Strategic Management Journal
Strat. Mgmt. J., **25**: 1045–1061 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/smj.414

NON-ADDITIVITY IN PORTFOLIOS OF EXPLORATION ACTIVITIES: A REAL OPTIONS-BASED ANALYSIS OF EQUITY ALLIANCES IN BIOTECHNOLOGY

ROBERTO S. VASSOLO,[1] JAIDEEP ANAND[2]* and TIMOTHY B. FOLTA[3]
[1] *IAE — Universidad Austral, Buenos Aires, Argentina*
[2] *University of Michigan Business School, Ann Arbor, Michigan, U.S.A.*
[3] *Krannert Graduate School of Management, Purdue University, West Lafayette, Indiana, U.S.A.*

Firms invest in exploration-oriented activities to seek competitive advantage and in response to changing environments. Real options formulations represent an emerging strand of thinking on such investments. In this paper we begin with the observation that firms often simultaneously invest in multiple exploration projects. We identify two sources of potential interactions among these real options investments. First, we investigate the effects of correlations between the outcomes in different options. Second, we analyze the effects of investments that are fungible across project options. We show that under different conditions multiple options can be sub-additive (due to redundancies in outcomes) or super-additive (due to fungible inputs). We test the implications of our model with data from the biotech industry and find supporting evidence. Our model and results have some interesting implications for the exploration literature and real options lens. Copyright © 2004 John Wiley & Sons, Ltd.

A significant amount of recent research has documented how environmental discontinuities may render a firm's investment in specific technologies, markets, or business models obsolete (Henderson and Clark, 1990; Eisenhardt and Martin, 2000; Zollo and Winter, 2002). When faced with the threat of such discontinuities, managers are challenged to invest in capabilities so that their firms can remain viable and successful in the future. Exploration enables a firm to build new resources to cope with changing markets or technological discontinuities (March, 1991). In this study, we examine the implications of multiple exploration investments made by firms.

The search for new capabilities almost always involves investments that are at least partially sunk, or irreversible; and irreversible investments that are exploratory in nature usually involve considerable uncertainty, possibly in domains distant from a firm's core capabilities. Under such conditions, real options models (Kogut, 1991; Bowman and Hurry, 1993; Arora and Gambardella, 1994; Kim and Kogut 1996, McGrath 1997; among others) help to understand the investments made by firms in exploration of new capabilities. The real options as well as other literatures to date have tended to focus on individual investment (i.e., one option at a time). As Nelson (1961) has pointed out, firms often consider a set of simultaneous and overlapping strategic investments, particularly in searching for new technologies. When firms have multiple real options that interact with one another, their individual values may be non-additive (McGrath, 1997). The implication is that the timing or likelihood of exercise of a single option may be influenced by the presence of correlated options in the firm's option portfolio.

We extend this previous work in two important ways. First, we consider that a firm's growth

Keywords: real options; fungibility; exploration; alliances
*Correspondence to: Jaideep Anand, University of Michigan Business School, 701 Tappan Street, Ann Arbor, MI 48109-1234, U.S.A. E-mail: jayanand@umich.edu

Received 28 January 2002
Final revision received 21 January 2004

options should not be evaluated in isolation. For example, if a firm makes multiple investments toward the same goal, there may be some redundancy, particularly when firms compete in a 'winner-take-all' scenario (Nelson, 1961; Mitchell, 1989). Second, we use advances in the resource-based view of the firm to isolate the conditions where interactions among growth options are non-trivial. For example, if several investments draw upon a common pool of resources within the focal firm, it may be able to take advantage of scope economies or learning spillovers. This also provides an important departure from prior work in finance that does not consider firms to be asymmetrically positioned to initiate and exercise their real options. We hope this work will be an important contribution to the understanding of how real options models explain firm behavior under conditions of multiple investments.

The remainder of the paper is organized as follows. The next section presents the model and derives propositions relating to the value of a firm's options in the presence of multiple overlapping options. The third section applies the model to the specific context, where a firm's collection of equity-based alliances is characterized as a portfolio of real options on new technological opportunities. In this sense, we follow prior work that has characterized equity-based strategic alliances as real options, but extend prior work by focusing on how interactions within the portfolio and resource fungibility influence option exercise. The fourth section introduces the sample and measures to test our hypotheses. Next, we discuss the results; we then suggest some directions for future research; and finally we conclude the paper.

PORTFOLIOS OF EXPLORATION ACTIVITIES

Option theory is useful for valuing the flexibility inherent in managers' investment decisions (Sanchez, 1993). Compared to traditional valuation methods, such as net present value (*NPV*), it more accurately accounts for the value of flexibility when investment decisions involve some irreversibility and the outcome of an investment is uncertain. With few exceptions, a characteristic of previous studies in the real option literature is a focus on isolated options that are independent of other options held in a firm's portfolio. However, interactions between real options are a common phenomenon. In the presence of interactions, the valuation of a portfolio of related options is not straightforward. Failure to consider the effect of interactions on investment decisions would lead to misleading explanations.

Hereafter, the focus of this study is on the implications of the independence assumption using the example of two investments, α and β, by a single firm. Trigeorgis and Mason (1987) suggested the value of a firm's investment is a function of its traditional *NPV* and its option value. Hence, having made an investment, its value can be characterized as

$$V_\alpha = NPV_\alpha + OV_\alpha$$
$$V_\beta = NPV_\beta + OV_\beta \quad (1)$$

where *NPV* refers to the passive *NPV*, and *OV* refers to the value of the underlying growth option, which is derived from a capability that gives the firm the right, but not the obligation, to take advantage of future growth opportunities. Since managers have discretion over the exercise of growth options, their value escalates with uncertainty due to the asymmetry in their pay-off distribution: if unexercised, their lowest value is zero, while their upper value is virtually unbounded. Thus, even if the passive *NPV* is negative, the investment may be valuable if there is potential for the industry conditions to far exceed the expected values that were used in calculating *NPV*. Under the assumption that investments α and β yield significant growth options that are independent from one another, the value of both investments can simply be added together:

$$V = V_{\alpha+\beta} = NPV_\alpha + OV_\alpha + NPV_\beta + OV_\beta \quad (2)$$

However, it is widely recognized that firms typically consider a set of simultaneous strategic investments in similar strategic domains and that these investments often exhibit important correlations (Madhok, 1997). For example, firms duplicate their commitment to increase the odds of achieving a first-mover advantage. Several finance studies show that extending single option analysis to multiple options analysis, in the presence of correlations between the underlying assets, can be very complex (Johnson, 1987; Kulatilaka and Perotti, 1998; Stulz, 1982; Trigeorgis, 1993). In these cases, the real option rationale is less intuitive and may be derived from the so-called exotic options models.

We propose a particular model for analyzing those decisions in which firms make multiple and redundant investments in order to achieve a first-mover advantage. The model is called 'an option on the maximum value of several assets' and was initially developed by Stulz (1982) for the case of two underlying assets and generalized by Johnson (1987) for the case of *n* assets. The consideration of these investments as an 'option on the maximum value of several assets' introduces particular complexities that affect the additivity nature of their values. Hereafter, these changes in the value of the portfolio are referred to as the portfolio effect (*PE*), and the equation of overall valuation becomes

$$V = V_{\alpha+\beta} = NPV_{\alpha} + OV_{\alpha} + NPV_{\beta} + OV_{\beta} + PE_{\alpha\beta} \quad (3)$$

Consideration of the portfolio as an 'option on the maximum value of several assets' illuminates the size of *PE*, and whether it is positive or negative.

