditional approaches. This is consistent with Bowman and Moskowitz's observation that using multiple forms of analysis can be advantageous and lead to sound decision as the different methods can act as a check on each other (Bowman and Moskowitz, 2001).

II. 3. 3. Application of real options theory in strategy research

Recent literature in strategic management provides support for the argument that many aspects of firm behaviors are consistent with real options theory. Kogut, one of the early advocates of using real option lens in strategy research, suggested that joint ventures are created as real options to expand into new product markets in response to future technological and market developments (Kogut, 1991). He argued that joint ventures are an attractive mechanism for investing in an option to expand in risky markets as joint ventures can share risks and decrease the total investment. The firm can exercise the option by acquiring the joint venture when the market for the technology or new product is proven. Thus he hypothesized that the timing of the acquisition should be triggered by a product market signal indicating an increase in the venture's valuation. Consistent with real options theory, he found that unexpected growth in the product market for the joint venture increases the likelihood of acquisition, but unexpected shortfalls in product shipments do not have significant effect on the likelihood of dissolution. Kumar (2005) also suggested that a joint venture confers the option to buy

(i.e., to acquire) and the option to sell (i.e., to divest) the venture. By keeping the joint venture, the firm maintains flexibility and keeps such flexibility options open. When the firm exercises the option to buy or sell, a joint venture is terminated through acquisition or divestment. He examined the impact of the acquiring or divesting of joint ventures on the value creation of a parent firm. Consistent with real options theory, Kumar found that ventures that are divested to refocus a parent firm's product market portfolio are associated with significant value creation, and that firms gain lesser value when they terminate ventures in uncertain and concentrated industries.

Using a real options perspective, Folta and Miller (2002) examined equity purchases of partner firms subsequent to initial minority equity investment. They argued that uncertainty, firm valuation, and the threat of preemptive rivalry influence the choice between flexibility and commitment. They hypothesized that the resolution of uncertainty for technologies motivates commitment decisions, and that when the underlying growth opportunity is at risk of preemption by rivals, greater uncertainty encourages commitment. Using data from minority investments in the biotechnology industry by established firms from outside of biotechnology, they found support for their hypotheses.

McGrath and Nerkar (2004) applied real options theory to explore pharmaceutical firms' motivation to invest in technological areas new to the firm. They considered a firm's R&D activities in a new technological area as the adoption of a new option. They identified three constructs—scope of opportunity of a firm's first patent in a new technological area, the firm's prior experience in the area, and competition in the area. They argued that these constructs influence the firm's propensity to continue its R&D investment in the area. Based on an analysis of the patents of firms in the pharmaceutical

industry, they found that firms' investments in new R&D areas as reflected by subsequent patents in these areas are consistent with the arguments based on real options theory.

II. 3. 4. Investment valuation with a real option approach

Myers (1977) was the earliest to view a firm's discretionary future investment opportunities as growth options, or call options on real assets, arguing that the firm has the discretion to decide in the future whether it will exercise such options. He suggested that the value of a firm and any other investments can be broken into the cash flows stemming from assets in their current use and those stemming from their redeployment or future expansion. The latter cash flows are only realized if the assets are redeployed or future investment opportunities are actually exploited. Therefore, they entail the value of growth opportunities---- the value of *growth option*s, or the *option to grow* (Kogut, 1991; Myers, 1977). In other words, the value of an investment (V) can be decomposed in terms of assets that are currently in place (V_{AIP}) and the embedded growth options (V_O):

$$(1) \qquad V=V_{AIP}+V_O$$

V_{AIP} can be measured by the discounted current earnings on the assets in place. The *growth option*, $V_{O,}$ emphasizes the value of embedded opportunities to gain return in the future (e.g., Kogut and Kulatilaka, 2001; Tong, Reuer and Peng, 2005). Researchers have found that many investments create future growth opportunities and can significantly contribute to growth option value. Investments in joint ventures, advertising, research and technology platforms can create highly valuable growth options (e.g., Myers 1977, 1984; Kogut, 1991; Kogut and Kulatilaka, 1994). Early investments can enable a firm to acquire a greater ability to expand in the future and to take better advantage of

future growth opportunities. For example, early R&D investments can lead to a new generation product or process; acquisitions can enable a firm to access new markets or strengthen desirable core capabilities.

These early investments may lead to future competitive advantages, including but not limited to, technological advantage, brand name recognition by consumers and lower future production cost (Kulatilaka and Perotti, 1998). These potential opportunities enhance the value of the investments beyond the current earnings. Studies found that in many firms the value of their growth options represents a considerable proportion of the firm value (e.g., Strebel, 1983; Kester, 1984). For example, Kester (1984) found that many firms' growth option value can be over 50 percent of market value and some can be as high as 90 percent. However, traditional valuation approaches such as NPV fail to recognize this value, because the growth opportunities are embedded in the investments and there is no clear cash flow. In the following, I will examine what factors impact the valuation of the investment (V).

According to the Black-Sholes model, the value of a stock call option is a function of five variables: the current stock price, the volatility of the stock price, the time to expiration date, the exercise price, and the risk-free rate of return. These variables are analogous to the features of real strategic investments. The current stock price for the call option is analogous to the value of asset in place in the real investment. The volatility of the stock is analogous to the variance of the return the firm will receive from the investment. The exercise price of a call option is analogous to the future expenditure needed by the firm to capitalize on the growth opportunities. The risk-free rate of return is analogous to the cost of capital of the firm. I argue that real options reasoning would suggest that by examining these features of the investment, firms can assess the

embedded growth option value and thus alleviate the behavior biases described in the previous section.

Past strategy research on uncertainty's influence on decision making usually considered uncertainty as a disincentive for investments, as managers and investors strive to avoid volatility in performance. Even studies taking a real options perspective mostly emphasize the value of waiting over immediate investment when there is substantial uncertainty. Scholars have interpreted the empirical finding that uncertainty is negatively related with firm investment levels as powerful support of real options theory (Carruth, Dickerson and Henley, 2000; Guiso and Parigi, 1999). Option theory, however, also suggests that the variance of asset price increases the value of the option written on the asset. This can be illustrated by the valuation of stock call options: the higher the volatility of stock price, the more likely the stock price may exceed the exercise price in the future. As option holders keep the upside potential but limit the downside risk, they receive the payoffs from the positive tail of the probability distribution. Therefore, although a rise in the volatility of an asset decreases its market value, it will increase the value of the option written on the asset (Copeland and Weston, 1992). This feature of options has important implications for managerial decisions about investments. Recent research actually has begun to indicate that higher uncertainty can mean greater opportunity for future growth rather than simply larger risk, and thus encourages investments (Kulatilaka and Perotti, 1998).

When valuating new investment initiation such as industry entry, a firm needs to consider two types of real options embedded in the investment decision: the option to defer and the option to grow (Folta and O'Brien, 2004). The former option addresses the

value of waiting and the latter address the growth potential. The relative value of the two options determines whether the investment is taken or not. Folta and O'Brien suggested that while the two types of options have opposing impacts on the investment decision, both options increase in value with increasing uncertainty. As a result, the net impact on the investment decision can be ambiguous. In most cases, before the investment is undertaken, uncertainty increases the value of the option to defer more than the value of the option to grow (Folta and O'Brien, 2004), so uncertainty often leads firms to wait. For an existing investment, however, the option to defer entry is killed and the firm obtains an option to grow once the investment is made. Therefore uncertainty of the return will increase the value of the option to grow and thus lead the firm to keep the investment. Recalling equation (1), I expect a positive relationship between uncertainty and the value of the investment:

Proposition 3b:

Real options perspective suggests that firms are less inclined to abandon investments with higher uncertainty, ceteris paribus.

This proposition contrasts with the behavioral theory of the firm and Proposition 3a above. The behavioral theory of the firm suggests that managers and firms typically exhibit uncertainty avoidance, which describes what is really happening in managerial decision making process. Thus, Proposition 3a is a descriptive argument about managers' actual behaviors.

Proposition 3b, however, suggests that, all else being equal, the higher the uncertainty of the return on an investment, the less likely it will be abandoned. This is

because real options theory indicates that such an investment can be highly valuable. Thus, this proposition is a prescriptive argument telling what the right decision is in a given situation. It predicts the impact of uncertainty on investment valuation in the opposite direction as in Proposition 3a, which comes from the behavioral bias of uncertainty avoidance. Therefore, I suggest that using real options theory can help to overcome or alleviate the uncertainty avoidance bias, and thus reduce the likelihood of committing type II error.

While traditional economic theory only considers assets that are currently in place, real options theory also counts the value of embedded growth opportunities. This portion of investment value is not captured by traditional economic theory. Therefore taking a real options perspective helps firms to reduce the possibility of under-valuation of investments and thus reduce the type II errors that occur from traditional economic models such as NPV.

Proposition 4:

Taking a real options perspective in investment valuation can help firms alleviate the problem of too early abandonment found in traditional NPV models.

Due to escalation of commitment, it is difficult for firms to terminate their investment projects once started. Based on the behavioral theory of the firm, I propose in Proposition 2 that escalation of commitment often prevents firms from abandoning investments in a timely manner. Proposition 2 is a descriptive argument about what will most likely be observed in managerial decision making. If firms take a real options perspective and re-examine their projects accordingly, however, they will be able to

assess whether these projects are still economically justified. Therefore, they can make abandonment decisions when it is needed, thus reducing the possible type I error due to commitment escalation.

Proposition 5:

Taking a real options perspective in investment evaluation can help firms overcome the commitment escalation problems predicted by behavioral theories.

Taken together, we have traditional economic models such as NPV approaches, and we also have behavioral theory and real options theory, all of which predict firms' investment abandonment decisions. The traditional economic theory is normative, which is about making the ideal decisions. Economic models, however, assume that the decision maker is fully informed and fully rational, able to compute with perfect accuracy such that the ideal decisions can be made. Such assumptions do not hold true in real managerial decision making process of firms. Therefore the economic models do not validly apply to the actual decision making process. The behavioral theory is descriptive, describing what is actually happening in firms' managerial decision making process. The decisions actually made are not necessarily optimal or in the best interest of firms, due to bounded rationality and behavioral biases. Real options theory is prescriptive in that it attempts to identify what the right decision is given the actual restrictions that firms have. Thus, I suggest, by using the real options perspective, managers can improve the efficacy of their decision making.

I do not suggest that real options theory should drive out the traditional economic theory or the behavioral theory. These theories are complementary rather than substitutes

for each other. Each theory addresses different aspects of managerial decisions and can add variance explanation. So, using behavioral theory of the firm and economic theory together can better explain organizational behaviors than either does separately, and combining three theories together we can achieve even better fit in models of investment valuation.

CHAPTER THREE

HYPOTHESES DEVELOPMENT

Schumpeter (1942), in his book *Capitalism, Socialism, and Democracy* pointed out that innovation is critical for the creation of private wealth, social welfare and economic growth. Since then an impressive body of literature has justified the positive impacts of innovation on firm performance in terms of productivity growth (Bean, 1995; Geroski, 1989; Goto & Suzuki, 1989), market share (Franko, 1989), profitability (Cannolly & Hirschey, 1984; Geroski et al., 1993; Roberts, 1999), market value (Lerner, 1994), adaptability and long-term competitiveness (Geroski et al., 1993; Mobey, 1988). As strategic management research focuses on understanding differentials in performance across firms (Helfat, 2000), study of firms' R&D investment is a key part of strategy research.

Though the statement that innovation is a key to superior performance in today's competitive business environment is far from controversial, innovation is characterized by extensive exploration and frequently confronted with significant uncertainties. As a result, valuation of a firm's innovation investment targets is often difficult. The traditional approach to evaluate R&D investments with the NPV calculation is not

adequate. In this chapter, based on the propositions and arguments in the previous chapter, I develop a series of testable hypotheses on why firms abandon investments already in existence.

To operationalize the propositions, I examine firms' R&D strategies and consider their innovations as real options. R&D investment strategy of firms is an appropriate context to apply real options theory. As pointed out by Bowman and Moskowitz (2001), real options theory advances our understanding and evaluation of risky and explorative projects and encourages experimentation and proactive exploration of uncertainty, which is a revolution in thinking. Scholars have agreed that real options theory is promising in its potential contribution to a theory of firm innovation (McGrath, 1997; Mitchell and Hamilton, 1988; Miller & Arikan, 2004). The presumptions of real options theory on path-dependency and uncertainty describe realistic circumstances for managerial decision making about R&D investment. Real options theory values flexibility, which is valuable under uncertain conditions but is often ignored in traditional valuation approaches. Thus models incorporating a real options perspective can more closely align with managerial practices regarding R&D investment. By using real options theory to study organizations we should become better at prescribing and predicting managerial decisions about innovation that are actually made and therefore advance a theory of firms' R&D investment strategies that may also generalize to other investment decisions.

A firm's R&D investments are investments in future opportunities. These innovation investments confer growth options that the firm hopes will lead to a competitive advantage. They are parallel to financial call options in many ways. Take stock option as an example. Investors purchase a stock call option because the stock price

may exceed the exercise price. Similarly, firms invest in R&D projects because they believe they may be able to earn returns from the innovated technologies in the future. By undertaking the investments, both the stock option investors and the firms acquire the right to exercise the option but they do not have further obligations. If stock price does exceed the exercise price by expiration date, investors can choose to exercise the stock option by purchasing the stock at the previously specified exercise price. Similarly, firms can exercise their growth options by leveraging the technologies in production or licensing the technologies. If the stock price does not exceed the exercise price by the date of expiration, stock option holders will let their stock options expire without taking any further action; likewise, firms may abandon some of their innovations if such innovations do not turn out to be very useful.

From a real options perspective, when firms are making decisions as whether to keep or abandon an R&D investment, they assess the value of the investment, which includes both the asset in place and the value of the embedded growth option. Then they abandon those with lower valuation. By doing so, firms are able to redirect valuable resources to more fruitful R&D activities. Unlike the evaluation of initiating new projects, which would be the adoption of new options, the evaluation of ongoing investments for abandonment decisions involves giving up positions resulting from previous investments. The forces governing the two types of valuation differ in importance. While limiting the downside risk is the governing force for the decision as to whether to defer an investment initiation, for valuation of the investment in existence the upside potential of the investment, i.e., the growth option value, is the primary governing force (Dixit, 1992).

