Real Options in Finance ⋆

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Abstract

Although the academic literature on real options has grown enormously over the past three decades, the adoption of formal real option valuation models by practitioners appears to be lagging. Yet, survey evidence indicates that managers' decisions are near optimal and consistent with real option theory. We critically review real options research and point out its strengths and weaknesses. We discuss recent contributions published in this issue of the journal and highlight avenues for future research. We conclude that, in some ways, academic research in real options has catching up to do with current practice.

JEL classification: G13; G31

Keywords: Real option; Capital budgeting

1 Introduction

This article provides a critical review of research in real options. A comparison with research in financial options may be a good starting point. Financial options have been traded for many centuries. Vanilla options are written on a traded asset or security such as a commodity, currency, stock or index. Option contracts can be clearly defined in a couple of lines and are highly standardized. The prices for these contracts are set in option markets. Kairys and Valerio (1997) and Moore and Juh (2006) provide evidence that option markets were fairly sophisticated and efficient more than a century before the Black-Scholes model became available. Research in options and derivatives

⋆ I thank Carol Alexander for helpful comments. I gratefully acknowledge financial support from the Cambridge Endowment for Research in Finance (CERF).
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took off in the 1970s, and led to the creation of specialist journals such as the Journal of Derivatives and the Journal of Futures Markets. Nowadays, off-the-shelf valuation formulas are available for many types of option contracts. In financial markets, where speed is of the essence, automated trading systems based on state of the art derivative research are likely to beat derivative traders without access to this research expertise.

The term "real options" was coined by Myers (1977) and refers to options embedded in investment opportunities such as the option to delay, expand, switch, suspend, contract or abandon an investment. Real options have been around for thousands of years and people have somehow managed to value and exercise them.[1] Conceptually, real options might appear simple. In practice they are not. A real option's underlying asset or payoff is often highly complex, not traded and subject to strategic interactions with its environment. Real options are usually not traded in the market. Absent a market price, investors attach a private (subjective) value to real options. Every real option is uniquely defined by its context and requires a tailor made valuation. There are few (if any) off-the-shelf real option valuation models, and adapting existing models to value specific real options is not always straightforward. Practitioners therefore often rely on their experience and intuition to value and exercise real options similar to a chess master who, in an instant, can evaluate a complicated position by recognizing and remembering patterns and narrowing down the infinite strategy space to a few candidate optimal strategies. The day where some kind of an automated "Deep Blue" real options manager will outperform a CFO is still a long way off (and might never arrive).

Real options papers have been published in a wide variety of journals depending on the research area they relate to. The earliest real options papers were published in finance and economics journals, but real options research has since branched out into areas as diverse as management science, strategy, insurance, taxation, environmental economics and engineering. A google scholar reveals that the number of papers with "real options" or "real option" in the title is 8090 of which 2825 since 2010.[2]

This article and the special issue it introduces focuses on real options in finance. The field of finance is also the birth place of real options research. Myers (1977) breaks down the firm in two distinct asset types: (1) real assets, which have market values independent of the firm's investment strategy, and (2) real options, which are opportunities to purchase real assets on possibly

[1] For example, hunter-gatherers had to decide on a daily basis whether to invest time and energy to pursue a prey in sight, or whether to wait for a better opportunity.

[2] The number of papers with the words "real options" or "real option" in the article exceeds 8 million, of which more than 2 million since 2010.

favorable terms. This approach builds on Black and Scholes (1973) and Merton (1974) who showed that corporate liabilities can be valued using option pricing techniques. The option-like feature arises from equityholders' limited liability, which gives them an abandonment option.