The sub-additivity property

If PE is negative, then the portfolio is *sub-additive* with regard to its option value. This suggests the value of a portfolio of real options is less than the value of the options if they were independent (i.e., not part of the same portfolio). Sub-additivity will result when an agent owns a group of competing investments. PE is negative because option investments are duplicated, and thus overlap with one another.[1] Even though the portfolio holder will have an 'option to switch' among investments, this value will never exceed the decline in value due to duplication. There is an optimal number of similar investments that maximize the value of the portfolio, but this number is always lower than number obtained under the assumption of independent investments. Therefore, when option investments in a portfolio are competitive, their value is *sub-additive*, which can be generally expressed as

$$PE_{\alpha\beta} = f(\rho_{\alpha\beta}) < 0 \quad (4)$$

[1] Portfolio theory (Markowitz, 1959) suggests the more correlated are two investments, the lesser is the value of their portfolio. This argument follows the same intuition, though it refers to option or up-side value.

Stulz (1982) and Johnson (1987) suggested that the option holder has the ability to switch to the option with the highest value among the correlated options. Since switching to the highest valued option erodes the value of the remaining options, there is a decreasing marginal return to holding correlated options. Therefore:

> *Proposition 1: When a firm invests in multiple and competing projects, correlations among the outcomes of the projects lead to a sub-additive value of the portfolio.*

The super-additivity property

If *PE* is positive, then the portfolio is *super-additive* with regard to its option value. This suggests the value of a portfolio of real options is greater than the value of the options if they were independent (i.e., not part of the same portfolio). The concept of super-additive option portfolios can be advised by insights from the resource-based view (Barney, 1991; Wernerfelt, 1984). A focus on how the resource-based view can advise real option value is compatible with recent studies that emphasize capability development within firms as a source of future competitive advantage (Kogut and Kulatilaka, 2001; Zhou and Peteraf, 2002).

Since Penrose (1959), the degree of commonality among firm activities and underlying resources has been identified as a source of competitive advantage. However, Markides and Williamson (1994) observe that generally this literature has tended to equate the benefits of relatedness with the static exploitation of economies of scope. A view that combines resource-based theory with real option insights allows analysis beyond 'exploitation' type advantages (e.g., scale and scope economies), and move toward a better understanding of advantages tied to exploratory behavior. For example, the cost of developing resources and capabilities may be viewed as the purchase price of an option to obtain new resources and capabilities. The purchase price may vary significantly across firms. Firms rich in intangible assets or resources with public good properties have few capacity constraints and may be able to apply them readily across the organization. These types of assets are fungible. Fungibility represents a firm-level capability that enables a firm to benefit from redeployment of existing capabilities to new endeavors, thus reducing the cost of each investment. Firms having fungible, unused capabilities have more growth options and, on average, pay a lower price for obtaining such options. Relatedly, synergies from scope economies and sharing of experience also lead to similar benefits since participation in one option reduces the entry cost for another. If the firm can leverage its capabilities and assets to make exploratory investments, the total value of the portfolio will be *super-additive*.[2] This relationship can be expressed as

$$PE_{\alpha\beta} = f(\rho_{F\alpha}, \rho_{F\beta}) > 0 \quad (5)$$

This leads to our second proposition.

> *Proposition 2: When a firm invests in multiple projects, fungibility of shared resources with the projects leads to a super-additive value of the portfolio.*

In summary, it is insufficient to focus exclusively on the independent effects of each of the options in a firm's portfolio. It is also necessary to include the level of correlation among options and the degree of fungibility between the option and the focal firm. A failure to consider both the sub-additive and super-additive properties with option portfolios will lead to a problem of misspecification in the analysis of the determinants of the value of the portfolio.

TECHNOLOGY ALLIANCES AS REAL OPTIONS

Strategic alliances are an important mode by which firms update their capability sets (Eisenhardt and Martin, 2000). Strategic alliances in R&D help firms spread risk, increase market power, share resources, and gain organizational learning (Mitchell and Singh, 1992). Alliances also allow organizations to obtain the desired benefits without the added costs of governance (Williamson, 1985).

A separate, but complementary stream has characterized strategic alliances as real options since a pioneering study by Kogut (1991). This research stream suggests that when a firm initiates an alliance, it gains access to a growth option for future expansion or to acquire its alliance partner, while retaining the option to defer complete commitment. Alliances enable the firms to learn about growth opportunities through close interaction with their partner, and thereby secure upside gains.

A standard result in this literature is that firms have a greater propensity to initiate equity alliances under high uncertainty (Folta, 1998). This view helps reconcile Williamson's (1988) concern that transaction cost analysis should not be applied uncritically when investments are exploratory in nature, such as investments in research and development in the face of uncertainty. Chi (2000) has argued that significant resource asymmetries must exist between partners for a real option to have strategic value. Chang (1995) modeled international joint ventures as a platform into international markets, where a platform is represented by an investment that offers expansion opportunities due to path dependency (Kim and Kogut, 1996; Kogut and Kulatilaka, 1994). However, Adner and Levinthal (2004) point out that such path dependency can arise out of endogenous rather exogenous factors.

In summary, the aforementioned theoretical and empirical work explains why alliances may have real option characteristics, and why such a perspective illuminates the context of strategic alliances. Despite these previous contributions, there remains considerable opportunity for further study. A particular limitation of this literature is that all previous studies focus on a single real option in isolation. McGrath (1997) emphasized this concern when she suggested that future studies should consider that there might be a significant cross-effect of uncertainty of one strategic alliance on the boundary conditions of other strategic alliances.[3] A second limitation of this line of research is that it has not emphasized insights from the

[2] It should be noted that the correlation here is not between a firm's portfolio investments but between the firm (F) and its investments. By this logic, the combination of the firm and its investment is super-additive, though the portfolio of investments may not be. However, under the following conditions, the portfolio of investments may also be super-additive: (i) the firm's stock of fungible resources is endogenous to the existence of a portfolio of investments, i.e., the firm invests more in such resources because it expects to make more of such investments; and (ii) the increase in value of the option due to fungible resources can further lead to a second-order change in correlations among investments.

[3] Luehrman (1998) explicitly considers strategy as a portfolio of real options, but does not consider the effect of interactions on the value of strategic alliances. Trigeorgis (1993) also developed a formal model for interactions, but he considers compound and not simultaneous effects.

resource-based view and capability perspectives (Zhou and Peteraf, 2002). Since interactions between alliances are a very common and important phenomenon in R&D alliances (Madhok, 1997), an emphasis on synergistic benefits across real options is needed to fully understand the configuration of a portfolio of strategic alliances. The following section develops hypotheses corresponding to both of these limitations.

Hypotheses

In this section, we develop specific hypotheses emphasizing the insight of real option thinking when appraising a firm's portfolio of strategic alliances. We begin by applying the standard model as used in previous research and then introduce further hypotheses corresponding to the cross-effects of uncertainty and synergy.