There is one critical distinction between an R&D investment as real option and a financial option in terms of the abandonment of these options. The stock option holders face an automatic expiration simply by taking no further actions: they just do nothing and the stock options expire. They do not need to make further decisions as to these options. Managers, however, do not have such an "automatic stopping event." They have to make explicit decisions to end the R&D investment and give up current positions proactively. For example, they have to decide that no more resources will be allocated to the investment. This sharp contrast with financial options is at the heart of the economic and behavioral issues associated with the abandonment of real options.

In the development of the hypotheses, I use arguments from traditional economic theory and behavioral theory of the firm in addition to real options theory. From the perspective of traditional economic theory, the value of assets in place, i.e., the current earnings, is the index used to make the abandonment decision. From the behavioral theory perspective, I identify two constructs that influence the abandonment decision: escalation of commitment and technological uncertainty (explorativeness). From the real options theory perspective, I identify five constructs that impact firms' abandonment decisions. Two of them are also found in the other two perspectives: the value of assets in place as represented by current earnings and technological uncertainty (explorativeness). Three others are distinctive to real options theory: scope of innovation, knowledge depth and knowledge complementarity. The hypothesis concerning current earnings based on real options theory is consistent with conventional NPV models. As to technological uncertainty (explorativeness), the behavioral theory of the firm and real options theory suggest competing hypotheses. I favor the real option hypothesis, arguing

that the real options perspective can help firms overcome behavioral bias, so it is prescriptive. I argue that using the NPV model only, or using the behavioral theory of the firm only, can lead to over-estimation or under-estimation of innovations, and that using real options theory can overcome or reduce such biases and result in more effective abandonment decisions.

Figure 1 gives a simple conceptual summary of the forces impacting the innovation abandonment decision. Each of these factors will be developed in the following pages. I am not going to calculate the option value explicitly or directly examine the impact of the option value on the abandonment decision. Rather, I will test the impact of the factors that influence the valuation of the innovation on the abandonment decision. Of these factors, knowledge depth and knowledge complementarity are at firm level and the other factors are all innovation specific.

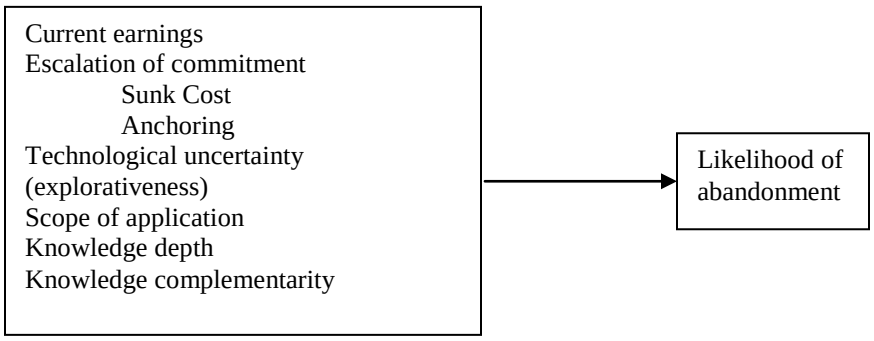

Figure 1

III. 1. Innovation specific factors

III. 1. 1. Current earnings

Traditional economic theory suggests that the value of an investment can be measured by calculating the discounted cash flow. Of the discounted cash flow approaches, NPV models are the most popularly used. Conventional NPV models suggest that the value of an investment is the present value of earnings from assets that are currently in place. An investment is justified if the present value of the cash inflow is larger than the present value of the cash outflow. Thus, the greater the discounted current earnings from an innovation, the more likely the firm is going to keep the innovation rather than abandon it.

From the real options perspective, the value of an innovation consists of the value of asset in place plus the value of growth options, as shown in Equation 1. The value of asset in place captures the NPV of current earnings from the innovation. The value of growth options may represent a significant portion of the total innovation value.

Option theory indicates that the higher the price of the underlying asset, the more valuable an option written on it. Thus higher current earnings of an innovation implies that the growth opportunity embedded in the innovation is more valuable. This prediction is consistent with NPV valuation approach. Both terms of Equation 1 have greater value with increase in current earnings. Accordingly, an innovation with higher current earnings is more valuable and the firm is more likely to keep it alive. Thus I come to the following hypothesis:

Hypothesis 1:

The more current earnings an innovation has, the less likely the innovation will be abandoned.

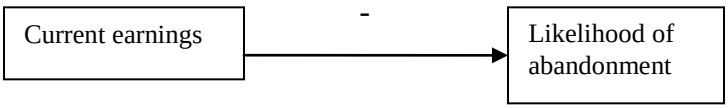

Figure 2

III. 1. 2. Escalation of commitment

Although most early studies of commitment escalation have concerned individuals and were conducted in laboratory experiments, recent research has started to lodge the research in organizational context. As noted above, one of the distinguishing factors of real options versus financial options is that real options on R&D investment or the like often require proactive behavior on the part of management. Research has found that organizational decision makers also have difficulties in making abandonment decisions and thus organizations may exhibit escalation of commitment. For example, Ross and Staw (1993) examined the escalation of commitment in the Shoreham Nuclear Power Plant, which wasted billions of dollars. Staw, Barsade, Koput (1997) and McNamra, Moon and Bromiley (2002) examined escalation in banks' commercial lending decisions. From the literature I discussed below I identify two sociocognitive factors that can lead to commitment escalation in investments: sunk cost and anchoring.

III. 1. 2.1. Sunk cost

Sunk cost refers to resources already invested in a project. According to traditional economic theory, a rational decision maker should only consider incremental costs and returns when he faces a choice between continued investment in a project or

termination of the investment. Objectively, the prior investment in the project should not impact the decision. However, research suggests that sunk costs, the investments already made in the project, may influence the decision to continue investment in an ongoing project. Arkes and Blumber (1985), for example, found that subjects are more willing to invest more funds in an ongoing project than in new project start up. In addition to the dichotomous effect of sunk cost, Garland (1990) found that the amount of sunk cost is positively related with the investor's willingness to continue investment in the project. Research has suggested multiple theoretical explanations for the sunk cost effects: self-justification (Staw, 1981; Teger, 1979), the desire not to waste resources already invested (Arkes & Blumer, 1985), and information-processing heuristics of framing of decisions (Kahneman and Tversky, 1979; Thaler, 1980; Whyte, 1986).

Because of the sunk cost effect, when managers make decisions in an organizational context prior investment in a project may increase the firm's commitment to the project. The larger the amount of sunk cost, the more biased the managers may be toward continuing an ongoing project, even in the face of negative feedback.

The resources a firm has spent in an effort to develop and deploy an innovation are the sunk cost of the innovation. Such investments are usually innovation specific and irreversible. The more the firm has invested in the innovation, the more prominent the sunk cost effect may become. The managers will have more motives to keep the innovation alive for self-justification of the prior input. They may think that "victory was just around the corner" (McNamara and VanDeMark, 1995) and consider abandoning it would be a waste of the already invested resources. The managers' framing of abandonment as loss results in a tendency to continue committing resources to the

innovation, even when the feedback is not positive. These lead to biased decision of undesirable commitment:

Hypothesis 2:

The more sunk cost there is in an innovation, the less likely it will be abandoned.

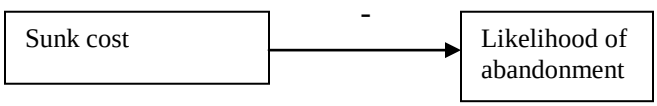

Figure 3

III. 1.2.2 Anchoring

The behavioral theory of the firm suggests that managers respond to the subjective environment that they perceive rather than the objective environment that they "really" face (Simon, 1982). Therefore, much as managers' behaviors are influenced by their subjective perception of the environment, the investment decisions of organizations are impacted by managers' perception of the value of the investment. As a result, if managers' perception of the value of the investment is subject to cognitive biases and heuristics, the managers will make biased investment decisions.

Sociocognitive literature has observed that managers have difficulty in changing beliefs. Once beliefs are developed, subsequent information processing tends to be biased in the direction of the preexisting belief (Crocker, Fiske, & Taylor, 1984). People often selectively filter information and interpret new information so as to maintain their beliefs (Fiske, 1991).

A common example of belief based bias is anchoring. "Anchoring" refers to the phenomenon that different initial values yield different estimates and that the final

estimates are biased toward the starting point, so there is “insufficient adjustment.” Tversky and Kahneman (1974) suggested that judgment under uncertainty exhibits anchoring and insufficient adjustment. People in many situations make estimates of likely outcome by starting from an initial value and adjusting this value to yield the final answer. The initial value, which acts as a starting point, may be given or it may be the result of some incomplete computation made by the people who make the estimates. In any case, people typically make insufficient adjustments based on the initial value.

Another cognitive heuristic, overconfidence, can make the anchoring effect even larger. Psychological literature shows that many people are often overly confident about their own relative abilities and are unreasonably optimistic about their futures (e.g., Kahneman and Tversky, 1979; Weinsten, 1980; Taylor and Brown, 1988). Such an optimistic bias is referred as overconfidence. Camerer and Lovallo (1999), for example, found that overconfidence leads to excessive business entry. They found that even when people accurately forecast competition and negative industry profits, they may decide to enter anyway because they believe their firm will succeed while most others will fail. The authors suggested that this can be one of the explanations for the high rate of business failure. While overconfidence may lead to excessive new business initiation, it also makes it hard for managers to terminate their existing investment projects. Because the decision makers may believe that, despite the unfavorable signals, they are still able to generate considerable returns, they may become more reluctant to adjust their initial expectation of the project.

Firms initiate innovation investments because they expect that the investments will produce positive returns. As time passes, some projects turn out to be less promising

than expected. Consequently, the managers ideally should revise their investment plan accordingly, abandoning those projects for which the economic value is no longer justified. Anchoring, however, may prevent managers from abandoning those projects in a timely manner. Holding feedback constant, the higher the initial expected future value of an innovation, the greater the adjustment that is needed for the managers to identify the real value.

In the light of the above, anchoring and insufficient adjustment tend to lead firms to stick to their prior expectation even when the signals are unfavorable and thus fail to terminate projects that are no longer justified. This applies to firms' innovation strategies; the managers' initial expectation of the usefulness of an innovation will impact their decisions between termination and persistence. The higher the initial expectation of an innovation, the more likely the managers will tend to keep it.

Hypothesis 3:

The higher the initial expectation of an innovation is, the less likely the innovation will be abandoned.

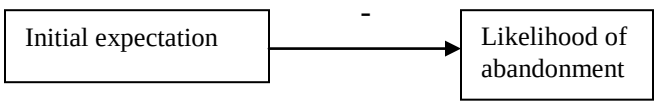

Figure 4

The remaining hypotheses are mostly based on the real option reasoning, which suggests that the higher the variance of the future returns on an innovation, the more valuable the growth opportunities embedded in the innovation. This is analogous to stock option pricing. When the downside loss is fixed, firms' investments increase in value

with increase in variance of returns, which means that the firms can access a greater range of potential upside outcomes. As Dixit (1992) pointed out, the upside potential to produce future earnings is actually the primary force that governs abandonment decisions. Therefore, innovations that have high variance in future returns should be more valued from a real options theory perspective, while such innovations are less valued using conventional approaches.

There are various types of factors from different sources impacting a technology's value, including the adoption and diffusion of new technologies, market and customer acceptance, and competitors' strategic actions (Rosenberg, 1996). In this study I identify and study four factors that influence the value of a firm's innovations: explorativeness of innovation, scope of application, firm's knowledge depth and knowledge complementarity. The first two factors are technology specific, and the latter two describe a firm's knowledge portfolio effect.

III. 1.3. Technological uncertainty (explorativeness)

As novel recombination of knowledge elements, innovations are characterized by significant uncertainty on the technology side. Technological uncertainty is an important aspect of uncertainty that innovations are faced with. When firms generate new innovations, they do not know for sure how useful the innovations may become in the future. I examine the explorative degree of innovation to denote the uncertainty of the return on the innovation from technological sources.

Innovations differ in the degree to which they are explorative: some innovations are oriented to employing and refining existing technological solutions, and other

innovations are more oriented to seeking new technological alternatives. They represent exploitation and exploration respectively as illustrated in March (1991). As exploitative innovations refine existing solutions, they conserve cognitive effort and resources and can lead to more predictable outcomes. There may even be the impulse to build on existing problem solutions in the context of innovation in general (Ahuja and Lampert, 2001). Explorative innovations, however, have less predictable future returns.

As discussed in the previous chapter, the behavioral theory of the firm suggests that firms typically make decisions in a manner that limits uncertainty. Therefore, when it comes to innovation strategies, the behavioral theory of the firm suggests that firms are inclined to keep exploitative innovations and abandon explorative ones.

Hypothesis 4a:

The more explorative an innovation is, the more likely it will be abandoned.

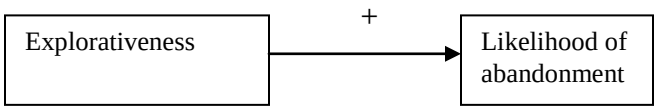

Figure 5

Real options theory, however, suggest the opposite: technological uncertainty increases the value of an innovation because higher uncertainty means higher growth option value. Explorative solutions to a problem are more risky than exploitative ones that build on technological antecedents (Hoskison, Hitt, and Hill, 1993; Hoskison, Hitt, and Ireland, 1994). However, experimenting with new solutions may lead to radically different innovation that is highly useful and fuels additional applications.

Explorativeness thus implies an increase in the variability of outcomes; it can result in failure but could also result in a significant breakthrough (Fleming, 2002).

Thus, higher explorative degree implies higher growth option value of an innovation. But it may take more time for the innovator as well as the market to recognize the true value of explorative innovations than for the exploitative ones. When the potential of an explorative innovation is unclear, waiting for further discoveries about the innovation has positive value. Therefore a firm will be inclined to keep such an innovation rather than abandon it in order to avoid losing the potential growth opportunities.