The valuation of the canonical types of real options took off in earnest with the seminal papers by Brennan and Schwartz (1985) and McDonald and Siegel (1986) who study the effect of uncertainty and irreversibility on the valuation and optimal exercise of real options. During the decade that followed research focussed on the pricing of real options such as entry and exit options (Dixit (1989)), incremental capacity choice (Pindyck (1988)), time to build (Majd and Pindyck (1987)), and the role of frictions and costly adjustments (Abel and Eberly (1994)). In an influential book, Dixit and Pindyck (1994) give a state of the art overview of real options research up to the mid nineties. The book focuses on real options within the context of a single, all-equity financed firm operated by an owner-manager. Firms operate as monopolists (with the exception of Leahy (1993) who considers entry and exit in a competitive industry equilibrium). Strategic considerations between firms, or between shareholders and other stakeholders do not feature in the book. [3]

All models in Dixit and Pindyck (1994) are in a continuous-time setting (barring a few discrete-time examples in the introductory chapters). Continuous-time methods have remained the most popular choice for academic research in real options. (The papers in this special issue are no exception as all are in continuous time.) Even though continuous-time valuation requires higher level maths (such as stochastic calculus), the valuations and exercise strategies are often more tractable than those generated by mathematically simpler discrete-time methods (such as the binomial model). Closed-form solutions in continuous time also allow real option valuation to be integrated with other methods, such as game theory. However, as the real options literature matures and tackles increasingly more complex problems, I anticipate that discrete-time methods may gain in popularity. First, many important decisions in economics and finance are made at regular intervals. For example, many firms pay dividends and release earnings on a quarterly basis. If one wants to model payout and earnings smoothing, and show how these decisions interact with the firm's financing and investment policy then a discrete-time setting may be required to study some aspects. Second, discrete-time models are conceptually simpler making them sometimes more straightforward to integrate valuation with, for example, game-theoretic considerations. Although potentially messy in practice, it is conceptually straightforward to determine an agent's optimal strategy at each decision node in a discrete-time setting. Developing optimal strategies in continuous-time and proving optimality can be trickier and more delicate. Third, continuous-time methods quickly lose their tractability

[3] One exception is the leader-follower model for entry in a duopoly by Smets (1993). Dixit and Pindyck (1994) identify stochastic games as an area for future research.

for problems with more than one state variable, or when path dependency matters. Admittedly, the curse of dimensionality and path dependency are challenges for real option valuation more generally.

From the mid nineties onwards the focus of real options research shifted from developing towards applying real options methods. Applications cover a variety of problems in economics and finance. Giving a comprehensive overview of this literature is beyond the scope of this paper, and I refer to related review articles (Sundaresan (2000), Strebulaev and Whited (2012)) and books (Trigeorgis (1996), Amram and Kulatilaka (1998), Chevalier-Roignant and Trigeorgis (2011), Smit and Trigeorgis (2012), Smit and Moraitis (2015)) that cover parts of this large field. Instead, I will give a critical review of the strengths (section 2) and weaknesses (section 3) of real options valuation. Section 4 then briefly discusses the areas of research that are relevant to the papers in this special issue, and points out how the papers in the special issue contribute to existing research. Conclusions and avenues for future research are presented in section 5.

2 Strengths of real option valuation

The success of real option valuation (hereafter ROV) can be attributed to a few key strengths. First, ROV methods generate dynamic models that allow us to make quantitative predictions. For example, a structural real options model of the firm (such as Leland (1994)) generates estimates for the firm's value, default probability, credit spread and many other variables of interest. The model allows us to predict what happens to those variables if, say, the volatility of the firm's assets increases from 20% to 30%. Static models only generate qualitative predictions that may not necessarily hold in a dynamic context (Pennings (2017) in this special issue provides such an example).

Second, structural real option models can (unlike their static counterparts) be brought to the data and tested. Structural estimations can be used to obtain parameter estimates of unobservables. This is useful in areas such as capital structure research where the relative costs and benefits of leverage have been central to the debate. Dynamic structural real options models allow estimates for expected bankruptcy costs, issuance costs and managerial preferences to be inferred. These estimates may shed light on the plausibility of a particular capital structure theory. We refer to Strebulaev and Whited (2012) for an excellent review on dynamic structural models in corporate finance and structural estimation.