The base case

We begin with a base case of real options without considering the effect of interactions among them. Say the firm faces the choice of whether to explore in uncertain environments by fully committing resources through in-house development or acquisitions, or by partially committing resources by adopting a hybrid form of organization like a strategic alliance or equity agreement. As discussed earlier, greater exogenous uncertainty about the value of a growth opportunity implies a higher value for the underlying growth option. Moreover, Nelson (1961) and McGrath and MacMillan (2000) have argued that in highly uncertain conditions it may be best to deploy, not one, but patterns of options. In particular, equity agreements are suitable for environments characterized by rapid innovation and geographical dispersion in the sources of know-how (Teece, 1992). Following the insight of McGrath and MacMillan, it may be more sensible to split the investment into several small ventures than to making a single large bet. When translating this real options logic to a decision surrounding governance choice, we would expect a negative relationship between uncertainty and exercise of the ongoing options (i.e., termination of alliances), a result which is consistent with previous findings (Folta, 1998; Kogut, 1991). In addition, in the case of technology exploration oriented alliances, technological uncertainty may be considered as an important source of exogenous uncertainty. Higher technological uncertainty will cause firms to keep their alliances instead of terminating them since the termination of an option reduces the set of possible avenues for the firm.[4] Under conditions of such uncertainty, firms would tend to prefer to enhance rather than reduce this opportunity set. The implicit assumption of previous studies is that what holds for a single option should hold for the portfolio, independently of the degree of relatedness. Therefore:

Hypothesis 1a: Higher technological uncertainty reduces the likelihood of firm alliance divestitures.

Hypothesis 1b: Higher technological uncertainty reduces the likelihood of firm alliance buyouts.

The above hypotheses do not take into account the interactions among the options within the portfolio of a firm. As noted above, potential misspecification can result from not considering that PE might be sub-additive or super-additive.

Sub-additivity

We now turn to implications of Proposition 1 for such a portfolio. This proposition deals with the presence of interactions among the strategic alliances that seek a first-mover advantage, and argues that correlations among outcomes of options reduce their combined value (*sub-additivity property*). The correlation between an ongoing options portfolio diminishes the expected gain of each of the options due to the option to switch. If a firm carries such related options in its portfolio, it will divest the least attractive of such related alliances, retaining the best potential alliances as possible candidates for future acquisition. Consequently, we will observe a positive relationship between uncertainty correlation and divestitures. In the case of technology based alliances, uncertainty

[4] There is some very interesting and insightful literature on divestitures in the strategy literature, for example, Capron, Mitchell, and Swaminathan (2001), Karim and Mitchell (2000), Bergh (1997), Bergh and Holbein (1997), Hoskisson *et al.* (1994), Montgomery, Thomas, and Kamath (1984) and Harrigan (1981). However, such studies deal with divestment of owned assets, procured through acquisitions, diversification, etc. But our research focuses on the timing of exit from equity alliances in uncertain environments.

correlation may be seen as the technological distance between them. Therefore:

Hypothesis 2: Lower technological distance between a focal alliance and the portfolio of other alliances enhances the likelihood of divestiture of the focal alliance.

Super-additivity

Proposition 2 assesses the effect of fungibility of input resources on the portfolio of strategic alliances. A resource is fungible or redeployable if it can be used by the target, either by a physical transfer of the resource or by a resource sharing without physical movement (Anand and Singh, 1997; Capron, Dussuage, and Mitchell, 1998). The value of the real option does not depend exclusively on uncertainty but also on the cost of buying the option. When the investment is partially redeployable or fungible among alliance agreements, the cost of a related option diminishes, making them more valuable (*super-additivity property*). Greater levels of fungibility therefore increase the probability of acquisition. Upon acquisition, such related alliances requiring common resource inputs can be consolidated with the existing capabilities of the firm, leading to economic gain. Greater fungibility reduces the costs of acquiring these options. In technology-intensive industries, fungibility of resources can be determined by the extent to which there is common technology between the alliance and the firm, i.e., an inverse of technological distance between them. Therefore:

Hypothesis 3: Lower technological distance between the firm and an alliance enhances the likelihood of alliance acquisition.

Hypothesis 1 summarizes the link between uncertainty and real options based on previous research, extending previous arguments to a portfolio of alliances. Hypothesis 2 is based on Proposition 1 regarding correlated outcomes, and Hypothesis 3 is based on Proposition 2 regarding fungible resources. Note the difference in dependent variables in these hypotheses. Hypothesis 1 predicts termination including both divestitures and acquisitions, Hypothesis 2 only predicts divestitures, while Hypothesis 3 only predicts acquisitions. We now turn to a description of the empirical context in which we test these hypotheses.

EMPIRICAL ANALYSIS

The biotech industry context

The context of our study is the biotechnology industry. The biotechnology revolution refers to a *technique* that comes from a *scientific* advance—the advent of molecular genetics and recombinant DNA. The emergence of modern biotechnology represents a technological discontinuity that has challenged the pharmaceutical industry. Small start-up companies performed the initial stages of applied research and commercial development in biotechnology. Between 1973 and 1987, 493 new biotechnology firms were created (Krimsky, 1991). The new companies developed a unique knowledge endowment that challenged pharmaceutical incumbents (Teitelman, 1989). As a strategic response to the lack of expertise in the new technology, large pharmaceutical corporations developed alliances with one or more biotech companies. The larger companies exchanged financial support and established organizational capabilities in clinical research, regulatory affairs, manufacturing, and marketing for the biotech start-ups' expertise and patents (Galambos and Sturchio, 1998). Pharmaceutical firms have initiated vertical relationships with biotechnological companies for at least two reasons. First, they have used alliances to block competitors in case certain biotech labs discover a valuable drug (Teitelman, 1989). In addition, they have used the strategic alliances to substitute for developing internal expertise judged of marginal value (Zucker and Darby, 1997). Stated differently, pharmaceutical companies have mainly used strategic alliances to explore new capabilities. It was not uncommon for a single pharmaceutical firm to initiate alliances with competing biotechnology laboratories. By the end of the 1990s, the shape of the pharmaceutical–biotechnological industry was different from that of the seventies. Pharmaceutical companies had established significant capabilities in the new field. However, even the largest firms were challenged to fund both basic and developmental research across the wide range of opportunities, and these problems, together with the necessity of achieving economies of scale in manufacturing and distribution, reinforced experiments with strategic alliances (Galambos and Sturchio, 1998).[5]

[5] The following data help to assess the magnitude of vertical relationships. In 1995, pharmaceutical companies spent about

In summary, the biotechnology industry is an appropriate context to test the relationship between real options thinking and resource-based theory because it involves: (i) a high level of R&D activity; (ii) a technological discontinuity that has challenged incumbents; (iii) an interesting variety in the response of pharmaceutical incumbents, including internal R&D, outright acquisitions, and various kinds of alliances as well as alliances followed by acquisitions; (iv) alliances that tend to be exploratory in nature and appear to be largely driven by the incentive to gain a first-mover advantage; and (v) high level of *exogenous* technological and market uncertainty. For these reasons, it is not surprising that the pharmaceutical–biotech has been widely used in previous research on such subjects (e.g., Arora and Gambardella, 1990; Folta and Miller, 2002; Powell, Koput, and Smith-Doerr, 1996; Rothaermel, 2001; Stuart, Hoang, and Hybels, 1999).

Data

A starting point for studying how pharmaceutical alliance decisions are influenced by portfolio effects is to generate a sample of pharmaceutical firms. Using BioScan and the North Carolina Biotechnology Industry databases, we identified the 30 pharmaceutical firms with the most equity alliances in 1989—the beginning of our sample period. The firms come from several different countries, including the United States, England, France, Germany, and Switzerland. During our sample period, consolidation in the industry reduced our set of firms to 17. We account for this consolidation by modeling the firms separately until the merger or acquisition took place. We used the sources identified above to generate the firms' portfolio of equity alliances with biotechnology firms and tracked how they changed between 1989 and 1999. We identified 363 equity agreements initiated between our 30 pharmaceutical firms and 183 different biotechnology partners during the sample period. Since our hypotheses are concerned with alliance termination decisions, we undertook an exhaustive search to discern whether these equity agreements were terminated or maintained. If the October 1999 issue of *BioScan* listed the equity partnership as ongoing, the alliance was coded as right censored. Otherwise, a systematic search was undertaken to understand the nature of the termination using sources in addition to those listed above, including Ernst & Young Biotechnology Industry Reports, Predicast F&S Index of Corporate Change, Lexis/Nexis, Dow Jones News Service, and SEC Schedule 13D filings. This effort enabled us to verify that there were 76 terminations: 14 instances where the pharmaceutical firm bought out the biotechnology partner and 62 divestitures.