Hypothesis 4b:

The more explorative an innovation is, the less likely it will be abandoned.

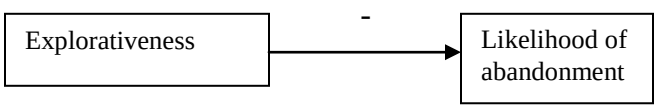

Figure 6

I expect that H4b is more likely to be consistent with actual managerial behaviors, because the upside potential is the primary force that governs abandonment decision for ongoing investments (Dixit, 1992). It would be very interesting to see whether actual managerial behaviors reflect the behavioral theory or real options theory. If Hypothesis 4a is supported, it shows that the descriptive behavioral theory is true but managers make suboptimal decisions. If Hypothesis 4b is supported instead, it suggests that we need to question the degree to which behavioral theory reflects managerial decision making.

III. 1.4. Scope of application

Scope of application is another technology specific characteristic of an innovation. A technology may be applied in more than one type of product or activity. Here I define *scope of application* as the degree to which an innovation can be leveraged in multiple products or activities. An innovation's scope of application may positively affect the variance of return on an innovation for three reasons.

First, a technology with a wide scope of application can be deployed in multiple products or activities simultaneously and thus generate higher return in total for a firm. Second, and relatedly, such a technology is a relatively more generalizable asset, thus it is more likely to be able to be leveraged by other firms at the same time. Therefore, in addition to leveraging the technology itself, the firm may also generate revenue by licensing the technology to other firms. Third, there are embedded switch options. As Moore (1994) suggests, "Many times the pioneering innovation is primitive, initially serves a specialized niche, and the most important use may not be the one envisioned." Berger, Ofek and Swary (1996) also show that generalizable assets produce more salvage value than specialized assets. When the innovated technology does not prove to be highly valuable in the originally desired use, the firm can still apply this technology in other fields, though it may need to end the original usage. As a result, an innovation with wide scope of application entails some flexibility for the firm, which is very valuable under uncertain circumstances according to real options theory. Therefore, an innovation with wide scope of application has higher growth option value, and a firm is more willing to keep it when information about the full value of the innovation is limited.

Hypothesis 5a:

The wider the scope of application of an innovation is, the less likely it will be abandoned.

However, there are also difficulties that managers will have to value and to really reap the benefit of application scope. To realize benefits from a wide scope of application may require additional coordination as well as complementary resources including technological knowledge, making such a task challenging and costly. Firms are limited in their knowledge breadth (Ahuja & Katila, 2002) so they may lack the ability to capture the marginal benefits from wider application scope of innovations. Although innovations with wide application may entail greater flexibility with embedded switch options, firms face obstacles in managing the switch options to harvest the flexibility benefits (Kogut, 1989; Kogut & Kulatilaka, 1994; Huchzermeier & Cohen, 1996, Tong & Reuer, 2007). Therefore, the firm that owns the technology and other firms may not be able to really exercise the embedded growth opportunities and reap the growth option value. Also, it can be complicated and costly to utilize the innovation in multiple products and activities so that the potential gains will be offset or even over weighted by the cost. Thus because of the firms' bounded rationality and limited resources including information processing capability we reach an alternate hypothesis:

Hypothesis 5b:

The wider the scope of application of an innovation is, the more likely it will be abandoned.

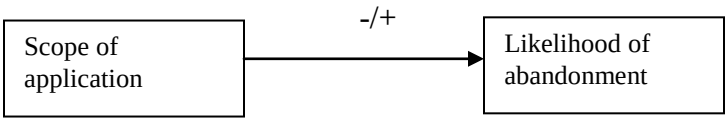

Figure 7

III. 2. Firm level factors

This section builds on real options theory while also bringing in other theory background, the Resource Based View and in particular, the Knowledge Based View and dynamic capability arguments. In addition to the innovation specific factors discussed above, firm differences may impact abandonment decisions. Because firms are heterogeneous in their resources and knowledge, each firm may perceive the value of an innovation quite differently. As Gimeno, Folta, Cooper and Woo (1997) proposed, the heterogeneity of firms' abandonment decisions should be of particular interest to strategy researchers. Folta & O'Brien (2007) have suggested that an examination of firm resources provides the basis for enlightening this heterogeneity. Guler (2007a) also found that firm level differences are significant predictors of firm actions, especially in unsuccessful investments.

I examine how a particular type of resource, a firm's knowledge portfolio, impacts its innovation abandonment decisions. KBV suggests that the key resource of a firm is its bundle of knowledge assets, and that the firm can build competitive advantage through the effective management of such knowledge assets (Grant, 1996; Kogut and Zander, 1992). Firms develop and apply knowledge in multiple technological areas, and engage in multiple R&D projects. Because firms integrate and deploy their knowledge to

create value, the return a firm can generate from its innovations is thus associated with the firm's pool of knowledge.

The dynamic capability literature also suggests that a firm's knowledge asset positions not only shape the firm's competitive advantage, but also impact the accumulation of the dynamic capabilities of the firm (Helfat, 1997; Teece et al, 1997). This further supports the argument that when firms evaluate their innovations, they should not only examine the technological content in the focal innovation itself, but also consider the firm's other resources especially its knowledge assets. The firm's current knowledge asset will therefore impact the firm's evaluation of the innovations, its investment in resource development and its R&D trajectory, and its innovation abandonment decisions.

This logic leads to another advantage of using real options theory as compared to conventional theories. Conventional theories based on cash flows typically assume independent evaluation of investments. Thus, those approaches ignore the joint effect of investments on future return but treat the value of investments as largely additive (McGrath & Nerkar, 2004). Real options theory perspective, however, allows interactions between investments. For example, Vassolo, Anand and Folta (2004) observed that there are potential sub-additive or super-additive interactions among real options investments due to redundancies in outcomes and fungible inputs respectively. In the following I identify two characteristic traits of a firm's knowledge portfolio that impact the variance of return on an innovation for a firm: *knowledge depth* and *knowledge complementarity*.

III. 2.1. Knowledge depth

I define *knowledge depth* as the degree to which a firm develops and accumulates knowledge within a specific technological area. By technological area, I refer to a technological domain in which the technologies share a similar function, use or structure. A firm's knowledge depth in a technological area can increase the variance of the return a firm can generate from its innovations in that area for the following reasons. First, a firm's innovations in areas where it has developed deep knowledge are likely to be more valuable than those in areas it is unfamiliar with. As the firm develops deeper knowledge in a technological area, it can better value new knowledge in that area. With familiarity and deeper understanding, the firm's ability to use the knowledge to innovate improves (Katila and Ahuja, 2002). Studies have shown that highly valuable innovations can derive from the new synthesis of well-known components (Nelson & Winter, 1982; Sahal, 1985; Utterback, 1994). Second, firms can better exploit their innovations in areas they are familiar with as they build up complex knowledge and insight; a firm can reuse methods or materials with greater efficacy (Eisenhardt & Tabrizi, 1995; Hoskisson et al, 1993). Third, firms are more likely to further extend their innovations to areas in which they have already accumulated substantial knowledge. RBV indicates that firms build their capabilities on what they are especially good at. As firms construct and accumulate knowledge through experience, their prior experience permits more efficient knowledge accumulation in subsequent periods (Cohen & Levinthal, 1990, 1994; Henderson & Clark, 1990). Helfat (1994) also found that firms tend to emphasize areas in which they have accumulated knowledge in the past. Consistent with these arguments, the dynamic capability view of the firm also suggests that deeper knowledge may facilitate both the

learning and application of knowledge and thus the firm may better realize its absorptive capacity to create or sustain its competitive advantage (Zahra and George, 2002).

Firms may perceive greater upside potential embedded in innovations in areas where their knowledge portfolios show a high level of knowledge depth and are inclined to keep such innovations. Therefore I have the following hypothesis:

Hypothesis 6:

The depth of a firm's knowledge portfolio in a technological area is negatively related to the likelihood that an innovation in that area will be abandoned.

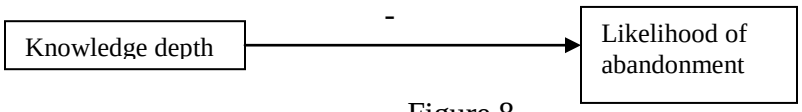

Figure 8

III. 2.2. Knowledge complementarity

Here I define *knowledge complementarity* as the degree to which the knowledge in different technological areas can be usefully combined. Two technological areas do not necessarily have to be close to each other in terms of technological specifics in order to have high knowledge complementarity. Rather, high knowledge complementarity between two technological areas implies that synergy may be achieved by combining knowledge components in these areas to generate valuable solutions. For example, Fleming and Sorenson (2001) found that it is easier and more fruitful to combine certain types of technologies than others.

I examine the complementarity of a firm's knowledge portfolio at the level of technological area. If the knowledge in a technological area can be usefully combined

with knowledge in other technological areas of the firm, then positive interactions are likely between the innovations in that area and the firm's knowledge in other areas. By tying the focal innovation with the firm's other technologies, it is likely that the firm can develop products of higher performance or generate new technologies of higher value than firms lacking the complementary technologies. Given an innovation, those firms without such complementary knowledge will be less able to discern application opportunities or fully exploit such opportunities. Firms with complementary knowledge therefore can access a wider range of growth opportunities and create greater value, which means greater absorptive capacity in the aspect of harvesting resources (Zahra and George, 2002). From the perspective of RBV, Knowledge complementarity can lead to competitive advantage as it meets the four criteria: valuable, difficult to imitate, unsubstitutable and not all firms have it (Barney, 1991). The firm's innovations in such a technological area thus tend to have a higher growth option value for the firm, making it worthwhile for the firm to keep these innovations.

Hypothesis 7:

The higher the knowledge complementarity between a technological area and a firm's other technological areas, the less likely the innovations in that technological area will be abandoned.

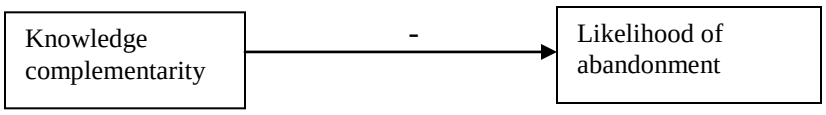

Figure 9

The following is a summary of the hypotheses (1-7) and theoretical bases.

	Independent variable	Predicted impact on likelihood to abandon	Level	Theory
H1	current earnings	-	innovation	Economic, Real option
H2	sunk cost	-	innovation	Behavioral
H3	initial expectation	-	innovation	Behavioral
H4a	explorativeness	+	innovation	Behavioral
H4b		-		Real option
H5a	scope of application	-	innovation	Real option
H5b		+		Behavioral
H6	knowledge depth	-	firm	Real option
H7	knowledge complementarity	-	firm	Real option

Table 2. A summary of Hypotheses1-7

As shown in Table 2, Hypothesis 1 is derived from both traditional economics theory and real options theory. Hypothesis 2 & 3 and Hypothesis 4a are based on behavioral theory, and the rest of the hypotheses are from real options theory. I do not claim that these theories are mutually exclusive. Rather, they address different aspects of managerial decision making in business context. Therefore, a model that includes all three perspectives should be better in predicting abandonment decisions than the other models.

Hypothesis 1 addresses the economic rationale from conventional NPV approach, which considers the NPV of an innovation but tends to under-estimate its potential value in the future thus lead to type II error. I expect that a model with Hypotheses 1 through 3 will better predict abandonment decisions than a model with Hypothesis 1 only, as Hypotheses 2 & 3 addresses managers' behavioral and cognitive biases. Such biases,

however, may lead managers to over-estimate or under-estimate the innovation value and cause type I and type II error. Further, a model with Hypotheses 4b through 7 added will even better prescribe the actual decision making of firms' innovation strategies. This is because by applying the real options perspective, managers can better judge the innovation value that includes the value of embedded growth opportunities, and overcome some of their behavioral biases.

These expectations are formalized in the following hypotheses:

Hypothesis 8:

The model that incorporates the current earnings, sunk cost and initial expectation of an innovation has greater explanatory power on the likelihood of abandonment than the model that considers the current earnings alone.

Hypothesis 9:

The model that incorporates the explorativeness, scope of application, knowledge depth and knowledge complementarity has greater explanatory power on the likelihood of innovation abandonment than the model that only considers the current earnings, sunk cost and initial expectation.

CHAPTER FOUR

METHODOLOGY

IV. 1. Research setting

This study is interested in the cross-sectional variation in firms' valuation of strategic investments and subsequent actions. The hypotheses pertain to the variation in innovation abandonment decisions, and the factors that explain that variation. Therefore the hypotheses entail the regressing of the likelihood of abandonment on the specified factors. I use patent data to test the hypotheses in the setting of the global chemical industry. The chemical industry is appropriate for study of firm innovation strategies for the following reasons. Technological development is critical to the performance of chemical firms, and firms in chemical industry proactively innovate to gain competitive advantage. Chemical firms tend to aggressively patent their innovations and their patents are regarded as effective and are widely and consistently used (Ahuja, 2000). Levin, Klevorick, Nelson and Winter (1987) showed that while in some businesses patents may not necessarily reflect a firm's technical knowledge and R&D activities, patents are an especially important source of technological advantage in the chemical industry. Thus, in this industry patents are a meaningful indicator of a firm's innovative output (Arundel & Kabla, 1998; Levin et al, 1987).

Patent data are widely used in management studies, as there are many advantages of using it. In addition to using patents as a measure of firm's innovative output, researchers also use patent data to measure firms' search behavior (e.g., Katila, 2002; Rosenkopf & Nerkar, 2001). Patents are directly and closely related to innovativeness; almost all major innovations are patented with very few exceptions. Patent data provides a rich source of information for specific innovation, including identifying the technology classification, the applicant, the inventor, and as well as providing indication of knowledge development. And the data availability adds to its attractiveness as a data

source. Patent data are readily available from national patent offices and other databases. Another important advantage of patent data is that it represents an externally validated measure of innovation (Griliches, 1990).