Third, ROV methods allow us to calculate values for investment projects and contingent claims on these investments. The seminal paper by Brennan and Schwartz (1985) shows how in the spirit of Black and Scholes (1973) and

Merton (1973) real options can be priced by finding a risk-free self-financing portfolio whose cash flows replicate those which are to be valued. The present value of the cash flow stream is then equal to the current price of this replicating portfolio. Merton (1998) argues that even if the underlying asset is not traded or its price not observed, its value can often be tracked by a portfolio of traded securities. To derive the option valuation formula one pretends "as if" the underlying asset is traded. Having a pricing framework is useful for cases where a significant fraction of a firm's value is attributed to real options (e.g. growth options). Of course, given that real options can only add value, one has to be careful not to inflate valuations.

Fourth, ROV encourages managers to think strategically about investments. ROV requires managers to identify the options at their disposal and pro-actively to determine under which circumstances or conditions they will be exercised. This leads to a pro-active and flexible management style in which managers act optimally as economic uncertainty unfolds. ROV provides a framework that bridges the gap between finance and strategy. In practice, first order mistakes are not made because of a second order mispricing of a real option, but because a valuable real option has been overlooked altogether. ROV is still useful as a conceptual framework even when those real options are (too) hard to value. To quote Amram and Kulatilaka (2000), ROV is "a way of thinking" that helps managers formulate their strategic options.

Finally, ROV provides a paradigm within which capital budgeting research can consolidate. Before Modigliani and Miller (1958) capital budgeting (and finance more generally) consisted of a collection of disparate theories, anecdotes and rules of thumb that were in no way based on a common set of principles and axioms. The papers by Modigliani and Miller (1958), Black and Scholes (1973) and Merton (1973) introduced core principles such as value additivity and arbitrage, allowing finance theories to be built on a common foundation and to consolidate into a coherent framework. Those theories can be tested, and anomalies that are encountered can spur research into new directions.

3 Real option valuation: weaknesses and challenges

The dynamic nature of ROV comes at a cost of increased complexity and decreased transparency. The mathematical complexity may partially explain why ROV is not (yet) the workhorse capital budgeting method in finance textbooks. Core finance courses to undergraduate and MBA students still rely on the static Net Present Value (NPV) method, with a proper study of ROV left for more advanced elective courses. In a survey by Graham and Harvey (2001), 75% of CFOs respond that they "always or almost always" use NPV, but only 25% claim to use real option methods. Block (2007) surveys the Fortune 1000 largest companies in the US and reports that only 14.3%

of respondents use real options in the capital budgeting process. The users come primarily from industries where sophisticated analysis is the norm such as technology, energy and utilities. The primary reasons given for non-use of real options in order of importance are "(a) lack of top management support; (b) discounted cash flow is already a proven method; (c) real options require too much sophistication and (d) real options encourage excessive risk-taking because CFOs believe that ROV overestimates the value of uncertain projects encouraging companies to invest in them".

These survey findings appear at odds with empirical studies reporting that managerial decisions and market prices for assets with real options are consistent with real options theory. Admittedly, the number of empirical studies is small and they focus on a few industries such as real estate (Quigg (1993), Cunningham (2006), Bulan et al. (2009)), oil (Paddock et al. (1988), Kellogg (2014)) and mining (Moel and Tufano (2002)). More importantly, the surveys do not necessarily contradict the empirical findings. Practitioners may actually apply real option thinking in a heuristic way. E.g. Kairys and Valerio (1997) study option trading in New York during the 1870s and concluded that financial markets exhibited a degree of sophistication that would easily be recognized by investors of today. Moore and Juh (2006)) examining equity options in early twentieth century Johannesburg concluded that "investors appear to have been able to process relevant information and come close to determining the fair value of derivatives." Likewise, today's managers may be able to exercise real options in a timely fashion. It is quite plausible that managers get valuations "approximately right". After all, competition ensures that managers who get it wrong (too often) lose their job. McDonald (2000) shows that commonly used "rules of thumb" such as hurdle rates, profitability indexes and payback rules can proxy for the use of more sophisticated ROV and provide close-to-optimal investment decisions for a variety of parameters.