Measures

We paid considerable attention to issues of reliability, validity and potential biases. For this reason, we use measures that were consistent with previous research and our fieldwork. Additionally, we computed normality tests to ensure all variables are sufficiently close to normal distribution to justify assumptions on normality.

Dependent variable

The hypotheses relate to the determinants of option exercise. Option exercise is defined as the timing of the exercise event—either in the form of acquisition or divestiture. The dependent variable examines the exercise decision (*termination*) surrounding existing equity alliances. As noted earlier, of the 363 equity alliances in our sample, we identified those as being terminated through acquisition or divestiture. Acquisitions were coded '1' if the pharmaceutical firm acquired their biotechnology partner, '0' otherwise. Divestitures were coded '1' if the pharmaceutical firm exited a biotechnology partnership, and '0' otherwise.

Independent variables

The variable that measures uncertainty is *Industry uncertainty*. Following Elton and Gruber (1997), we measure uncertainty as the monthly standard deviation of the returns of an industry index. Other potential measures of uncertainty, such as variance in revenues, are not applicable in biotechnology because the majority of firms lack revenues from product commercialization. We measured industry

U.S. \$3.5 billion to acquire biotech firms, approximately \$1.6 billion for R&D and licensing agreements with biotech firms, and from \$1.2 to \$7.5 billion on in-house biotechnological R&D (Davidson, 1996).

uncertainty as the standard deviation of a biotechnology stock index:

$$\textit{Industry uncertainty} = \left(\frac{1}{T-1}\right) * \sum_{t=1}^{T} (\text{returns}_t^2 - \mu_t) \quad (6)$$

where T = number of tradable days of the period; and μ_t = average return for the period T.

An index is a single descriptive statistic that summarizes the relative change in an underlying group of variables (stocks in this case). Initially, we tried to use an index that already existed in the literature. However, the three existing indices for the Biotechnology industry started in 1991, 1992, and 1993 (the Dow Jones Biotech Index, the Biotechnology Amex Index, and the Biotechnology Nasdaq Index, respectively). In addition, these indices were based on only one to four biotechnology labs. As a consequence, it was necessary to build a new index, which was broader based as well as lasting throughout the time period.

Our index in this study is therefore based on 10 public biotech companies that were public during the whole period. The selection of the labs followed the criterion of having a similar number of companies within each particular major subject grouping in order to have a balanced index. Daily stock prices were gathered from the Center for Research in Security Prices (CRSP) database. Monthly values for the index were taken from the last tradable day of the month. Following Standard and Poor's use, the index is capital-weighted (as opposed to firm weighted). The index was adjusted in response to new stock offerings by any of the companies as per Standard and Poor's manual in order to avoid spurious upside gains.

We use measures of technological distance to approximate the potential for sub-additive or super-additive portfolio effects. Sub-additive portfolio effects are captured by a measure of distance between equity partners in a pharmaceutical firm's alliance portfolio. The starting point is to calculate dyadic measures of technological overlap among biotechnology partners in a portfolio. Technological overlap of β on partner α in portfolio F_y is measured as the ratio of common technological domains among partners α and β divided by the number of total technological domains of α. We convert this to a measure of distance by taking one minus this ratio. Say each firm or lab i has a vector of technological endowment for every year y, with $t_i y = \{t_0, \ldots, t_N\}$, t_j being the technological domain j and N the total number of possible technological domains. If the firm is conducting research in the technological domain j, $j = 1$ ($j = 0$ otherwise). The technological distance between α and β for year y is equal to

$$\textit{Technological distance}_{\alpha\beta_y} = 1 - \left(\frac{t'_{\alpha y} * t_{\beta y}}{t'_{\alpha y} * t_{\alpha y}}\right) \quad (7)$$

If there are more than two partners in portfolio F_y, then we use the minimum of the distances for partner α. This constitutes our measure of *portfolio distance,* which is used to test Hypothesis 2.

In contrast to the approximation for sub-additive portfolio effects described above, super-additive effects are captured by a measure of technological distance between a pharmaceutical firm and one of its biotechnology partners. It is measured by one minus the ratio of common technological domains of pharmaceutical firm and one of the partners in its portfolio divided by the total number of technological domains of the pharmaceutical firm. We call this variable *partner distance* and use it to test Hypothesis 3. Lower values of partner distance suggest a higher possibility of redeploying assets from the pharmaceutical firm to the biotechnology partner.

These measures of technological distance are similar to the one used by Stuart and Podolny (1996), except that their measure is based on patent citations. Patent citations are fine-grained but, strictly speaking, patents are the result of past capabilities. We chose to adopt a measure of technological involvement in domains identified by *BioScan*. Since these domains represent the firm's stated area of technological expertise, we believe it to be a more forward-looking measure of a firm's technological capabilities. Prior studies have made use of this classification scheme in identifying a firm's technological participation. (e.g., Rothaermel, 2001). Examples of the 143 technological domains that appear in *BioScan* in 1999 include Aids Therapeutics, Bone Therapeutics, and DNA Probes.

Control variables

We incorporate control variables for transaction-level effects, pharmaceutical firm effects, and biotechnology partner effects. All the variables of this section, except for those that explicitly control for the transaction effect, were calculated for the year prior to the transaction.

Transaction-level control variables

Interest rates influence the opportunity cost of an investment. We expect higher interest rates to favor divestiture and deter buyout. As a proxy for risk-free interest rate, *Interest* is measured using the 1-year Treasury Bill rate. *License* was coded '1' if a technology licensing agreement was initiated simultaneous to an equity agreement, and '0' otherwise. The presence of a license agreement indicates interfirm linkages beyond the equity stake that enhance the investor's inside position (relative to outside bidders). *Option* is coded '1' if there was an explicit contractual buyout agreement or a specific option to acquire additional equity at a prespecified price, and '0' otherwise. *Foreign transaction* is coded '1' if the home offices of a pharmaceutical firm and its equity partner were in different countries, and '0' otherwise. Previous research suggests that country differences may accentuate the risk of opportunistic behavior due to international differences in institutions and governance (Bishop, 1994).

Pharmaceutical firm control variables

Consistent with prior research (Burgers, Hill, and Kim, 1993; Gulati, 1995), we consider that organization size may approximate the financial resource position of pharmaceutical firms and influence alliance activity. Our measure of firm size is the logarithmic transformation of *Pharmaceutical sales* (millions). The data were gathered from Compustat, Lexis-Nexis, Global Access, and the annual reports of the firms. We control for the innovative ability of pharmaceutical firms by a measure of the *number of technological domains* in which the incumbent is investigating, since broader research scope seems to indicate a higher commitment to innovation.

Biotechnology firm control variables

To approximate the value of the underlying asset in an equity partnership, it would be ideal to gather data on the market value of the biotechnology partner. Unfortunately, since almost 50 percent of the biotechnology companies are not public, we are not able to use the stock market value of the firms. Instead, we use the *industry returns*, based on the biotechnology industry index adjusted by the risk-free interest rate (*interest*). In an attempt to better control for the value of a particular biotechnology firm, we use a count variable that measures the *total number of a biotechnology target's technological domains* (Rothaermel, 2001). It is a proxy of the knowledge endowment of the lab and, therefore, of its value. Firms active in more technological domains may have larger growth options associated with them.