There are some well-documented limitations of the use of patent data (Cohen & Levin, 1989), however. For example, not all innovations are patented. Firms may differ in their propensity to patent their innovations (Cohen and Levin, 1989; Griliches, 1990), and this difference is more significant across industries than within. These problems can be solved by a research design limited to a single industrial sector in which patents are a meaningful indicator of innovation, as I have done here. By doing so, the researcher can control for inter-industry differences in patenting propensity as the factors that affect patenting propensity are likely to be stable within a specified intra-industry context (Basberg, 1987; Ahuja, 2000).

IV. 1. 1 Patents as real options that provide potential returns

Firms proactively engage themselves in creating new technological innovations in order to pursue competitive advantages. In many industries, firms resort to patent systems to protect and exploit their property rights to such innovations. Firms can exercise their patent rights in three ways: by litigating, licensing or leveraging (Teece, 1998).

Litigation is the enforcement of intellectual property rights. When the firm holding a patent finds that the patent has been infringed, the firm can litigate by suing the infringing firm for lost royalties and damages (Lanjouw & Schankerman, 2001; Somaya, 2003). Licensing, the second type of exercising a patent, is the partial sale of such intellectual property rights (Gallini & Wright, 1990). A firm can license its patents to

other firms for royalty payments, or cross-license the patent to other firms and receive in exchange the other firm's technology (Grindley & Teece, 1997). The third type of patent right, leveraging, is typically exercised through internal corporate venturing. Here the firm commercializes these patents by developing and introducing new or enhanced products into market on its own (Block & MacMillan, 1993).

Patents parallel stock call options in many ways. With a granted patent, a firm has the returns from current uses and the exclusive right to benefit from the patented technology in the specified period. While investors have the right to exercise stock options by trading the stocks at exercise price, firms have the exclusive right to exercise their patents rights through litigation, licensing or leveraging the innovated technologies into products and services. The investments that are needed to exercise the patent rights, i.e., to commercialize the patents, are analogous to the exercise price on the real option. The patent holding firm has the right, but not the obligation, to exercise these three patent rights. If the stock price does not exceed the exercise price, stock option holders will not exercise their options but simply let the options expire. Similarly, firms holding patents may choose to let the patents expire and abandon their patent rights, if they find that the patent entails inadequate current earnings and growth potential. I treat patents as real options in this study, consistent with prior research (e.g., Pakes, 1986; Teece, 1998; Nerkar, Paruchuri and Khaire, 2007).

It is appropriate to regard patents as real options for the following four reasons: First, there is significant uncertainty about the returns to the patented technology. The value of a patent is revealed over time. Researchers have found that most patents are of little value and only a small number of patents turn out to be very valuable. Although

firms apply for patents for those innovations they consider valuable, at the time of application they do not clearly recognize the total potential of these innovations. Therefore there is still substantial uncertainty about how much return the innovation can bring even if the patent is granted (Pakes, 1986).

Second, one important feature of an option is the asymmetric pay-off distribution to the investment: an option enables the holder to keep the upside potential but limit the downside risk to the fixed option price. This is also true for the distribution of potential returns to patents, which are asymmetric. Because holding a patent does not commit the firm to follow-on commercialization activities, a firm can limit the downside risk to the patent related fee and make decisions about commercialization later. Thus the firm acquires the right to obtain exclusive return that can be substantial but control the potential downside loss.

Third, related to asymmetric distribution of returns, the flexibility in subsequent decision making makes patents an appropriate context to apply the real options perspective. Firms do not have to decide from the beginning exactly how they are going to commercialize the patent. Rather, they collect updated information and make a series of decisions about whether they should keep the patent, and how they should make sequential investments into the commercialization.

Fourth, patents can be regarded as real options since patents can have significant upside potential that is not reflected in current earnings. A firm may be exercising some patent rights and produce earnings, but in addition to these earnings, it is likely that these patents may be used in other applications and lead to future growth. This upside growth potential can constitute a large portion of the value of the patented innovation, especially

when it is still in the early stage of technology development and there is still substantial uncertainty about the future use. Even a patent that currently does not yield cash inflow can still be highly valuable because it may be used in the future. Therefore, conceptualizing patents as real options can capture the embedded value in patents while traditional valuation approaches such as NPV tend to misjudge the real value of patents by ignoring the future growth opportunities.

The literature on firm innovation has seen studies that operationalized real options using patents. Pakes (1986) is among the first studies that see patents as firms' investment in R&D activities. Nerkar and his colleagues have conducted a series of studies that examine firms' innovation strategies by treating patents as options. McGrath and Nerkar (2004) considered a firm's second patent granted in a technological area as an option for the firm to enter that area. Nerkar and MacMillan (2004) considered patents real options that give the flexibility of deferment and provide potential competitive advantage and superior rents. Nerkar, Paruchuri and Khaire (2007) proposed that patents are options that give the holders the potential right but not the obligation to sue others. Li and Hesterly (2006) also used patents as options for firms to make follow-on investments.

Patent data offer a rare opportunity to examine firms' investment abandonment decisions. In many countries patents are protected for a specified period of time and it is required that patent holders renew their patents periodically after the grant until the statutory limit is reached (typically 15-20 years). At each renewal time, the firm will decide whether to renew their granted patents according to their judgment of the value of these patents. Either the assignee firm pays the maintenance fee and renews the patent, or it abandons the patent. The United State patent system, for example, usually protects

granted patents for 20 years. Since 1983, all US patents' assignees need to decide whether to renew the patent at the end of the 3.5th, 7.5th, 11.5th years following the grant. After the initial granting of the patent by the United States Patent and Trade Office, a maintenance fee of $890 is required after 3.5 years, $2050 after 7.5 years, and $3150 after 11.5 years (as shown in Figure 10)[1,2]. Other countries such as France, Germany and Britain have similar patent maintenance request (the European Patent Office requires annual patent renewal).

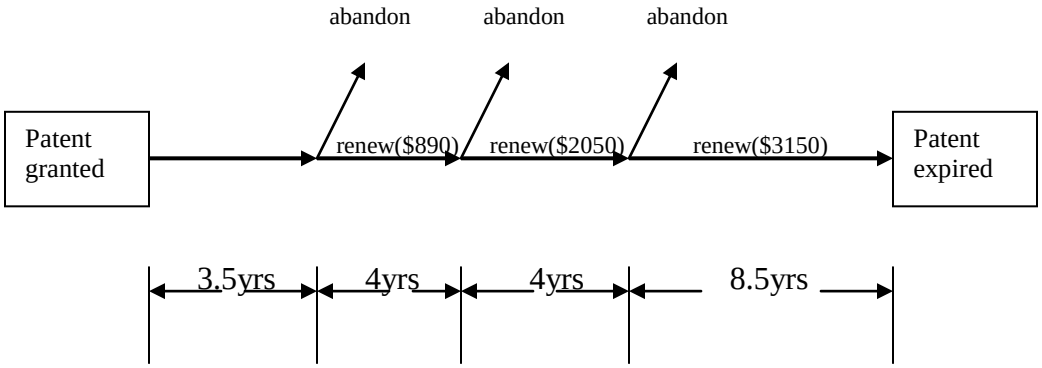

Figure 10: U.S. Patent renewal decision

If the firm decides that the patented innovation is yielding considerable current earnings or may lead to considerable growth opportunities, it is willing to pay the maintenance fee and keep the patent in force. If a firm, based on information at hand, decides that a patent has only quite limited value in terms of the sum of current earnings

[1] The owner of a US patent has an additional six month grace period to pay the fee. The patent rights expire after that unless reinstatement is granted. If a patent expires due to nonpayment of maintenance fee, the owner may petition the USPTO (United States Patent and Trademark Office) for consideration to reinstate the patent. Reinstatement may be granted if the firm can show that the failure to pay on time is unavoidable. If reinstatement is granted, however, the patent owner needs to pay the maintenance fee plus an additional surcharge for reinstatement. Reinstatement may also be granted if the late payment of maintenance fee is unintentional, with a surcharge much higher than if it is unavoidable.

[2] Effective December 8th 2004, the maintenance fee increases to $900 due at 3.5 years, $2300 due at 7.5 years, and $3800 due at 11.5 years.

and potential future returns, it simply does not pay the maintenance fee and just lets the patent expire. In other words, it abandons the patent and forgoes the embedded growth options. Whether the firm chooses to renew or abandon the patent is thus based upon both the current earnings and the growth option value of the patent.

If the firm renews a patent, the firm has the right to gain potential payoff from the patent during the next period of time but does not have further obligations. In addition, it gains the right to wait to decide whether to renew the patent later on. As information about the patent value is revealed over time, this waiting can have positive value. If a firm decides not to renew the patent, it abandons its exclusive right to the patented technology forever. As both the maintenance fee and the abandonment decision are irreversible, the firm needs to make the decision carefully. In this study, I do not try to explicitly calculate the option value. Rather, I study factors that impact the perceived value of the patents and examine how these factors are related to the patent abandonment decision.

Most patents are applied for in the early development phase. Because of the non-trivial maintenance fee, and the management of patented innovation involving human labor and financial costs, a firm will only keep those patents it highly values. Although it may be argued that the amount of maintenance fee is not significant so that firms may renew all their patents, the actual costs of maintaining patents may be much more significant than the maintenance fee. Lowe and Veloso (2004) argued that there may be significant organizational costs of maintaining patents such as monitoring and litigating and internal management costs. They suggested that firms' patent abandonment decision is a planned and structured process that involves attorneys, scientists and business

development. Previous research also shows that firms consistently abandon some of their patents. Schankerman and his colleagues found that more than half of all patents are voluntarily abandoned by nonpayment within ten years of the date of patent application (Schankerman and Pakes, 1986; Cornelli and Schankerman, 1999). Lanjouw (1998) made a similar observation. Pakes (1986) reported that fewer than 7% of patents are renewed for full term and that in Germany the proportion is around 11%. Econometric studies have confirmed that the patent renewal request influences the decision to patent and that firms held more valuable patents longer (Pakes, 1986; Schankerman and Pakes, 1986; Schanderman, 1998; Lanjouw, 1998). In this study I choose to examine the first renewal decision, where uncertainty about the total return is most significant. My focus is not the amount of renewal fees as hurdles but the conditions that lead to firms' abandonment decisions.

IV. 1. 2 Extant literature on patent abandonment

There are a limited number of preceding studies on patent abandonment and renewal in the literature. Most of them examine issues of policy effectiveness and are concerned with the improvement of social welfare. Cornelli and Schankerman (1999), for example, argued that differentiated patent lives can be better than a uniform patent life in terms of social welfare. They suggested that patent renewal fees can be an incentive device to implement a policy of optimally differentiated patent lives. Scotchmer (1999) also discussed optimal patent length, but concluded that the patent renewal system is not better than a uniform patent life. Some researchers use patent renewal data to operationalize patent value. Among them, Pakes and Schankerman (1984) were the first

to develop a deterministic model that uses patent renewal data to infer the value of patent protection. Since then other studies have also used patent renewal data to estimate the value of patent rights (Schankerman and Pakes, 1986; Sullivan, 1994; Pakes, 1986; Lanjouw, Pakes and Putnam, 1998; Schankerman, 1998). Pakes (1986), for example, suggested that because the value of patented innovations is very disperse and highly skewed, the use of a simple count of the number of patents either applied for or granted is a very noisy measure of innovation value. He argued that renewal data can be very helpful to measure the value of patents.

While the extant literature on patent renewal focuses on policy issues and patent value estimates, which are measurable after the renewal decisions are made, there is a lack of research on the patent renewal decisions themselves: how do firms decide whether to renew or abandon their patents? Which factors influence their decisions? Recent studies in strategic management start to examine these research questions and provide insightful thoughts. Nerkar and MacMillan (2004) examined firms' patent abandonment decisions by incorporating learning of the focal firms. Li and Hesterly (2006) proposed that different rent-seeking goals of firms impact their patent abandonment decisions. They found that at the industry level, firms focusing on Ricardian rents should have a greater tendency to continue R&D projects and delay abandonment decisions than firms focusing on Schumpeterian rents. Lowe and Veloso (2004) found that search of new knowledge influences patent renewal. These studies, however, are mostly limited to certain individual patent features and have not examined the impact of firm specific characteristics. Therefore further research on patent

abandonment is still needed to advance the understanding of the actual managerial decisions.

IV. 2. Data and Sample

I choose the U.S. patents of firms granted in year 1994 and year 1995 in the world chemical industry (4-digit SIC code 2800-2899) as the empirical setting of the study. The literature has often seen studies using real options theory to examine firms' R&D in the context of the chemical industry (e.g., Dixit and Pindyck, 1994; Trigeorgis, 1996). By choosing firms in one industry instead of multiple industries that vary in many aspects including technology, I avoid the substantial inter-industry differences. Meanwhile, I choose a relatively broad conceptualization of the industry by working at the 2-digit SIC level. By doing so, I am still studying firms that are similar in technological knowledge and related in term of R&D activities, which will improve the generalizability of the findings.

I use U.S. patent data for all firms to maintain consistency, reliability, and comparability, as patenting systems differ across nations (Ahuja, 2000). Doing so can ensure that the patents studied face largely the same institutional environment. I include the foreign firms in the sample to improve the generalizability of the findings. Firms that are based in countries other than United States also patent their innovations they consider important in the U.S.

I use the NBER patent database (Hall, Jaffe and Trajtenberg, 2001) and the United States Patent and Trademark Office (USPTO) public online database to collect

patent data for all the firms. I use "utility patents" only.[3] I use COMPUSTAT to collect data on firms' sales, cash, number of employees, and R&D expenditures. The unit of analysis in this dissertation is the individual patent renewal and the associated content of the patent, and the level of analysis is the firm.