Second, ROV being a sophisticated valuation method can sometimes lead to a false sense of accuracy and focus the attention too much on the valuation model, and too little on the model assumptions and inputs. If the model assumptions and inputs are wrong, then ROV will get the valuation "precisely wrong".

Third, the identification and valuation of real options involves a certain amount of subjectivity. Given that real options can only add value, one has to be careful not to inflate values. For example, ROV was used during the high tech bubble of the late nineties in order to explain and justify the inflated prices of some internet and high tech firms that yet had to generate profits. Also real options could be used by unscrupulous managers in order to push through pet projects that destroy firm value.

Fourth, ROV is in essence a dynamic version of NPV in which the discount rate gets adjusted as uncertainty unfolds, real options get exercised and the riskiness of the project changes. This insight goes back to Black Scholes (1973) who showed that options can be valued using the CAPM framework but with an option beta that varies over time and depends on the option elasticity. ROV and capital budgeting methods more generally tend to focus on the discounting process (i.e. the denominator) and how discounting is affected by the firm's capital structure and risk. Relatively little attention is paid to the cash flow process (i.e. the numerator) and its statistical and economic properties. The usual justification is that predicting cash flows such as sales and costs is beyond the scope of finance and falls under the remit of marketing or operations management. But the sales and production manager may produce sales and cost predictions not with a (exclusive) view to generate precise and unbiased valuations. Often their forecasts may be produced for different purposes such as planning, budgeting and managerial compensation. These forecasts may not be ideal for valuation purposes and lead to real option exercise policies and valuations that are biased. Likewise, annual accounts are not constructed with a view to give us the most accurate valuation of a firm's assets in place. Figuring out how available data can best be used for valuation purposes remains a big challenge.

Fifth, ROV gets intractable when multiple state variables are introduced (Bellman's so-called curse of dimensionality). This poses serious challenges for investments with multiples sources of uncertainty. The Least-Squares Monte Carlo model (LSM model) by Longstaff and Schwartz (2001) has produced a significant breakthrough on this front. The LSM model combines Monte Carlo simulation, dynamic programming and statistical regression in a flexible procedure to value nearly all types of corporate investments. But, the use of complex statistical techniques and software packages may turn the valuation process into a black box. Due to its numerical nature, the LSM model is not that useful for the development of theoretical work.

Finally, although real option methods value managerial flexibility (i.e. how managers optimally respond to economic shocks), ROV due to its complexity is not a particularly flexible valuation framework if managers cannot in advance identify the firm's options but have to discover and exercise them as uncertainty unfolds. Inserting newly discovered real options into an existing valuation framework is not always straightforward due to the complicated interactions between real options and assets in place.

4 Recent advances in real options

The five real options papers in this issue contribute to four different strands of literature. Davis (2017) contributes to a strand of early real options papers that focus on the effect of uncertainty and (ir)reversibility on investment. Leippold and Stromberg (2017) contributes to a literature on ROV in incomplete markets. The papers by Pennings (2017) and Goto et al. (2017) belong to a large literature on strategic real options. Finally, Koussis et al. (2017) contribute to a growing literature on dynamic real options models in corporate finance.

4.1 Real options, uncertainty and (ir)reversibility

The real options literature has examined the role of uncertainty and irreversibility on the optimal timing of investments. For good reasons, much more attention has been devoted to uncertainty than irreversibility, with many studies assuming investment costs to be completely sunk. Partial irreversibility has been considered and the common belief is that perfectly reversible investments fit on one end of a continuous spectrum between fully irreversible and fully reversible investments, with full reversibility restoring the standard NPV approach.[4] The paper by Davis (2017) in this special issue shows that this common belief is not generally valid.