Econometric model

This study uses a hazard rate model. An important advantage of hazard rate modeling is that it allows incorporating the right-censored variables. Right censoring occurs when some observations have not experienced a termination (buyout or divestiture) at the end of the period. In the case of our sample, every equity agreement held at the end of the period (December 1999) is right censored. Hazard rate models incorporate this phenomenon as part of the governance decisions to be explained rather than ignoring these data. In addition, the dependent variable in survival techniques is duration, or waiting time, prior to an event. This is appealing in studies that explore why firms differ in the timing of their actions (governance choices here).

Our analysis models the dependent variable as the hazard rate of terminating an equity partnership. We observed two different types of termination events—divestiture and acquisition—and modeled their hazard rates separately. The first set of models defined the dependent variable as the hazard rate of *divesting an equity alliance*. The second set of models defined the dependent variable as the hazard rate of *acquiring a majority stake* of the biotechnology partner. When using such a parametric model it is necessary to assume that the time until an event occurs follows a specific distribution. In both sets of models, the hazard rate was specified as a Gompertz function of the independent variables and the vector of control variables. The Gompertz distribution was selected among several alternatives based on the Akaike Information Criterion.

The use of maximum likelihood estimation requires the assumption that events are uncorrelated across observations. If the events are correlated across observations, parameters have inflated standard errors. Given that each pharmaceutical firm has multiple investments, this assumption is highly questionable in our data. To cope with this problem, both sets of hazard models incorporated the 'robust' and the 'cluster' options available in STATA. The 'robust' option corrects standard error for each parameter by specifying that the Huber/White/sandwich estimator of variance is to be used in place of the traditional calculation. The 'robust' option, when combined with the 'cluster' option, allows for the presence of observations that are not independent within cluster (i.e., same pharmaceutical firm).

RESULTS

Table 1 shows descriptive statistics. It is interesting that, on average, partner distance (0.89) is larger than portfolio distance (0.80). This implies that pharmaceutical firms explore in technologically distant domains, but they do so within a fairly tight or constrained portfolio, on average. Table 2 shows the Pearson correlation coefficients. Several relationships are noteworthy. First, note the low correlation between the two measures of technological distance (−0.02). This information reinforces the conclusion that the two measures represent two different constructs (i.e., corresponding to our Hypotheses 2 and 3). Second, the high and negative correlation between the partner distance and the number of biotech lab technologies (−0.59) is also interesting. The presence of correlation between these two variables increases the standard error of their coefficients, diminishing their explanatory power. Third, we note the somewhat high correlation between *option* and *license* (0.30). This shows, from a contractual perspective, that sometimes pharmaceutical firms take two precautionary measures to ensure the appropriability of biotech firm's discoveries.

The results from the hazard rate models are exhibited in Tables 3 and 4. Table 3 presents the exponentiated coefficients—hazard ratios—for the factors that influence the rate of divestiture. When the exponentiated coefficients are greater than one, it means the hazard of divestiture increases with time; when the coefficients are less than one, the hazard of divestiture decreases with time (to arrive at unexponentiated coefficients, we could simply take the exponents of the coefficients presented). The advantage of reporting exponentiated coefficients is that it allows an easier interpretation of results. For example, Model 1 reports the base model with control variables. In this model we see that the presence of an option clause significantly decreases the likelihood of divestiture ($p < 0.10$). Specifically, the hazard of divestiture is multiplied by 0.53 when an option clause accompanies an equity partnership. This clause guarantees the appropriability of any discovery and, therefore, favors the option strategy of 'wait and see.' The other control variables, when significant, also behave as expected. Higher interest rate, by increasing the opportunity cost of the investment, increases the likelihood of divestiture ($p < 0.05$). Larger pharmaceutical firms are less likely to divest, meaning they are more willing to keep their options open ($p < 0.001$). Finally, higher industry returns decrease the likelihood of divesting the alliance ($p < 0.01$). Firms delay the

Table 1. Descriptive statistics for termination sample

Variable	Mean	S.D.	Min.	Max.
Divest	0.22	0.41	0	1
Buyout	0.03	0.16	0	1
Industry uncertainty	0.00038	0.00067	0.00009	0.00562
Partner distance	0.89	0.08	0	0.59
Portfolio distance	0.80	0.14	0	1
Interest	0.05	0.01	0.03	0.09
License	0.56	0.50	0	1
Option	0.33	0.47	0	1
Foreign transaction	0.49	0.50	0	1
Log. Pharmaceutical sales	8.88	0.74	6.62	10.59
# of Pharm. technologies	23.48	10.86	3	42
# of Biotech. technologies	6.94	5.43	1	30
Industry returns	0.01	0.03	−0.08	0.12

Table 2. Pearson correlation coefficients for termination

	Variable	1	2	3	4	5	6	7	8	9	10	11	12
1	Divestiture	1.00											
2	Buyout	−0.08	1.00										
		(0.10)											
3	Industry uncertainty	0.01	0.02	1.00									
		(>0.1)	(>0.1)										
4	Partner distance	−0.13	−0.03	−0.02	1.00								
		(0.01)	(>0.1)	(>0.1)									
5	Portfolio distance	−0.12	0.03	−0.00	−0.02	1.00							
		(0.05)	(>0.1)	(>0.1)	(>0.1)								
6	Interest	0.09	−0.06	−0.16	−0.07	0.16	1.00						
		(0.10)	(>0.1)	(0.01)	(>0.1)	(0.01)							
7	License	−0.03	−0.03	−0.00	−0.09	0.01	0.02	1.00					
		(>0.1)	(>0.1)	(>0.1)	(0.10)	(>0.1)	(>0.1)						
8	Option	−0.07	−0.11	0.05	0.02	0.04	0.02	0.30	1.00				
		(>0.1)	(0.05)	(>0.1)	(>0.1)	(>0.1)	(>0.1)	(0.01)					
9	Foreign transaction	−0.03	−0.01	0.08	0.00	−0.06	−0.00	−0.16	−0.05	1.00			
		(>0.1)	(>0.1)	(>0.1)	(>0.1)	(>0.1)	(>0.1)	(0.01)	(>0.1)				
10	Log. Pharmaceutical sales	0.05	0.06	0.08	−0.10	−0.18	−0.17	−0.05	0.00	0.01	1.00		
		(>0.1)	(>0.1)	(>0.1)	(0.05)	(0.01)	(0.01)	(>0.1)	(>0.1)	(>0.1)			
11	# of Pharmaceutical technologies	0.01	−0.02	0.09	−0.08	−0.15	−0.23	0.11	−0.03	−0.01	0.21	1.00	
		(>0.1)	(>0.1)	(0.10)	(>0.1)	(0.01)	(0.01)	(0.05)	(>0.1)	(>0.1)	(0.01)		
12	# of Bio. technologies	0.10	0.01	0.04	−0.59	0.05	0.07	0.06	−0.02	0.03	0.08	−0.01	1.00
		(0.05)	(>0.1)	(>0.1)	(0.01)	(>0.1)	(>0.1)	(>0.1)	(>0.1)	(>0.1)	(0.10)	(>0.1)	
13	Industry returns	0.05	−0.01	0.14	0.03	−0.01	0.28	−0.01	0.07	0.06	0.14	0.02	0.00
		(>0.1)	(>0.1)	(0.01)	(>0.1)	(>0.1)	(0.01)	(>0.1)	(>0.1)	(>0.1)	(0.01)	(>0.1)	(>0.1)