The patent's grant date is used rather than the application date, as I am examining how factors at the time of the renewal decision impact the likelihood of abandoning the patent, and the abandonment decision has to be made certain years after the grant date not the application date. Because I am interested in the cross-sectional variation in investment valuation in this study, I examine patents that are granted in two years and control for the year. The reason to include two years' versus one year's patents in the sample is to have a sample of adequate size. By examining the abandonment decision of these patents, I control the time to expiration date, which is one of the factors determining option value in the Black-Sholes model. I choose to examine patents granted in year 1994 and year 1995 for the study. By choosing two years at least 13 years after the renewal system was installed, I avoid any problems that may have occurred in the initial set up of the system. Finally, the year 1995 is the most recent year that NBER has updated data that allows the empirical study to be conducted. The official published NBER patent data set include citation data made by patents granted in 1975-1999, which allows a four-year window of forward citation examination for patents granted up to the year of 1995.

I first identify firms in the 2-digit SIC code "28" that are traded in North America in year 1994 and year 1995 using COMPUSTAT, as firm performance and other factors

[3] Utility patents are any new and useful method, process, machine, device, manufacture, or composition of matter, or any new and useful improvement thereof. In my sample I exclude plant patents (with initial P), design patents (with initial D), reissued patents (with initial RE), reexaminations (with initial B) and other non-utility patent documents such as statutory invention registration (SIR, with initial H). For most firms, these non-utility patent documents account for a very small proportion of their total patent documents.

that are needed for the analysis require that data base. Then I used NBER database to check for patents from these firms that were granted in the year 1994 and 1995 and dropped firms that do not have successful patent applications in those two years. (This is because I am examining firms' patent abandonment decisions. Such firms do not need to choose between renewal and abandonment for any 1994 or 1995 patents four years later.)

The data include 7394 patents, of which 3805 patents are granted to 90 firms in year 1994 and 3589 patents granted to 90 firms in year 1995. After dropping observations with missing data (NBER data set does not have the variable of originality for some patents, and in COMPUSTAT the data of some firms' sales, R&D expenditure and/or cash are missing), the final data include 7000 patents, of which 3582 are granted in year 1994 to 85 firms and 3418 are granted in year 1995 to 83 firms. The 7000 patents belong to 91 firms from 5 countries: DNK (Denmark), GBR (Great Britain & N. Ireland), IRL (Ireland), NLD (Netherlands) and USA[4].

IV. 3. Measures

IV.3.1 Dependent variable

Patent abandonment

The dependent variable is whether a patent granted in year 1994 or 1995 is abandoned or renewed at the end of the fourth year after the initial grant. A dummy variable (*abandon*) is used: 1 if the patent is abandoned, 0 if renewed. I collect patent renewal information from the electronic official Gazette published weekly on USPTO website. In the Gazette USPTO gives notices of expiration of patents due to failure to pay

[4] While the firms belong to 5 countries, the first inventors of these 7000 patents are more scattered, located in 25 countries.

maintenance fee and any applicable surcharge. In addition, I also check the Errata and Erratum in the Gazette notices to incorporate the possible corrections announced by USPTO on patent expiration.

IV. 3.2 Independent variables

Current earnings

I use the non-self citations received by a patent from the grant date onward to 4 years later as a proxy for the current earnings on the patent (*nonselfcite*), taking into account the six month grace period. By non-self citations, I mean those received citations from U.S. patents that are granted to other assignees. Patents may receive citations from subsequent innovations patented by the same assignee (self-citations) and other unrelated assignees (non-self citations). While there is no accessible means of collecting information for a large sample study about the exact current earnings on a patent through litigation, licensing and internal leveraging, the forward non-self citations of the patent provide valuable information reflecting the current earnings of the patented innovation. Many patent studies have found that the number of forward citations a patent receives from subsequent patents is highly correlated with its technological impact as well as its social and economic value (e.g., Albert et al, 1991; Trajtenberg, 1990). For most patents, the bulk of their forward citations are received six years after grant (Jaffe et al, 1993). So when the first renewal decision has to be made, a firm still cannot precisely value the patent just by relying on the number of citations received (Nerkar and MacMillan, 2004). However, these citations reflect the likelihood that litigation may take place, the patent

may be licensed to other firms, and the holding firm may commercialize it into new products during the prior four years and into the future. Scholars have argued that self-citations and non-self citations have different meanings as the self-citations are related to a firm's prior endeavors (Sorenson and Stuart, 2000; Bogner and Bansal, 2007). Thus, the number of non-self citations received by the end of the four years can be used to proxy for of the patent's current earnings.

Explorative degree

To measure the explorative degree of a patent (*explore*), I use the measurement formula that Trajtenberg, Jaffe and Henderson (1997) developed to measure the originality of a patent.

$$(2) \quad Explore = 1 - \sum^{ni}{}_{j} S^2{}_{ij}$$

where S_{ij} *is* the percentage of citations made by patent i that belong to technology class j, out of the total number of technology classes *ni* that the patent cites. The more original a patent is, the more explorative it is.

Sunk cost

While the measure of current earnings (*nonselfcite*) described above uses citations received from subsequent U.S. patents granted to the focal firms, I use self-citations (*selfcite*) to proxy for sunk cost that is already invested in the deployment of the focal patent. It is difficult to accurately measure the resources firms have invested in each of their innovations for a large sample study. Furthermore, such information may be unavailable to researchers for business confidential reasons. The self-citations of a patent offer an opportunity to approximate sunk cost that is associated with the patented

innovation, as self-citations manifest the financial resources and other resources such as managerial attention and R&D efforts the firm has devoted to the focal innovation, and such resources once invested typically cannot be reversed. In addition, self-citations also signal the technological trajectory underlying the deployment of the innovation. They are, hence, a type of sunk cost related to the deployment of the focal patent, although not the sunk cost used to create the focal patent. When the first patent renewal decision is made only 4 years after the grant, higher sunk cost may make a firm tend to renew the patent to gain more time for more favorable signals to be revealed. I calculate the number of a patent's forward U.S. patent citations that belong to the same firm from the grant date onward to 4 years later.

Initial expectation

I proxy initial expectation of a patent's value with the number of claims a firm made according to the front page of the patent (*claims*). The inventor of a patented innovation makes claims on his or her innovation when applying for patent. These claims appear in their own section of the patent. Tong & Frame (1994) pointed out that during litigation proceedings, the claims made by the firm help to explain what is non-obvious and non-trivial. The number of claims of a patent reflects a firm's *a priori* perception of the usefulness and potential value of the patent.

Scope of application

I use the number of classes that the patent is assigned *(clsno)* by the USPTO to measure the scope of application of a patent. The more classes into which a patent is

classified, the more likely the patent can be applied broadly. Some researchers suggested that three-digit-level patent classes are too broad and that patent subclasses should be used (Thompson and Fox-Kean, 2005). However, other scholars have argued that class level classification is more reliable and can be used with greater confidence (Henderson, Jaffe, Trajtenberg, 2005). I follow the latter researchers because the subclass classification utilized in U.S. patent system is not nested thus using the number of subclasses can lead to biased conclusion. I collect this variable directly from the public website of USPTO.

Knowledge depth

I measure the knowledge depth of a firm in a technological area (*depth*) with backward citation data. This use of backward citations to measure firm knowledge is consistent with other studies that have used patent backward citations as a measure of knowledge held by a firm (e.g., Ahuja and Lampert, 2001). I define a technological area consistent with the U.S. patent classification, using patent class to represent a technological area. I look at all backward citations a firm's patents make, and calculate how many times the firm cites patents in a patent class. The more a firm cites from a patent class, the more it accumulates insight and knowledge in this technological area (Katila, 2002). Although there are studies using patent backward citations to measure a firm's knowledge, to my knowledge this measurement of a firm's knowledge depth using backward patent citation is new. I collect backward citation data for a five year period (1989-1993 for patents granted in 1994, and 1990-1994 for patents granted in 1995) to capture the bulk of the firm's knowledge accumulation. This five year window is used

rather than the entire patent stock of the firm because technological knowledge experiences loss with time. The use of a five year window is consistent with prior studies such as Fleming (2001) and Ahuja & Katila (2001). This measure is natural-log transformed to reduce the skewness of the data.

Knowledge complementarity

The knowledge complementarity between a technological area and a firm's other technological areas (*comple*) is measured using the citations the patents in one class made to and received from the patents in the other classes in which the firm has patents granted. The past citations between technological areas imply the degree to which value can be created by combining the knowledge from those areas. Fleming and Sorenson (2001) suggested that some technological areas are more linked to each other than other areas and combining knowledge components from these areas are more likely to lead to valuable solutions. Based on that logic, I operationalize the measure of knowledge complementarity by using the entire U.S. patent history in the period year 1975 through 1998, and using the following formula:

$$comple = \sum^{j} (cite_{ij} + cite_{ji}), \qquad (3)$$

where i represents the primary class the focal patent is in, j is the number of the firm's other patent classes, $cite_{ij}$ is the number of patents in class i that cite patents in class j, and $cite_{ji}$ is the number of citations that patents in class i receive from patents in class j. The patent history before year 1975 is not used as NBER data does not include patent citation information prior that year. This, however, should not be a problem as 24 years' patent history should capture the bulk of interdependencies between technological areas,

especially when knowledge loss is considered. The information up to year 1998 is used because it is the complementarity information prior to patent renewal decision that may be used by firms to facilitate their abandonment versus renewal decisions. To reduce data skewness, the measure is also natural-log transformed. If a firm does not have patents granted in any other class, this measure is given the value of 0. This measurement of knowledge complementarity using patent backward citations is unique. Although the literature has addressed knowledge complementarity, especially the alliance literature, many studies have coarsely operationalized it. Some studies used qualitative questionnaires to quantify it, which may provide valuable insight as to managers' judgment. However, quantification of objective data is still needed to corroborate the observation from questionnaires completed by managers. Plus, it is not feasible to get managers' perception of knowledge complementarity for many refined technological classes through survey for a large sample empirical study.

IV.3.3 Controls

Firm size

Firm size is controlled using a firm's annual sales (*sales*) (in millions). I lag this variable by one year. The variable is natural-log transformed.

Financial resources availability

I control the financial resources availability of a firm by measuring its free cash flow (*cash*). This variable is also lagged by one year and naturally logged. I expect a positive impact of this variable on patent renewal. The more financial resources are

available, the more likely a firm is to renew its patents, all other things equal. As expected, preliminary analysis finds that firms' *sales* is highly correlated with firms' *cash*. The correlation between these two variables in the sample is as high as 0.8019 and is highly significant. Including both variables in a regression model could lead to a multicollinearity problem. To tackle this issue, I regress the cash measure on sales and obtain a new variable *orthcash*, which equals to the residual of the regression. This new variable is orthogonal to sales and used as the cash measure in the regression models.

Firm nationality

There are country differences that may affect a firm's patent abandon decisions. I use a dummy variable to indicate whether a firm is from US or other countries (*d_us*). A patent in the U.S. may be more important for a U.S. firm than a foreign based firm.

Pharmaceutical firm or not

Pharmaceutical firms may be biased toward keeping more of their patents granted than other types of firm do due to the extremely heavy investment in R&D and the long time required for R&D activities in this industry. I use a dummy variable (*d_drug*) to control whether the firm is in the four-digit SIC 2834 pharmaceutical industry, 1 if yes, 0 otherwise.

Innovation orientation

I measure a firm's innovation orientation using its R&D intensity (*rnd_int*), calculated as the firm's R&D spending over the firm's sales. I expect that the more a firm

is innovation oriented, the more it builds competitive advantage on innovativeness, so it may be more likely to keep its patents in force.

Diversification

I control for firm diversification using the number of 4-digit SIC segments it reports sales in COMPUSTAT (*seg_no*). I expect that diversification positively impacts a firm's likelihood to renew its patents as it may possibly apply the innovations in multiple businesses.

Year dummy

As the sample include patents granted in year 1994 and 1995, I control for the grant year by having a year dummy (*d_1995*). By doing so, I eliminate the possible heterogeneity due to any undetected systematic differences between patents granted in the two years.

IV. 4. Model specification

Logistic analysis is used to examine how the independent variables and the control variables impact the likelihood a patent will be abandoned. The model is specified as follows (showing dependent variable and independent variables only):

$$Logit(abandon)=\beta_1 * nonselfcite + \beta_2 * selfcite + \beta_3 * claims + \beta_4 * explore + \beta_5 * clsno + \beta_6 * depth + \beta_7 * comple + \sigma \quad (4)$$

As the 7000 patents in the sample belong to 90 firms, regressions of patents renewal without controlling for unobserved firm heterogeneity will produce biased findings. One possible consequence is that the regressions may artificially increase the statistical significance level of the estimates of coefficient. To deal with this concern, I cluster by firm when I run the logistic regressions. Doing so allows me to isolate the patent abandonment likelihood from unobserved firm effects that could bias the estimation.

CHAPTER FIVE

RESULTS

Unless otherwise noted, all the patent related information is from the NBER database. I use multiple data files in the NBER data set: *PAT63_99*, which is the main NBER data set that includes all the utility patents granted from year 1963 through year 1999; *CITE75_99*, the citations file, which includes all citations made by patents granted in 1975-1999; and the *Compustat* file, which contains the patent assignee information and thus allows one to match and link out patents with firm data available in the Compustat data base. I use SAS to merge these data and calculate all the independent variables except for *clsno*, which is collected from the USPTO website. Then I merge these variables with firm level data from Compustat and derive the control variables. After the data merging with *SAS* code of more than twenty pages, I run the data analysis using logistic regressions with *STATA logit* routine.

V. 1. Descriptive Statistics

Table 3 shows the descriptive statistics for all the variables and Table 4 gives the correlation matrix. While the regressions only use *orthcash* but not *cash*, I include *sale* in the descriptive statistics table in order to illustrate the original firm slack resource information.