Davis (2017) presents a modified version of the seminal real options paper by Brennan and Schwartz (1985) in which the degree of (ir)reversibility is summarized by a single parameter. He shows that the orthodox NPV rule is not applicable to the special case of reversible lumpy investments. Furthermore, completely reversible investments have little in common with investments that are partially irreversible. E.g. under complete reversibility volatility, risk preferences, and the growth rate of the future cash flows play no role in the investment decision. The optimal decision rule is static in nature in that it compares at each instant the current net cash-flow with "Jorgenson's (1963) opportunity cost of capital". (Investment decisions are therefore made as in the textbook macro-economic representation of the firm employing lumpy rental capital.) There is no need for optimal timing or for an NPV analysis. This simple static rule is, however, valid only for the limiting case of perfect reversibility. Introducing the slightest form of irreversibility invalidates this approach and necessitates the ROV approach.

4.2 Real options and incomplete markets

The paper by Leippold and Stromberg (2017) in this issue contributes to a growing literature on ROV in incomplete markets. Earlier papers exploring the implications of incomplete markets on asset pricing more generally include Constantinides and Duffie (1996), Duffie et al. (1997), Basak and Cuoco (1998), and Chacko and Viceira (2005). Miao and Wang (2007) extend the

[4] With the exception of Shackleton and Wojakowski (2001), the existing literature has not studied the treatment of completely reversible lumpy investments.

standard real options approach to an incomplete markets environment and show that risk aversion and undiversifiable idiosyncratic risk delay the entrepreneur's investment decision. Related real options papers include Henderson (2007), Hugonnier and Morellec (2007) and Chen et al. (2010).

Leippold and Stromberg (2017) put the strategic leader-follower model of Huisman and Kort (2004) in an incomplete markets setting. Each entrepreneur has to decide strategically when to invest and whether to adopt an existing technology for production or wait for a more efficient technology to become available for adoption. In addition, they let entrepreneurs hedge at least the systematic part of their investment risk in the financial market. Hence, they decide on the optimal time to exercise their real investment option and, in contrast to Huisman and Kort (2004) where entrepreneurs have no access to financial markets, they also have to make optimal intertemporal portfolio decisions. Hence, Leippold and Stromberg (2017) also provide an answer to how the optimal portfolio choice is affected by strategic considerations regarding technology adoption.

They find that the effect of non-diversifiable risk on the timing of the entrepreneurs option is ambiguous, and depends on the frequency of technological change and risk aversion. Consequently, the presence of non-diversifiable risk may accelerate or delay the optimal investment timing compared to complete markets. This result contrasts with Miao and Wang (2007) who show that non-diversifiable risk delays investment by a monopolistic risk averse agent. Leippold and Stromberg (2017) offer new insights into the determinants of optimal portfolio choice for both current and prospective entrepreneurs. The greater the technological innovation and the higher the correlation between operating net income and the risky asset, the more the prospective entrepreneur (follower) should reduce the portfolio allocation to the risky asset. At the same time, the current entrepreneur (leader) should increase the portfolio allocation to the risky asset, in anticipation that the follower optimally exercises the investment option, should the more efficient technology arrive.

4.3 Strategic real options

4.3.1 Real options and surplus sharing

In some cases the payoff of a real option is shared between several parties. While there exists an extensive literature on bargaining and how it affects agents' incentives to invest or spend effort, most models are static in nature or do not deal with uncertainty. There are few models that study bargaining or surplus sharing in a dynamic real options framework. Notable exceptions include papers that study debt renegotiation between equityholders and creditors (e.g. Mella-Barral and Perraudin (1997), Fan and Sundaresan (2000)), debt renegotiation with many creditors (e.g. Hege and Mella-Barral (2005)), sharing of merger or takeover surplus (e.g. Lambrecht (2004) and Morellec and Zhdanov (2005)), and the sharing of investment payoff between a principal and agent (e.g. Grenadier and Wang (2005)).