Table 3. The hazard rate maximum-likelihood regression for divestitures ($N = 435$, divestitures = 61)

Variable name	1	2	3	4	5
Interest	6.53e + 43*	1.41e + 49*	9.28e + 43*	1.32e + 44*	5.41e + 48*
	(2.82e + 45)	(7.64e + 50)	(4.10e + 45)	(5.68e + 45)	(2.94e + 50)
License	0.83	0.78	0.78	0.84	0.75
	(0.25)	(0.23)	(0.23)	(0.26)	(0.23)
Option	0.53†	0.53*	0.55†	0.53*	0.55†
	(0.18)	(0.17)	(0.18)	(0.17)	(0.18)
Foreign transaction	0.70	0.85	0.71	0.70	0.85
	(0.19)	(0.23)	(0.98)	(0.19)	(0.23)
Log. Pharmaceutical sales	0.54**	0.52***	0.52***	0.53***	0.51***
	(0.11)	(0.10)	(0.10)	(0.11)	(0.10)
# of Pharmaceutical technologies	0.99	0.99	0.99	0.99	0.99
	(0.012)	(0.01)	(0.01)	(0.01)	(0.01)
# of Lab technologies	0.98	0.98	0.98	0.99	0.99
	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)
Industry returns	1.37e − 08**	5.28e − 07**	6.70e − 09**	9.86e − 09**	2.57e − 07**
	(8.33e − 08)	(2.95e − 06)	(4.23e − 08)	(5.97e − 08)	(1.54e − 06)
H1a: Industry uncertainty		5.08e − 221†			2.2e − 204†
		(1.42e − 218)			(6.0e − 202)
H2: Portfolio distance			0.21*		0.26†
			(0.16)		(0.21)
Partner distance				4.09	2.17
				(9.66)	(4.38)
Log-likelihood	−51.64	−46.99	−49.84	−51.43	−45.74
Log-likelihood ratio test		9.31**	3.61†	0.43	11.79**

Standard errors appear in parentheses. †$p < 0.10$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 4. The hazard rate maximum-likelihood regression for acquisition of alliance partners ($N = 435$, acquisitions = 14)

Variable name	1	2	3	4	5
Option	0.11*	0.11*	0.11*	0.12†	0.11†
	(0.12)	(0.12)	(0.11)	(0.14)	(0.13)
H1b: Industry uncertainty		2.72e − 39			1.29e − 122
		(7.28e − 37)			(3.65e − 120)
Portfolio distance			87.09†		269.34
			(241.33)		(965.73)
H3: Partner distance				0.0008†	0.0003*
				(0.003)	(0.001)
Log-likelihood	−50.10	−50.05	−48.14	−47.66	−44.91
Log-likelihood ratio test		0.08	3.91*	4.87*	10.37*

Standard errors appear in parentheses. †$p < 0.10$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

exercise of the option in order to benefit from potential upside gains.

Model 2 incorporates industry uncertainty. A likelihood ratio test comparing Model 2 with Model 1 indicates that the addition of this variable provides significant explanatory power ($p < 0.001$). Examination of the individual coefficient for industry uncertainty suggests there is a negative effect ($p < 0.10$) on the rate of partnership divestiture. This result is consistent with Hypothesis 1a, and consistent with models that emphasize the effect of uncertainty on a single transaction in isolation.

To test our conjecture about the importance of portfolio effects, Model 3 introduces a measure of portfolio distance. When compared to Model 1 using a likelihood ratio test, Model 3 provides a significant ($p < 0.10$) improvement in fit.

The individual coefficient for portfolio distance is significant ($p < 0.05$) and less than one, indicating that higher portfolio distance decreases the rate of divestiture. Specifically, a one-unit increase in portfolio distance multiplies the hazard of divestiture by 0.21. Conversely, lower portfolio distance increases the likelihood of divestiture. This result is consistent with Hypothesis 2. Model 4 adds the variable relating to the partner distance. Partner distance did not significantly contribute to model fit, but no relation was hypothesized for models estimating divestiture. Finally, we can see from Model 5 that the main relationships hold up in a full model, although the effects of these variables do not seem as strong as when they are introduced separately.

Table 4 considers a similar set of models as Table 3, while presenting the hazard rates for acquisitions, or buyouts, of biotechnology partners by pharmaceutical firms. Since there were only 14 buyout events, we chose to limit the number of control variables to better ensure model convergence. Unreported models with a full set of control variables were much less stable and produced high standard errors for our independent variables, though none of the reported relationships changed in those models. The only significant control variable in those unreported models was option ($p < 0.01$), so we retained that control for our analysis, while dropping the others. Obviously, without important controls, we believe our results should be interpreted with caution. Model 1 suggests that when pharmaceutical firms have equity partners with option agreements they have a decreased likelihood of buyout. Again, by ensuring appropriability, the presence of the clause leads to the option strategy of 'wait and see.' Industry uncertainty is added in Model 2 and it does not significantly improve model fit. This is contrary to expectations in Hypothesis 1a, which argued that uncertainty would lower the likelihood of partner buyout. Portfolio correlation is added in Model 3, and a likelihood ratio test suggests this variable significantly improves model fit relative to Model 1. The significant ($p < 0.10$) coefficient for portfolio correlation indicates that higher portfolio correlation increases the likelihood of partner buyout. We had no expectations about the effect of portfolio correlation on partner buyout. Model 4 tests Hypothesis 3, which argued that pharmaceutical firms with more fungible resources are more likely to acquire the partner. A likelihood ratio test indicates that Model 4 provides a significant ($p < 0.05$) improvement over Model 1. The individual coefficient for partner distance is significant ($p < 0.10$) and less than one, suggesting that partner distance has a negative effect on partner buyout, as expected in Hypothesis 3. Specifically a one-unit increase in partner distance multiplies the hazard rate of buyout by 0.0008. Stated differently, the lower technological distance between a pharmaceutical firm and a biotechnology partner, the greater the likelihood that the pharmaceutical firm will buy the partner. Once again, Model 5 tests whether these results hold up in a full model. Partner distance continues to have a significant negative effect on buyout, while the effect of portfolio correlation disappears in the full model.

DISCUSSION

The theoretical arguments and empirical results presented above reveal interesting patterns of interactions among exploratory investments made by firms. Most previous research has focused on individual investments of this kind. This paper underscores the importance of our emphasis on the interactions within a portfolio between the portfolio and the firm, and suggests that models excluding such interactions risk being underspecified. We suggest that when a firm has an exploratory investment that is more highly correlated with the rest of the firm's exploration activities, it is more likely to divest that investment. We also suggest that when a firm's exploratory investments are more similar to its own capability domain, they are more likely to internalize such investments.

Theoretically, we motivated our hypotheses by an integration of real options theory with the resource-based view. Our results partially confirm a central claim of prior research in real options theory—that exogenous uncertainty influences whether firms exercise their real options. However, the intent of our study was to go beyond this central claim, and focus attention on the implications of a firm having a portfolio of options.

By highlighting the possibility of sub-additivity and super-additivity between strategic options, this study seeks to provide valuable insights for both scholars and practitioners. From the academic perspective, this study provides a framework to determine the optimality of the portfolio of R&D strategic alliances or other options.