Table 3

Descriptive Statistics

	Variable	Observation	Mean	Std. Dev.	Min	Max
1.	abandon	7000	0.1267143	0.3326764	0	1
2.	nonselfcite	7000	1.751143	3.159622	0	50
3.	selfcite	7000	0.9338571	3.100276	0	50
4.	claims	7000	13.44657	10.23448	1	134
5.	explore	7000	0.4504804	0.2735831	0	0.9091
6.	clsno	7000	1.961429	1.080922	1	8
7.	depth	7000	4.082262	2.081432	0	7.364547
8.	comple	7000	7.302482	2.443513	0.6931472	12.10537
9.	sale	7000	8.670805	1.446928	0.0723207	10.43817
10.	cash	7000	5.54363	1.519965	0.1475576	7.792349
11.	orthcash	7000	-4.94E-09	0.9079949	-3.417985	2.953134
12.	rnd_int	7000	0.0177293	0.0258944	0.0006946	0.5356074
13.	seg_no	7000	2.824143	1.626001	1	6

Table 4

Correlations

Variable	abandon	nonselfcite	selfcite	claims	explore	clsno	depth	comple	sale	orthcash	rnd_int	seg_no
abandon	1											
nonselfcite	-0.0541 **	1										
selfcite	-0.0444 **	0.1404 **	1									
claims	-0.0547 **	0.1329 **	0.1006 **	1								
explore	-0.0346 **	0.0271 **	0.023 *	0.061 **	1							
clsno	0.0358 **	0.0075	0.0377 **	0.0533 **	0.1958 **	1						
depth	0.0288 **	0.056 **	0.0893 **	0.0087	-0.1413 **	-0.0667 **	1					
comple	-0.0406 **	0.044 **	0.0505 **	0.0039	-0.0766 **	-0.0049	0.5755 **	1				
sale	0.038 **	0.0113	-0.0182	-0.0611 **	-0.0146	-0.0542 **	0.3429 **	0.1971 **	1			
orthcash	-0.0305 **	0.0381 **	0.104 **	-0.0021	-0.0659 **	0.0399 **	0.1445 **	0.0615 **	0	1		
rnd_int	-0.0093	0.0025	0.0013	-0.0069	-0.0652 **	0.0742 **	-0.0489 **	-0.0377 **	-0.3093 **	0.2204 **	1	
seg_no	-0.0132	-0.0084	-0.0335 **	-0.0041	0.0348 **	-0.0637 **	0.1816 **	0.0561 **	0.6431 **	-0.0883 **	-0.2239 **	1

n = 7000 patents

** p<.05

* p<.1

Table 4 provides the correlation matrix for all the variables. It shows that the highest correlation between any two of the independent variables is r= 0.5755 between knowledge depth (*depth*) and complementarity (*comple*), and the highest correlation between any variables is r= 0.6431 between two control variables of firm size (*sale*) and diversification (*seg_no*). All the other correlations are below 0.35. This level of correlation indicates that problems of multicollinearity are unlikely to be manifested in the data. Moreover, the table also shows a low level of correlation between the measures of patent level characteristics: current earnings (*nonselfcite*), sunk cost (*selfcite*), initial expectation (*claims*), and scope of application (*clsno*). This low correlation also suggests that these measures capture distinctive dimensions of the value of a patent. To further check whether there is multicollinearity issue with the variables, I calculate the VIF (Variance Inflation Factor) of independent variables and control variables. Table 5 reports the VIF of these variables. The result shows that the data conform to the non-multicollinearity assumption: the highest VIF is 2.01 and the mean VIF for all the variables is only 1.32, both much lower than the generally accepted cut off value of 10 (Kutner, Nachtsheim, Neter, 2004).

Table 5
Variance Inflation Factors

Variable	VIF	1/VIF
sale	2.01	0.496677
seg_no	1.75	0.570194
depth	1.7	0.586546
comple	1.51	0.662691
rnd_int	1.18	0.846977
orthcash	1.1	0.905669
original	1.08	0.929488
clsno	1.06	0.944926
selfcite	1.05	0.954439
nonselfcite	1.04	0.96247
claims	1.04	0.963427
Mean VIF	1.32	

V. 2. Hypotheses Testing

Table 6 presents results of the logistic regression models of abandonment likelihood. I provide seven models. All seven models are significant. All the models with independent variable(s) have chi square above 24, and are highly significant ($p < 0.0018$ for Model 2, $p < 0.0000$ for all the other Models with independent variable(s)). Model 1 in Table 6 is the base model that comprises only the control variables. Model 2 adds the variable for Hypothesis 1, current earnings. Model 3 contains the predictor variables for Hypotheses 2 and 3, sunk cost and initial expectation. Model 4 includes the predictor variables of uncertainty, scope of application, knowledge depth and knowledge complementarity. Model 5 and 6 are the nested models of Model 2 & 3, and Model 2 & 4

respectively. Model 7 is the full model that includes all the independent variables and control variables to test the impact on patent abandonment likelihood.

Table 6

Logistic Regression Models of Abandonment Likelihood

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Nonself citations		−0.0748 ***			−0.0604 **	−0.0729 ***	−0.0587 **
		0.0269			0.0257	0.0265	0.0253
Self citations			−0.0821		−0.0703		−0.0727 *
			0.0521		0.0489		0.0435
Number of claims			−0.0161 ***		−0.0140 **		−0.0149 ***
			0.0062		0.0058		0.0057
Explorativeness				−0.4585 **		−0.4226 **	−0.3900 *
				0.2239		0.2150	0.2119
Number of patent classes				0.1360 ***		0.1351 ***	0.1431 ***
				0.0479		0.0478	0.0481
Knowledge depth				0.1237 ****		0.1280 ****	0.1394 ****
				0.0383		0.0380	0.0383
Knowledge complementarity				−0.1276 ****		−0.1253 ****	−0.1243 ****
				0.0301		0.0301	0.0299
Firm size (sale)	0.2345	0.2447	0.2285	0.2272	0.2363	0.2332	0.2176
	0.1574	0.1574	0.1561	0.1439	0.1566	0.1438	0.1430
Cash	−0.1166	−0.1114	−0.0974	−0.1344	−0.0966	−0.1303	−0.1181
	0.1342	0.1348	0.1363	0.1250	0.1364	0.1253	0.1268
R&D intensity	1.4928	1.4153	1.1792	0.8747	1.1506	0.7746	0.4659
	2.5875	2.5602	2.5592	2.6811	2.5463	2.6553	2.6354
Diversification	−0.1711	−0.1797	−0.1726	−0.1845	−0.1789	−0.1921	−0.1905
	0.1401	0.1370	0.1368	0.1337	0.1350	0.1309	0.1296
US firms	−0.7191 **	−0.7186 **	−0.6867 **	−0.6850 **	−0.6912 **	−0.6968 ***	−0.6805 ***
	0.2903	0.2820	0.2789	0.2715	0.2728	0.2618	0.2540
Drug firms	−0.2186	−0.2268	−0.2386	−0.2633	−0.2379	−0.2707	−0.2789
	0.3535	0.3424	0.3581	0.3368	0.3485	0.3261	0.3312
Year 1995	0.0518	−0.0004	0.0413	0.0562	0.0015	0.0047	0.0058
	0.1072	0.1080	0.1057	0.1048	0.1070	0.1057	0.1054
Constant	−2.7907 **	−2.7121 **	−2.4841 **	−2.3678 **	−2.4525 **	−2.2947 **	−2.0352 *
	1.1747	1.1630	1.1607	1.0771	1.1542	1.0651	1.0493
Chi square	15.04 **	24.56 ***	71.99 ****	47.04 ****	75.01 ****	50.41	128.69 ****
Log likelihood	−2632.98	−2619.88	−2614.93	−2598.81	−2606.77	−2586.49	−2572.18
Log likelyhood improvement vs. the base model		13.1	18.05	34.17	26.21	46.49	60.8

Note: The table gives parameter estimates; the robust standard error is below each parameter estimate.

**** $p < 0.001$

*** $p < 0.01$

** $p < 0.05$

* $p < 0.10$

Model 1 tests the effects of control variables on the likelihood to abandon a patent. Only the country dummy variable is significant, having a negative effect on abandonment likelihood, suggesting that patents belonging to U.S. firms are much more likely to be renewed. This finding is consistent with prior studies (Lowe & Veloso, 2004) and makes intuitive sense as technological innovations patented in U.S. are more important for U.S. firms than for foreign based firms. All the other control variables do not have significant impact on patent abandonment (after clustering by firms). These effects of control variables largely remain in the subsequent models.

Hypothesis1 predicts a negative relationship between current earnings and the abandonment likelihood. In Model 2, the coefficient for the non-self citations is negative and significant, supporting the hypothesis. This estimation is consistent in Model 5 through 7 (in the full Model, $\beta_{nonselfcite} = -0.0587$, $p < 0.05$), offering strong support for Hypothesis 1. This finding is consistent with findings from prior research (Nerkar & MacMillan, 2004).

Hypothesis 2 predicts that sunk cost reduces abandonment likelihood. The coefficient for the self-citations in Model 3 and Model 5 are negative but not significant. In the full model, the coefficient for self-citations is negative and significant at $p < 0.1$ ($p < 0.95$, very close to the non-significant level). Thus hypothesis 2 only receives partial support. This finding is slightly different from prior research. Nerkar & MacMillan (2004), for example, found a strong negative relationship between self-citations and patent abandonment ($p < 0.01$ in all their models). Li & Hesterly (2004) also found that

firms tend to keep patents with high percentage of self-citations for a longer period of time than those patents with low percentage of self-citations.

Hypothesis 3 predicts that initial expectation will negatively impact the patent abandonment likelihood. The parameter coefficient for claims is significantly negative in Model 3 at $p< 0.01$ and Model 5 at $p< 0.05$, and also the full model at $p< 0.001$. This result offers strong support for Hypothesis 3. This finding is consistent with Li & Hesterly (2004), who found that the number of claims of a patent delay the abandonment timing.

Hypothesis 4 regards the impact of innovation explorativeness on patent abandonment. While the behavioral theory of firm predicts a positive impact on patent abandonment likelihood (Hypothesis 4a), real options theory predicts the opposite relationship (Hypothesis 4b). In all the Models that contain this variable, i.e., Model 4, Model 6 and Model 7, the parameter coefficient for explorativeness is negatively significant. In the full model, $\beta_{explore} = -0.39$, at $p< 0.1$. These results offer strong support for the hypothesis from the real options perspective (H 4b) but not for the hypothesis based on the behavioral theory of the firm (H 4a).

Hypothesis 5a proposes that the scope of application for a patent reduces the abandonment likelihood thus a negative coefficient for the number of classes is expected, and Hypothesis 5b predicts the relationship to be of an opposite sign. Contrary to Hypothesis 5a expectation, the parameter coefficient for this variable is significant but has the opposite sign: it is positive at a highly significant level in all the models that include this variable. In the full model, for example, $\beta_{clsno}= 0.1431$ at $p< 0.01$. Thus Hypothesis 5b receives support but not Hypothesis 5a. This finding is also only partially

consistent with prior studies. Nerkar & MacMillan (2004), for example, found that the scope of a patent is not significantly associated with patent abandonment likelihood.

Hypothesis 6 predicts that a firm's knowledge depth in a technological area decreases the likelihood that patents in that area will be abandoned. Thus a negative coefficient for knowledge depth is expected. Contrary to this expectation, knowledge depth is significant but has the opposite sign: the parameter coefficient for knowledge depth in all the models that contain this variable (Model 4, Model 6, and Model 7) is positive at a highly significant level, i.e., $p< 0.001$. In the full model, $\beta_{depth}= 0.1394$. This result suggests that, the more a firm develops knowledge in a technological area, the more likely the firm tend to abandon rather than renew its patents in that area.

Hypothesis 7 proposes that the higher the knowledge complementarity between a technological area and a firm's other technological areas, the less likely the innovations in that technological area will be abandoned. Consistent with this expectation, the coefficient for knowledge complementarity in all the models that include this predictor variable (Model 4, Model 6, and Model 7) is negative and highly significant. In Model 7, $\beta_{comple} = 0.1243$ at $p< 0.001$. The result provides strong support for this hypothesis.

I use the Wald test, which approximates the likelihood ratio test, to examine the improvement in explanatory power for nested models. Model 2 is enhanced over Model 1, (likelihood improvement = 13.10, chi square= 7.70, $p< 0.01$), suggesting that including the number of non-self citations as a predictor variable significantly improves the explanatory power with the control variables only. Similarly, Model 3 and Model 4 also have obtained enhanced explanatory power over the base model (Model 1) by including the predictor variables based on the behavioral theory and real options theory (likelihood

improvement = 18.05, chi square= 19.03, p< 0.0001; likelihood improvement = 34.17, chi square= 32.81, p< 0.0000). Hypotheses 8 and 9 regard the model fit and improvement when the behavioral theory of the firm and the real options perspective are considered. Hypothesis 8 proposes that adding the effect of sunk cost and initial expectation, we can better predict the likelihood that an innovation will be abandoned. Hypothesis 9 suggests that the incorporation of the explorativeness, scope of application, knowledge depth and knowledge complementarity can further improve the model fit for innovation abandonment likelihood. Model 5 is nested within Model 1 and tests Hypothesis 8. The Wald test result shows that this model has significantly enhanced explanatory power over Model 2 by introducing the variables from the behavioral theory (self-citations and number of claims) (likelihood improvement = 13.11, chi square= 16.79, p< 0.001). This result thus provides support for Hypothesis 8. Model 7 is nested within Model 5 and tests Hypothesis 9. The Wald test result shows that this full model has obtained explanatory power over Model 5 by further introducing the variables from real options theory (explorativenss, number of classes, knowledge depth and complementarity) (likelihood improvement = 34.59, chi square= 34.47, p< 0.001). This result offers support for Hypothesis 9.

I also examine a model with predictor variables based on NPV and real options theory, Model 6, which is nested with Model 2. Compared to Model 2, this model is of better fit (likelihood improvement = 33.39, chi square= 2.26, p< 0.000), suggesting that considering the effect of variables based on real options theory enhances the explanatory power on abandonment likelihood than the model with NPV variable only.

Comparing all the models conducted, Model 7 (the full model) has the greatest likelihood improvement and explanatory power as shown by the Wald test. Therefore, it is the best-fit model.

Table 7 presents the results for Model 7 with odds ratios reported.