Pennings (2017) contributes to this line of research by modelling the timing and amount of relationship specific investment by an upstream supplier in order to trade with a downstream buyer. Standard bargaining models that take the timing of investment as exogenous show that the possibility of holdup causes the seller to underinvest (relative to an integrated firm that faces no holdup problems). Pennings (2017) shows that the underinvestment result may no longer hold if the timing of investment is endogenously chosen by the seller. In particular, he shows that the optimal level of the seller's investment equals the efficient investment level of an integrated firm for payoff functions that are multiplicatively separable in time and the level of investment. However, bargaining with the buyer leads to inefficiently *late* investment, creating a different type of underinvestment. The paper illustrates that a dynamic model can lead to results that are significantly different from its static counterpart.

4.3.2 Strategic market entry in booms and busts

Goto et al. (2017) study the strategic entry problem of two asymmetric firms operating in an economy that can switch back and forth between booms and busts according to a Markov switching process.

A large number of papers have studied strategic market entry in a real options setting following the influential paper by Grenadier (1996). A smaller number of studies (Hassett and Metcalf (1999), Guo et al. (2005), and Hackbarth et al. (2006)) study the effect of regime shifts on the optimal investment strategy. These studies show that the optimal decision rule is not described by a simple threshold for the marginal revenue of capital. Instead, the optimal investment policy is characterized by a different threshold for each regime. Regime shifts can also easily lead to lumpy capacity investments.

Goto et al. (2017) introduce Markov regime switching into Pawlina and Kort (2006) who model the investment strategy of two competing firms with different investment costs. While in existing models the cost advantaged firm enters the market first, Goto et al. (2017) show that with regime switches there can be instances where the less profitable firm enters first. The model predicts that a preemptive equilibrium is more likely to occur in a boom than in a bust, particularly for moderate levels of regime switching intensity.

Goto et al. also study their model's implications for the equity risk premium and in doing so contribute to a recent strand of papers that study the effect of real options on equity returns (see e.g. Berk et al. (1999), Kogan (2004), Carlson et al. (2004), Zhang (2005), Cooper (2006) and Aguerrevere (2009)). These studies show that negative productivity or demand shocks increase risk and lead to higher expected returns. The relation between the state of the economy and firm risk can, however, be highly non-monotonic for firms that combine real options with operating leverage (Hackbarth and Johnson (2015)) or for firms that switch between internal production and outsourcing (Lambrecht et al. (2016)). Goto et al. (2017) show that the equity risk premium can be non-monotonic with respect to the level of demand between leaders' and followers' investment thresholds. They show that the firm's beta in a bust is higher than in a boom. Their study shows a negative relationship between the beta and the expected growth rate of profits.

There is still a lot we do not understand about the return dynamics of corporate debt and equity. Studying the effect of real options on expected returns may be a fruitful area for future research.

4.4 Real options and corporate finance

Koussis et al. (2017) develop a real options model to explore corporate liquidity and dividend policy. As such the paper contributes towards a growing strand of literature on dynamic corporate finance models (see Strebulaev and Whited (2012) for a comprehensive review). The state variable in most models is either a stock variable, such as the firm's risky assets (e.g. Fischer et al. (1989), Leland (1994)) or a flow variable that drives the firm's cash flows (e.g. Mello and Parsons (1992), Mauer and Triantis (1994)). The former typically assume that all profits get reinvested (but there are exceptions like Fan and Sundaresan (2000)) whereas the latter usually assume that all profits are paid out as dividends to equityholders, and losses are covered through equity issues.

Modelling both liquidity and dividends can significantly complicate the analysis as one needs to keep track of the cumulative earnings retained within the firm. Recently, a number of papers have tackled the challenge of modeling a more meaningful and realistic payout policy. In a Modigliani and Miller world, payout does not matter. Some papers (e.g. Hennessy and Whited (2005, 2007), Gryglewicz (2011) and DeAngelo et al. (2011) and Décamps et al. (2011, 2016)) obtain an optimal payout policy by introducing frictions such as taxes, transaction and adjustment costs and bankruptcy costs. These models typically generate a target liquidity level below which no payout occurs. For example, in Bolton, Chen and Wang (2011), firms pay out cash only when cash holdings are large, so that the shadow price of cash held for future investment is small and the costs of holding cash become burdensome.