Previous research has not explicitly considered the effects of redundancies among investments made by the firm in the context of exploration in particular or in general. Redundancies that drive sub-additivity in our study are particularly interesting in the case of real option investments, since they have to be balanced against the benefit of flexibility based on switching among investments. Sub-additivity among exploratory investments is particularly relevant when first-mover advantage exists. An extreme case of first-mover advantage is the 'winner-take-all' situation. An example of this might be a patent race, where rents accrue to the first firm that makes a discovery, but none to the follower firms. In such settings with 'winner-take-all' properties, the investments made by the firm in the same technology or market are considered as substitutes. An alternative scenario that we did not explore in this study would be the case of *complementarity* among investments, as studied in Arora and Gambardella (1990). In such a case there would be positive rather than a negative effect of one investment on another, leading to another kind of super-additivity.

Our study also sheds light on how firms accumulate new capabilities and are able to share existing capabilities among projects. In this sense, we illustrate the redeployment of capabilities from one organizational context to another: internalization of biotech knowledge by pharmaceutical firms, and sharing of fungible resources between the pharmaceutical firm and its external investments.

From a practitioners' perspective, this study provides the basis for analyzing how efficiently their firms are creating and building their portfolios of strategic alliances in R&D and, therefore, how well they are building technological capabilities. Further, beyond the immediate context of the empirical analysis, the model has implications for other instances where real options perspectives have been deemed appropriate in previous research. These include entry into uncertain product and international markets.

Recently, Adner and Levinthal (2004) have argued that the literature on real options has overextended the application of this concept. They conclude that real options formulations are valid in application only when there is an explicit option or when the source of uncertainty is exogenous. Our defense against such criticism is twofold. First, Table 1 shows that about a third of our alliances contain an option clause and more than half contain a license clause. Thus, the majority of alliances in our sample therefore contain some version of an explicit option clause. Second, in analysis not shown in the paper, we tested to see if alliances undertaken by pharmaceutical firms in a particular technological domain led to increased propensity for outright acquisitions, as would be expected if the source of uncertainty was endogenous. We found that this was not the case; rather alliances in a technological domain predicted further alliances within that domain in the future. Therefore, we believe that the dominant form of uncertainty in our setting is exogenous, which is appropriate for real options formulations.

Our analysis using real option theory complements other views that have been used to examine situations involving multiple strategic alliances. Researchers have used transaction cost theory to diagnose whether a firm's alliance history curbs or accentuates opportunistic behavior in the context of repeated alliances with the same partner. Network theorists also have studied firms with multiple alliances, but their emphasis has been on the role of social networks as a substitute for hierarchy. Moreover, they have not been concerned with transitional governance decisions, such as the ones we study. Real options analysis provides an important complement to these approaches while departing from neoclassical investment theory. It also takes into account two important features of exploration-oriented investment decisions. First, most investments are at least partially irreversible since they cannot be fully recovered and costlessly redeployed in the event of a negative shock. Second, managers can adapt and revise their strategies in response to unexpected market developments that cause cash flows to deviate from their original expectations.

However, our empirical study has several other limitations. An important empirical limitation is that the sample is restricted to a particular industry. Furthermore, the sample only includes those firms that appear in *BioScan*, possibly reducing the generalizability of results. Future research would need to show evidence of applicability to broader samples in order to counter this limitation. A second limitation is that the study does not consider non-equity strategic alliances such as research agreements. It can be argued that such alliances also represent firm options, and should be considered a legitimate part of a firm's portfolio. Further, our measure of technological distances does not capture the weights of firms' investments. In our empirical analysis, we implicitly assume that each of the technologies is equally important and there is an identical investment associated with it. Unfortunately, our data constraints do not leave us with any way to control for investment amount in each technology; therefore, we are, for example, not able to compute an entropy measure based on firms' investments.

Also, cash constraints and past performance (e.g., discoveries, patents) of biotech labs also may significantly explain some governance choices (Chatterjee and Singh, 1999). Finally, observations for different governance choices are not balanced. There are relatively fewer observations for buyout than divestiture. We hope these limitations do not substantively affect the support for our model and propositions.

Besides overcoming the above limitations, future research must consider some other related theoretical issues. It is interesting to compare the implications and assumption of the real options and the network approaches. Recent studies have used network theory for generating interesting hypotheses and explaining ambiguous empirical findings regarding alliances. The network literature has substantially contributed to the understanding of the configuration of the portfolio of alliances (e.g., Powell *et al*., 1996). In general, network theory suggests a distinct cooperative element in the behavior of firms. In sharp contrast, the real option lens uses transactions as its main element of analysis. It would be interesting to compare and integrate predictions from these different behavioral traditions. Finally, another possible extension is to explicitly consider the effect of the presence of competitors, since multiple options analysis is even more challenging when the firm faces rivalry for the investment opportunity (Kulatilaka and Perotti, 1998).

CONCLUSION

By applying real options and resource-based perspectives to exploratory investments made by firms, we investigate the portfolio effects in such investments. Previous research has shown that the real options lens can be useful in understanding how firms can cope with exogenous events in their technological and market domains. Unfortunately, previous real options models have generally made the somewhat unrealistic assumption about the independence between real options. This study enhances this literature by relaxing such assumptions, and integrating some conclusions from the resource-based view in a real options formulation.

We have shown the need to incorporate interrelations among investments when valuing portfolios of real options. When strategic options are mutually competitive and correlated, the value of the portfolio is sub-additive. Consequently, a failure to incorporate this correlation could lead to overinvestment. In addition, the focal firm may possess fungible resources with public good properties that can be potentially leveraged in multiple settings, thus reducing the investment required and causing the portfolio to be super-additive. A failure to recognize this effect may lead to underinvestment, with some projects being more under-valued than others. We have found some empirical evidence in support of our model, though future research needs to overcome our limitations.

ACKNOWLEDGEMENTS

We are very grateful to Gautam Ahuja, Ashish Arora, Arnold Cooper, Connie Helfat, Will Mitchell, Dan Schendel, and Mark Shanley for helpful comments on previous versions of this paper. We also gratefully acknowledge the comments of participants in the seminar series at Illinois, Michigan, Purdue and Wharton, and at the Academy of Management meetings, BYU–Utah Strategy conference, Ohio State Alliance conference and the Strategic Management Society meetings, where earlier versions of the paper were presented.

REFERENCES

Adner R, Levinthal D. 2004. What is not a real option: considering boundaries for the application of real options to business strategy. *Academy of Management Review* **29**(1): 74–85.

Anand J, Singh H. 1997. Asset redeployment, acquisitions and corporate strategy in declining industries. *Strategic Management Journal*, Summer Special Issue **18**: 99–118.

Arora A, Gambardella A. 1990. Complementarity and external linkages. *Journal of Industrial Economics* **38**: 361–376.