Table 7

Results for Logistic Regression on Abandonment Likelihood

(Model 7 Odds Ratios Reported)

	Odds Ratio		Robust Std. Err.	[95% Conf.	Interval]
nonselfcite	0.9429847	**	0.0238907	0.8973033	0.9909916
selfcite	0.9298793	*	0.0404372	0.8539075	1.01261
claims	0.9851839	***	0.0056297	0.9742114	0.9962798
explore	0.6770455	*	0.1434513	0.446958	1.025579
clsno	1.153852	***	0.0554638	1.050109	1.267844
depth	1.149625	****	0.043978	1.066582	1.239134
comple	0.8831327	****	0.0263631	0.8329445	0.936345
sale	1.243063		0.1778046	0.93916	1.645307
orthcash	0.8885819		0.1126731	0.6930495	1.139281
rnd_int	1.593467		4.19945	0.0091007	279.006
seg_no	0.8265812		0.1071394	0.6411429	1.065654
d_us	0.5063418	**	0.128592	0.3078012	0.8329469
d_drug	0.7565967		0.2505842	0.3953186	1.448044
d_1995	1.005787		0.1059977	0.8180878	1.236552

Note:
******p< .0001**
*****p< .001**
****p< .05**
***p< .10**

To acquire more intuitive explanations of the implications of the parameter coefficient estimation, I also calculated the marginal effects on the probabilities of the independent variables of the full model. By using the *Stata* command of mfx, those

marginal effects in the probabilities are calculated when the dependent variable is at its mean value. Table 8 reports the marginal effects on the patent abandonment probabilities of the predictor variables.

Table 8
Marginal Effects on Abandonment Likelihood

Variable	dy/dx	Std. Err.	z	P>|z|	[95%	C.I.]
nonselfcite	-0.0060152	0.0027	-2.22	0.026	-0.011314	-0.000716
selfcite	-0.0074492	0.00437	-1.71	0.088	-0.016008	0.00111
claims	-0.0015295	0.00063	-2.45	0.014	-0.002755	-0.000304
explore	-0.0399628	0.022	-1.82	0.069	-0.083089	0.003163
clsno	0.0146632	0.00444	3.3	0.001	0.005967	0.02336
depth	0.0142872	0.00431	3.32	0.001	0.005841	0.022733
comple	-0.0127342	0.00267	-4.77	0.000	-0.017963	-0.007506
sale	0.022294	0.01543	1.45	0.148	-0.007945	0.052533
orthcash	-0.0121039	0.01271	-0.95	0.341	-0.037011	0.012803
rnd_int	0.0477394	0.27013	0.18	0.86	-0.481703	0.577182
seg_no	-0.019515	0.01392	-1.4	0.161	-0.046794	0.007764
d_us*	-0.0888401	0.03766	-2.36	0.018	-0.162657	-0.015023
d_drug*	-0.0274631	0.03165	-0.87	0.386	-0.089496	0.03457
d_1995*	0.0005913	0.01079	0.05	0.956	-0.02055	0.021733

Note:
1. Marginal effects after logit
   y = Pr(abandon) (predict)
   = .11589616
2. (*) dy/dx is for discrete change of dummy variable from 0 to 1

This table suggests that when the dependent variable (abandonment likelihood) is at its mean value, an additional non-self citation reduces the likelihood to abandon the patent by 0.60% (i.e., it is 0.60% more likely to be renewed); an additional self-citation reduces the abandonment likelihood by 0.74%; an additional claim decreases the abandonment likelihood by 0.15%; an additional unit of originality reduces the likelihood

that the patent will be abandoned by 0.39%; an additional number of class the patent is classified into boosts the abandonment likelihood by 1.47%; an additional unit of knowledge depth increases the abandonment likelihood by 1.43%; and an additional unit of knowledge complementarity increases the renewal likelihood by 1.27%. If a patent belongs to a U.S. firm, it is 8.88% more likely to be renewed than if it belongs to a foreign based firm.

Table 9 provides a summary of the hypotheses testing results.

Table 9

Summary of Hypotheses Test Result

Independent variable	Predicted impact on abandonment likelihood	Theory	Findings
current earnings	-	Economic, Real option	support
sunk cost	-	Behavioral	partial support
initial expectation	-	Behavioral	support
explorativeness	+	Behavioral	no support
	-	Real option	support
scope of application	-	Real option	no support
	+	Behavioral	support
knowledge depth	-	Real option	opposite sign (+)
knowledge complementarity	-	Real option	support
model fit improved by incorporating behavioral theory			support
model fit further improved by incorporating real otpions theory			support

CHAPTER SIX

DISCUSSION

The principal purposes of this research are to explore whether firms make abandonment decisions in accordance with real options theory, and the relative strength of the traditional economic theory, the behavioral theory of the firm and real options theory in explaining firms' abandonment decisions. I developed and tested a set of hypotheses in the context of firms' decision making concerning innovation abandonment. The results from the empirical analyses provide evidence that taking a real options perspective improves the explanatory power of firms' investment abandonment decisions and thus increases our ability to understand as well as predict such managerial decisions. My study suggests that, 1) firms' actual innovation abandonment decisions are consistent with the predictions made from real options theory; and 2) a real options perspective provides better explanation of firms' abandonment decisions than traditional economic theory and the behavioral theory of the firm.

Research has shown that competitive success often requires firms to make abandonment decisions in a timely manner. However, traditional approaches to decision making are not adequate to help firms make abandonment decisions: conventional NPV models tend to undervalue investments and thus lead to premature terminations of projects that have positive potential; in addition, behavioral biases introduce noise into the firms' investment valuation process and thus their abandonment decisions. As a result, organizations sometimes make abandonment decisions that appear inappropriate. Many studies in the past few decades have looked for evidence and the cause of inappropriate abandonment decisions. However, relatively few studies have examined how firms can

eliminate the biases in making their abandonment decisions and improve such decisions. The traditional economic theory is normative, but unrealistic to use given the many complications and limitations in actual managerial decision making. The behavioral theory is descriptive in describing what is actually occurring, but does not provide insight into what should be done. In this dissertation I suggest that real options theory may be used to enhance our understanding of firms' actual abandonment decisions. While my findings show that real options theory offers better explanatory power of firms' actual abandonment decisions, they lead us to the next critical step for future research: what is the prescriptive potential of this theory in enhancing managerial decision making?

VI. 1. Three theories as reflected in the data

The empirical results show that all three theories, traditional economic theory, the behavioral theory of the firm and real options theory are reflected in the data. Hypothesis 1, which is based on traditional economic logic and consistent with real options theory, receives support, suggesting that firms do consider the current earnings from assets in place. But this predictor variable does not dominate the decision making of abandonment. Hypotheses 2, 3 and 5b also receive support, suggesting that the behavioral theory of the firm perspective is reflected in the data and we can conclude that managers exhibit behavioral biases in abandonment decisions. More specifically, the logistic regression results suggest that, all things being equal, higher initial expectations and sunk costs both make a firm tend to continue the investment. Regarding the impact of uncertainty, Hypothesis 4b based on real options theory receives strong support, but not Hypothesis 4a, which is based on behavioral theory. This suggests that firms do not exhibit the

uncertainty avoidance bias as predicted by the behavioral theory of the firm in their abandonment decisions, at least in the context of patented innovation renewal. Firms value the explorativeness thus the uncertainty of innovations rather than simply trying to circumvent it by giving little chance to innovations that carry high levels of uncertainty. We can conclude that adopting a real options perspective may help firms eliminate this uncertainty avoidance bias. Hypotheses 4b through 7 except 5b are based on real options theory. The results show evidence that a real options perspective is reflected in managerial decision making for abandonment decisions: in addition to the current earnings of the investment, firms also consider the growth option value embedded in the investment. More specifically, results suggest that the explorativeness and technological scope of innovations, and the firm's knowledge portfolio are associated with the firm's innovation abandonment decisions.

As traditional NPV models cannot capture the value of embedded future growth opportunities, the NPV models are conservative in the valuation of investments, especially those with high levels of uncertainty. Firms that rely on such models to evaluate their investments and make investment decisions accordingly inevitably fall into the trap of underestimating their strategic investments. As a result, such firms do not invest enough in growth opportunities that are explorative thus uncertain but with high potential in the future as they should (Kougut and Kulatilaka, 1994). The real options reasoning, however, can recapture some value lost through the NPV valuation by adding in the value of growth options. The NPV valuation captures a base estimate of value of assets that are currently in place, and the option valuation adds in the value of the right to decide whether to pursue investment opportunities in the future. Therefore, taking a real

options perspective may help firms to be more willing to invest in explorative activities. The empirical data indicate that in the actual decision making of firms, managers consider factors beyond the NPV valuation models. This suggests that real options theory can help explain why firms sometimes pursue exploration activities, which cannot be fully explained with the NPV models.

The results suggest that firms exhibit behavioral biases due to insufficient adjusting and sunk cost. The data show that firms are not prone to abandoning innovations that carry high levels of uncertainty, in accord with the real options perspective. In the full model, the biases due to initial expectation and sunk cost are still present. However, the impact of sunk cost is at a relatively low level of significance and is significant in only one model, although very close to the 0.1 significance level in the other models. This suggests that firms exhibit only some of the behavioral biases in abandonment decisions.

An important result of the study lies in testing the relative strength of each model in predicting decision outcomes. It is important to note that this study does not propose real options theory as a replacement of either traditional investment valuation models such as NPV or behavioral theories as explanations for abandonment decisions. Rather, a real options approach provides a complementary perspective, taking into consideration of uncertainty, information asymmetry and path dependency. The comparison between the model based on NPV only and the model based on both NPV and the behavioral theory of the firm supports Hypothesis 8, showing that these two theoretical perspectives are not mutually exclusive to each other. The enhanced model fit suggests that the incorporation of the behavioral theory improves the explanatory power of firms' abandonment

decisions over the conventional NPV model. Hypothesis 9, which further compares the model based on NPV and behavioral theory and the model that incorporates all three theoretical perspectives, is also confirmed, suggesting that taking a real options perspective further improves the explanatory power. In addition, further comparison of the model that only contains predictor variables based on real options theory and models that also incorporate current earnings from NPV and the full model shows that the full model provides the "best-fit" model.

What is particularly interesting is that managers seem to behave according to all three theories. The results suggest that when making abandonment decisions, firms consider the current earnings as suggested by NPV models, exhibit some behavioral biases, and also utilize real option reasoning. Taking a real options perspective does not eliminate or lessen the significance of the other two theories (with the exception that firms value innovation explorativenss in accord with real options theory instead of circumventing explorativeness as predicted from behavioral theory). This shows that real options theory is not exclusive to the traditional economic logic or behavioral theory. Rather, the finding that the full model offers the best fit suggests that real options theory can act as a framework that ties together the other two theories. By taking the real options perspective and incorporating the other theories, we can have a better model to predict firms' strategic abandonment decisions.

The findings of this dissertation also confirm an argument that has recently captured academic attention in real option studies: firms manage a portfolio of real options, which may interact with each other and thus should not be evaluated in isolation (Vassolo et al, 2004; Anand et. al, 2006). In these studies, Vassolo, Anand and their co-

authors show that under different conditions multiple options can be sub-additive or super-additive. In this research, I also find that a firm's knowledge depth and knowledge complementarity significantly impact its patent abandonment decisions. This finding provides support that a firm's options are not independent from each other; therefore the valuation of its investments should consider the path dependent accumulation of resources and capabilities. Otherwise, investment decisions made based on isolated valuation will lead to overinvestment or underinvestment by ignoring the interrelations among investments.

It is important to note that in the context of strategic management, real options theory should be viewed as a decision tool rather than a valuation tool that is used to precisely estimate the value of investments. Unlike the well-defined financial options, the option pricing models such as the Black-Scholes Model cannot readily be used on complex business projects. It is impossible to get the exact risk and opportunities profile for strategic options on real assets. It can be extremely hard to find appropriate values for the input variables. MacMillan (2006) pointed out that for sequential investments such as firms' R&D, the value of a sequence of options is not strictly additive. In addition, the financial option pricing models do not differentiate the uncertainty source. For example, financial option pricing models including the Black-Scholes Model suggest that higher uncertainty means higher option value. For real options, however, the uncertainty from the side of costs will penalize rather than add to the growth option value (MacMillan et al, 2006). Therefore, when managers adopt a real options perspective and use real options reasoning to facilitate managerial decision making, they cannot use option pricing models mindlessly.

Fortunately, though it is impossible to apply straightforward option pricing models to calculate the exact value of a strategic investment, firms often do not need to have a precise valuation for a specific project. As Putten & MacMillan (2004) pointed out, "Simple and quick is what's needed for most valuations…". Often the relative valuation of the firm's investments is what managers need to know. Porter (1996) has noted that "Strategy is making trade-offs in competing." By comparing the valuation of multiple investment projects that compete for the firm's limited resources, managers are able to decide whether a given investment opportunity is preferable to other investment opportunities. Then they make investment decisions and allocate resources accordingly. As strategy is about resource allocation under conditions in which the resulting performance is not clear, real options theory can provide a very insightful perspective.

VI. 2. Two significant results opposite to real option prediction

Two significant opposite results deserve further discussion. First is the lack of support for the proposed negative impact of patent application scope on abandonment likelihood as in Hypothesis 5a. Contrary to the real option expectation but consistent with the behavioral theory argument, the scope of application of a patent significantly increases the likelihood that the patent will be abandoned. This result also contradicts with the findings of many extant studies that argue that patent scope or breadth is positively associated with the valuation of the patent or the innovator's profit function. Lerner (1994) for example, found that the breadth of patent protection significantly positively affects firm valuation. McGrath & Nerkar (2001) found that firms are more likely to further invest in new R&D activities in technological areas in which their first

patents are wider in scope. Shane (2001) also found that patented innovations of wider scope are more likely to be commercialized through new firm formation. All these studies utilize the number of patent classes to operationalize the patent scope.

This finding suggests that managers may be biased in the evaluation of innovation scope. Two potential explanations exist for this finding in addition to the difficulties that managers may have in their valuation of innovation scope as discussed in the hypotheses development. First, it may be that when making innovation abandonment decisions, managers do not consider the positive potential because of the application scope of patents. This leads us to question the optimality of managers' decisions: are they making decisions that lead to the best result? While the real options reasoning helps us better predict managerial decisions in other aspects examined in this study, should it be prescriptive regarding patent scope in abandonment decision making? Given that prior research has found that scope is valuable for innovations, it is likely that using a real options reasoning here may result in better performance. Future research is needed to examine whether applying real options reasoning in this respect, i.e., retaining patents of wide application scope for a longer period, will lead to results better off for firms.