A few papers (e.g. Lambrecht and Myers (2012, 2017)) model payout as set by risk averse managers who want to maximize the life-time utility of rents (i.e. compensation) they extract from the firm. Agency models of this type generate payout smoothing, and financial policies that depend on managers' preferences and utility function. Payout is linked to permanent income (Lambrecht and

Myers (2012)) or the firm's cumulative retained income (Lambrecht and Myers (2017)).

Koussis et al. (2017) model dividends and liquidity within a 3-date model. They first presents a simpler two-date model that is solved analytically using a Black-Scholes (1973) style valuation framework, and subsequently solve the extended 3-date model numerically. At time 0 the firm chooses its level of dividends and debt. At the intermediate date the firm pays the debt coupon, decides whether to exercise a growth option and how much cash to save. Equity and debt claims are settled at time 2. In line with existing papers, the authors find that high levels of cash have a net positive effect on firm value in the presence of growth options and high external financing costs (see e.g. Gamba and Triantis (2008)). The role of bankruptcy risk is, however, less standard. Koussis et al. (2017) show that high default risk can actually reduce equityholders' incentives to retain cash. While cash may reduce the likelihood of default, cash savings will be lost to equityholders if default occurs. High default risk therefore creates incentives preemptively to distribute cash to equityholders. As a result high (low) earnings retention maximizes firm value when default risk is low (high), and when growth options and external financing costs are high (low).

This type of "cash in and run" behavior identified by Koussis et al. (2017) may be inefficient ex ante. Exploring the role of debt covenants in mitigating this behavior may be an interesting avenue for future research.

5 Directions for future research and conclusions

We can identify at least four broad areas for future research in real options and capital budgeting more generally: real option applications, further development of real option methods, empirical studies and tests of ROV, and surveys or studies that provide insights in the way practitioners value and exercise real options.

The scope for more real option applications is vast. Real option methods are now being applied to a large variety of problems in finance, economics and other academic disciplines. For example, most papers in this special issue apply ROV to some economic problem in order to gain new insights. The body of papers applying real options is likely to grow significantly in the foreseeable future.

Making further advances in real option methods will become increasingly more difficult after three decades of research in real options, and almost half a century after the publication of the Black-Scholes formula. One obvious outstanding challenge is to develop a tractable and transparent framework that studies portfolios of real options and disentangles the intricate interaction between real options and their exercise strategies. Heuristic approaches that provide near-optimal solutions may be of value here. The effect on real options of market incompleteness, risk aversion, managerial preferences and behavioral biases are other challenging and promising areas of research. Another methodological contribution may be to integrate optimal stopping problems more effectively with other decisions for which the timing is predetermined. For example, dividends are typically modeled as a flow variable in existing continuous-time models, whereas many companies pay lumpy dividends on a quarterly basis. Current models in continuous time cannot fully capture dividend smoothing and how payout interacts with other corporate decisions.

We need more empirical studies that test whether firms behave according to what real options theory predicts. Existing studies focus on a few industries. Hopefully future studies will cover a wider variety of industries and investment decisions.

Finally, we know from existing surveys that many managers do not formally apply ROV. Yet, the decisions of successful managers are near-optimal. This raises the question as to how exactly managers value projects and make investment decisions, and what the secret is behind their success. The capital budgeting process adopted by practitioners is still a black box to academics. Opening up this black box may provide us with many new insights. Identifying practitioners' heuristic rules or "rules of thumb" will not only teach us how capital budgeting is being done in practice, but it may also help us to refine formal real option theory and to take into account managers' subjective judgement, preferences or behavioral biases. After all, real option valuation, which combines capital budgeting with corporate strategy, is not a science but an art.

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