Arora A, Gambardella A. 1994. Evaluating technological information and utilizing it: scientific knowledge,

technological capability, and external linkages in biotechnology. *Journal of Economic Behavior and Organization* **24**(1): 91–115.
Barney JB. 1991. Firm resources and sustained competitive advantage. *Journal of Management* **17**(1): 99–120.
Bergh DD. 1997. Predicting divestiture of unrelated acquisitions: an integrative model of ex-ante conditions. *Strategic Management Journal* **18**(9): 715–731.
Bergh DD, Holbein GF. 1997. Assessment and redirection of longitudinal analysis. *Strategic Management Journal* **18**(7): 557–571.
Bishop M. 1994. Corporate governance. *The Economist*, January 29: SS3.
Bowman E, Hurry D. 1993. Strategy through an options lens: an integrated view of resource investments and the incremental-choice process. *Academy of Management Review* **18**: 760–782.
Burgers WP, Hill CWL, Kim WC. 1993. A theory of global strategic alliances: the case of the global auto industry. *Strategic Management Journal* **14**(6): 419–432.
Capron L, Dussuage P, Mitchell W. 1998. Resource redeployment following horizontal mergers and acquisitions in Europe and North America, 1988–1992. *Strategic Management Journal* **19**(7): 631–661.
Capron L, Mitchell W, Swaminathan A. 2001. Asset divestiture following horizontal acquisitions: a dynamic view. *Strategic Management Journal* **22**(8): 817–844.
Chang SJ. 1995. International expansion strategy of Japanese firms: capability building through sequential entry. *Academy of Management Journal* **38**(2): 383–407.
Chatterjee S, Singh J. 1999. Are tradeoffs inherent in diversification moves? A simultaneous model for type of diversification and mode of expansion decisions. *Management Science* **42**(1): 25–41.
Chi TL. 2000. Option to acquire or divest a joint venture. *Strategic Management Journal* **21**(6): 665–687.
Davidson S. 1996. Hidden biotechnology worth over $7.5 billion a year. *Nature Biotechnology* **14**(May): 564.
Eisenhardt KM, Martin JA. 2000. Dynamic capabilities: what are they? *Strategic Management Journal*, Special Issue **21**: 1105–1121.
Elton EJ, Gruber MJ. 1997. *Modern Portfolio Theory and Investment Analysis*. Wiley: New York.
Folta TB. 1998. Governance and uncertainty: the tradeoff between administrative control and commitment. *Strategic Management Journal* **19**(11): 1007–1028.
Folta TB, Miller KD. 2002. Buyout options in equity partnerships: the effects of uncertainty and rivalry. *Strategic Management Journal* **23**(1): 77–88.
Galambos L, Sturchio JL. 1998. Pharmaceutical firms and the transition to biotechnology: a study in strategic innovation. *Business History Review* **72**(Summer): 250–278.
Gulati R. 1995. Social structure and alliance formation patterns: a longitudinal analysis. *Administrative Science Quarterly* **40**: 619–652.
Harrigan KR. 1981. Deterrents to divestiture. *Academy of Management Journal* **24**(2): 306–321.
Henderson RM, Clark KB. 1990. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly* **35**(1): 9–30.
Hoskisson RE, Johnson RA, Moesel DD. 1994. Corporate divestiture intensity in restructuring firms: effects of governance, strategy and performance. *Academy of Management Journal* **37**(5): 1207–1252.
Johnson H. 1987. Options on the maximum or the minimum of several assets. *Journal of Financial and Quantitative Analysis* **22**(3): 277–283.
Karim SZ, Mitchell W. 2000. Path-dependent and path-breaking change: reconfiguring business resources following acquisitions in the U.S. medical sector, 1978–95. *Strategic Management Journal*, Special Issue **21**: 1061–1081.
Kim D, Kogut B. 1996. Technological platforms and diversification. *Organizational Science* **7**(3): 283–301.
Kogut B. 1991. Joint ventures and the option to expand and acquire. *Management Science* **37**(1): 19–33.
Kogut B, Kulatilaka N. 1994. Operating flexibility, global manufacturing, and the option value of a multinational network. *Management Science* **40**(1): 123–139.
Kogut B, Kulatilaka N. 2001. Capabilities as real options. *Organization Science* **12**(6): 744–758.
Krimsky S. 1991. *Biotechnology and Society: The Rise of the Industrial Genetics*. Praeger: New York.
Kulatilaka N, Perotti EC. 1998. Strategic growth options. *Management Science* **44**(8): 1021–1031.
Luehrman TA. 1998. Strategy as a portfolio of real options. *Harvard Business Review* **76**(5): 89–99.
Madhok A. 1997. Cost, value and foreign market entry mode: the transaction and the firm. *Strategic Management Journal* **18**(1): 39–61.
March JG. 1991. Exploration and exploitation in organizational learning. *Organization Science* **2**(1): 71–87.
Markides CC, Williamson PJ. 1994. Related diversification, core competencies and corporate performance. *Strategic Management Journal*, Summer Special Issue **15**: 149–165.
Markowitz H. 1959. *Portfolio Selection: Efficient Diversification of Investments*. Wiley: New York.
McGrath RG. 1997. A real options logic for initiating technology positioning investments. *Academy of Management Review* **22**: 974–996.
McGrath RG, MacMillan I. 2000. *The Entrepreneurial Mindset*. Harvard Business School Press: Boston, MA.
Mitchell W. 1989. Whether and when: probability and timing of incumbents entry into emerging industrial subfields. *Administrative Science Quarterly* **34**(2): 208–230.
Mitchell W, Singh K. 1992. Incumbents' use of pre-entry alliances before expansion into new technical subfields of an industry. *Journal of Economic Behavior and Organization* **18**: 347–372.
Montgomery CA, Thomas AR, Kamath R. 1984. Divestiture, market valuation, and strategy. *Academy of Management Journal* **27**(4): 830–840.
Nelson RR. 1961. Uncertainty, learning and the economics of parallel research & development efforts, *Review of Economics and Statistics* **43**: 351–364.

Penrose ET. 1959. *The Theory of the Growth of the Firm*. Basil Blackwell: London.

Powell WW, Koput KW, Smith-Doerr L. 1996. Interorganizational collaboration and the locus of innovation: networks of learning in biotechnology. *Administrative Science Quarterly* **41**(1): 116–145.

Rothaermel FT. 2001. Incumbent's advantage through exploiting complementary assets via interfirm cooperation. *Strategic Management Journal*, Special Issue **22**(6–7): 687–699.

Sanchez R. 1993. Strategic flexibility, firm organization, and managerial work in dynamic markets: a strategic options perspective. In *Advances in Strategic Management*, Shrivivasta P, Huff A, Dutton J (eds). JAI Press: Greenwich, CT; 251–291.

Stuart TE, Podolny JM. 1996. Local search and the evolution of technological capabilities. *Strategic Management Journal*, Summer Special Issue **17**: 21–38.

Stuart TE, Hoang H, Hybels RC. 1999. Interorganizational endorsements and the performance of entrepreneurial ventures. *Administrative Science Quarterly* **44**: 315–349.

Stulz RM. 1982. Options on the minimum or the maximum of two risky assets. *Journal of Financial Economics* **10**: 161–185.

Teece DJ. 1992. Competition, cooperation, and innovation: organizational arrangements for regimes of rapid technological progress. *Journal of Economic Behavior and Organization* **18**: 1–25.

Teitelman R. 1989. *Gene Dreams: Wall Street, Academia, and the Rise of Biotechnology*. Basic Books: New York.

Trigeorgis L. 1993. The nature of option interactions and the valuation of investments with multiple real options. *Journal of Financial and Quantitative Analysis* **28**(1): 1–22.

Trigeorgis L, Mason SP. 1987. Valuing managerial flexibility. *Midland Corporate Finance Journal* **5**(1): 14–21.

Wernerfelt B. 1984. A resource-based view of the firm. *Strategic Management Journal* **5**(2): 171–180.

Williamson OE. 1985. *The Economic Institutions of Capitalism*. Free Press: New York.

Williamson OE. 1988. Technology and transaction cost economics: a reply. *Journal of Economic Behavior and Organization* **10**: 355–363.

Zhou L, Peteraf MA. 2002. Resource matters! A strategic review of real options volatility. Academy of Management Annual Meeting, Denver, CO.

Zollo M, Winter SG. 2002. Deliberate learning and the evolution of dynamic capabilities. *Organization Science* **13**(3): 339–351.

Zucker LG, Darby MR. 1997. Present at the biotechnological revolution: transformation of technological identity for a large incumbent pharmaceutical firm. *Research Policy* **26**: 429–446.