Second, it is possible that technology may be different from other types of assets in that the generalizability of a technology does not always add to its value potential. Instead, there may be a trade-off between the generalizability and the specialization of a technology such that a more generalizable technology has lower potential than a specialized technology. Thus, unlike physical assets, generalizable technology on average may be less valuable than specialized technologies. As Table 4 shows, the class number of a patent is not significantly correlated with the non-self citations received and the

coefficient is small, suggesting that other firms may not value the patent scope on average. The table also shows a positive correlation between patent scope and self-citations, suggesting that the assignee firm may perceive higher potential of the patent and commit more resources to capture the potential. However, it is questionable that any significant growth opportunities are actually embedded and the firm may really reap the growth option value. Still, this finding suggests that further exploration with the refined implications of innovation scope will be necessary and fruitful. For example, future research may use the international patent classification instead of the U.S. classification to measure patent scope and compare the findings.

The second significant opposite result is the lack of support for proposed negative relationship between a firm's knowledge depth in a technological area and the likelihood the firm will abandon innovations in that area. Contrary to Hypothesis 6, I find a significant positive association between knowledge depth and abandonment likelihood. This suggests that firms do consider the degree to which they have accumulated knowledge in the technological area. While deeper knowledge allows a firm to better evaluate the potential of innovations, a potential explanation for this finding is that with greater knowledge depth, firms are more acute in realizing the limitations and shortfalls of the innovations. While deep knowledge may allow firms to perceive higher potential of certain innovations, it may also enable firms to recognize that certain innovations are limited in the possible exploitation and further extension. Given the fact that most innovations are incremental in improvement over currently available solutions and only have insignificant value, greater knowledge depth can enable firms discern innovations that do not pose high potential. In addition, deeper knowledge in an area also implies that

the firm has more solutions (thus more options) available in that area so that the marginal gains of new solutions is relatively less, and the firm will be more cautious in having more options in the area. In addition, having new options implies the firm may need to divert resources from current options thus the value of current options decreases (McGrath and Nerkar, 2004). Therefore greater knowledge depth makes firms become stricter with the valuation of innovations in the technological area rather than the opposite, helping firms abandon such innovations more ruthlessly. To conclude, this opposite finding does not imply that the real options argument is not reflected in the data. Rather, it actually offers evidence that managers act in accord with the real options reasoning by considering the future potential of the innovations, only that deeper knowledge helps to better screen innovations that are less promising.

VI. 3. Additional findings

A closer look at the results regarding scope of patent application and patent claims also reveals some important and interesting insights. Past research on patents often use two types of measures for patent scope, the number of patent classes or subclasses, and claims of patents. From a theoretical point of view, a patent's number of classes and claims reflect different aspects of the patent. Which class or classes a patent is assigned into is determined by the patent examination officials and thus is externally validated. The claims are made by the inventors prior to the patent grant, as an *ex ante* estimation based on the inventors' judgment of the inventive contribution. In the U.S., claims appear on the main page of the patent identified with the lead words: "I claim….". The patent claims thus represent the initial expectation of the patent value before the patent grant

process as anticipated by the inventors rather than the patent officials. This comparison suggests that a patents' number of classes is more appropriate as an objective measure for its scope. The correlation between the two variables as shown in Table 4 is only 0.0533 ($p<0.05$). In the logistic regression models on patent abandonment likelihood, the coefficient signs for the two variables are also opposite: while the number of claims is consistently negatively associated with the abandonment likelihood in the reported models, the class number is positively related with the likelihood to abandon the patent. This further confirms that the number of claims does not capture the same component of application scope as does the number of patent classes.

The findings regarding self-citations and non-self citations are also worth discussion. The correlation between the two variables is low, 0.1404 ($p< 0.05$) and they have different effects on patent abandonment likelihood. While non-self citation consistently has a significant negative impact on abandonment likelihood, self-citation is only significant in the full model at a low significance level. This confirms the argument that self-citation and non-self citation have different meanings and that researchers should be aware of this when using patent citations in research. The finding also suggests that at least in the context of innovation abandonment, firms do not exhibit strong bias because of sunk cost.

In order to better understand these findings, I compared them with Li & Hesterley (2006) and Nerkar & MacMillan (2004). Both used empirical settings different from my study. Li & Hesterley (2006) only examined patents that are abandoned, either in the first renewal round (at the end of the 4th year) or those patents renewed in the first round but abandoned in the second renewal round (at the end of the 8th year). They sampled patents

granted to U.S. manufacturing firms (SIC between 2000 and 3999) in 1995 and abandoned in 1999 or 2003. Then they looked at the relationship between their predictor variables and the timing the patents are abandoned. Nerkar & MacMillan (2004) only sampled patents granted in 1995 and in the pharmaceutical classes of 514 (Drugs) and 424 (Bio affecting compositions) as defined by USPTO. They looked at how the experiential learning and learning from others influences the patent renewal decisions, individually and jointly. The use of different dependent variables and the sample selection difference between my study and these studies may explain the partial consistence of the findings.

VI. 4. Implications

The findings in this dissertation suggest that real options factors are significantly considered in making abandonment decisions. The real options variables utilized in this study help to assess the value of the focal innovation in a more comprehensive way than if only current earnings are considered. As the full model offers the best fit, we can conclude that real options theory provides a framework of broader perspective that can incorporate NPV, behavioral theory and the future growth potential of investment when there is considerable uncertainty.

Researchers argue that the real option lens sheds economic insight onto the flaws in the behavioral processes that emerge in many firms, and offers guidance for better strategic decision making (McGrath et al, 2004). The findings of a strong and significant relationship between real options variables and abandonment decisions suggest a need to empirically investigate the relationship between real options reasoning and abandonment

decision outcomes. Thus the findings suggest further research opportunities. By empirically testing for the "best fit" model from among the alternative perspectives, we are only able to discern the best explanation for what is actually happening in firms' managerial decisions, not what the optimal decision should be. Future study can advance further and examine the prescriptive potential of real options theory in strategic management by testing whether utilizing real options reasoning significantly improves decision making quality. For example, future research can look at whether firms should be more careful when abandoning innovations with wide scope and retain those innovations for a longer period of time.

The results of this study also have several other theoretical implications. First, this study has implications for real options research. It shows that managers use a real options perspective to help them decide when to change course. So far the majority of real options research in the field of strategy focuses on the initiation of new projects, which are viewed as the adoption of new options. Little research has been conducted on firms' implementation of real options perspective over time, such as the evaluation of previously acquired options and the decision to exercise or the decision to abandon. In fact, because abandonment decisions have been considered to be desperate and uncommon management decisions (Porter, 1976), the examination of abandonment decisions remains largely an unexplored territory in strategy research. In addition, regardless of the considerable scholarly attention and the promising potential of real options theory in strategy research, empirical study is still rather limited (McGrath and Nerkar, 2004). Especially, so far we still lack empirical evidence as to whether managers revise strategic decisions and abandon investments in accordance with real options theory.

By demonstrating how firms decide to terminate innovations in accordance with real options perspective, this study provides further support for and advances real options theory in the context of strategic management.

Second, this study has implications for RBV and dynamic capability research. Firms undertake investments to develop and deploy their resources. Firms' dynamic capabilities involve not only the ability to incorporate certain processes into ongoing routines but also the ability to leave out certain processes (Eisenhardt and Martin, 2000). However, most RBV research has focused on resource development and redeployment, and relatively few studies have examined how firms make discontinuation decisions, which are more complex and subjective than the decisions to continue. This study provides insight into how firms evaluate their investments and decide which to abandon, which is directly linked to the continuous development and renewing of firms' dynamic capabilities. Therefore this study helps to explain the sources of heterogeneity of organizational capabilities and to build a more dynamic resource-based view (Helfat & Peteraf, 2003). For example, research found that firms may fall into competency traps when favorable performance with an inferior procedure leads a firm to accumulate more experience with it thus keeping experience with a superior procedure inadequate to make it rewarding to use (Levitt and March, 1988). Such competency traps may cause firms to fail to conduct exploration or accumulate experience with new procedures. Real options theory, however, suggests that managers may appreciate the future growth potential of explorative procedures and conduct further experimentation and thus reduce the likelihood of falling into competency traps. Further, it is important for firms to both engage in exploring activities and also discontinue those projects and ventures that no

longer entail high potential early and cheaply to cut losses in time (McGrath et. al, 2006). This study shows that the real options perspective can shed insight on the balance between exploring projects and timely abandonment.

Third, this study shows that in the context of strategic management real options theory can be usefully tied with other strategy theories. In the development of hypotheses concerning the impact of knowledge depth and complementarity on firms' innovation abandonment decisions, I build my arguments based on real options theory and also other theories such as RBV, KBV and the dynamic capability view of the firm, taking into consideration of certain firm level factors. By combining the real options perspective with established strategy research we can apply real option reasoning to examine a wide range of strategic management issues and practices. For example, tying real options arguments with firms' resource development, accumulation and deployment, the learning aspect of knowledge and the development of organizational dynamic capabilities, we can gain new insights in firms' assessment of investment projects, their decisions concerning investment in resources and their R&D trajectory. In the mean time, linking real options theory with other strategy theories also furthers the advancement of real options theory.

Fourth, it has implications for the innovation literature. Although the innovation literature has seen widespread attention to firm patents and patent characteristics, renewal or abandonment decision making so far remains a topic that is rarely explored. Thus, this study advances the understanding of managing an innovation portfolio by trimming the low value ones and keeping the promising ones. Specially, this study analyzes and tests how technological uncertainty impacts firms' innovation abandonment decisions. This is an essential feature of technological innovations but is inadequately addressed in

innovation literature. Past research has measured macroeconomic uncertainty by calculating the variance of indicators such as exchange rates (Campa, 1993), inflation and output prices (Huizinga, 1993); or industry-specific uncertainty as reflected in the volatility of sales (Kogut, 1991), stock market returns (Folta and Miller, 2002) or GDP contributions (Folta and O'Brien, 2004). Relatively few studies explicitly examine the uncertainty a firm faces from technological sources. Although Folta (1998) proposed to examine technological uncertainty, empirically he operationalized the measure using stock market returns rather than examining the technologies themselves in a more direct way.

Fifth, this study has implications for research on the management of firms' sequential investments. A firm's multi-stage projects require regular assessment and revision if necessary. This study expands our understanding of firms' revision of their investment decisions. Although the empirical test of this dissertation is conducted in the setting of innovation portfolio management, the same reasoning can apply to the valuation of multi-stage projects of other types. For example, the venture capital business is an appropriate context where uncertainty is high and the capability to terminate low-potential projects is critical. We can expect that by adopting a real options perspective and considering factors associated with the projects' future potential such as uncertainty and interactions among the firm's other business investments, we can better predict firms' investment continuation and abandonment decisions.

This study also has managerial implications for practitioners as it illustrates the impact of a series of factors on abandonment decisions. Managers may make use of the findings to facilitate the valuation of their ongoing investments, including innovations.

Specifically, they should make sure to consider the growth potential embedded in firms' investments in addition to current earnings, especially the positive potential rooted in uncertainty and the interactions between the focal investment and the firms' other investments.

VI. 5. Limitations and future research

This study also has several limitations. Although a single industry research design helps to alleviate the inter-industry differences, the generalizability of the findings to other industries is questionable. Replication of the research in other industries and different time frames is desirable. Industry characteristics may matter to the extent that real option reasoning is used. Industries vary in their reliance on patents. In industries where patents provide effective protection of technology, firms appropriate a significant portion of the value of their innovations. Therefore, firms can consider the total value potential of innovations for the society when making abandonment decisions. When the patent system and legislation provide weak protection from value appropriation by the firms with innovations, the firms need to consider the spillover variation. In using the real option lens, they need to consider the portion of upside potential that they may possibly appropriate, rather than the total potential of the innovation for the society. The impact of institutional environmental factors in other industries can be studied.

This study only examines the first renewal decision. Future studies can examine the subsequent renewal decisions, when more information is revealed and uncertainty resolves with time. The comparison of the decisions in these stages is going to be interesting. Future research can be extended to conduct longitudinal studies to examine

how the change in a firm's resources and capabilities influence its decisions. Studies can also examine whether those patented innovations renewed in the first round but abandoned later are worth the delay, what is the optimal timing of abandonment, and whether the real options argument may help firms make the abandonment decisions earlier without losing much of the growth option value.

This study raises a lot of interesting future research questions. The most important question is to further explore whether real options theory improves managerial decision making quality and lead to better performance. Although this study uses proxy for a firm's *a priori* perception, it does not perfectly capture the influence of escalation of commitment and other psychological factors. Future research can employ questionnaires to detect the impact of such factors and further rule out these influences. To look more closely, it is desirable to use surveys to test whether managers conscientiously use real option reasoning to evaluate investments and make the abandonment decisions or they do this sub-conscientiously. Future studies can also consider the possible interactions between the variables examined in the study and other variables at the patent level, firm level or industry level.

In this study I only examine the effect of uncertainty from the technological source, which is originated in the innovation generation process, leaving out the other possible types of uncertainty. Future studies can consider the impact of uncertainty from other sources, such as market demand, ownership structure, product market focus, technological relevance, and nationality or geographic locations.

It is possible that firms tend to rely on real option reasoning to a greater extent in some situations than in others. I suspect that firm strategy, structure and resources are

likely to impact the extent that real option reasoning is used in organizational context. For example, we can question whether exploration-oriented firms are more likely to make innovation abandonment decisions in accord with real options theory. Competition and institutional factors may also impact the likelihood that real option reasoning is used. For example, does competitive rivalry positively moderate the use of real option reasoning, because growth option value is more valued when competition is intense? The characteristics of the top management team may also have influence on when growth option value is more recognized and emphasized. It is fruitful to conduct research on those contingencies under which the real option reasoning is more likely to be used.

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