Real Options in Infrastructure: Revisiting the Literature

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Abstract: Infrastructure networks are essential to support the world's economic development. Governments around the world, in both developed and developing economies, have dedicated significant shares of the public budget to infrastructure development and refurbishment. Nevertheless, there has been an increasing concern about the selection of economically more interesting projects. The large sunk investments, as well as the uncertainty surrounding these projects, require new and more sophisticated investment analysis techniques. Simultaneously, there has been a recent trend towards increasing the flexibility in these projects to allow a more progressive adaptation to changing market conditions, thus decreasing the overall risk affecting these investments. The flexibility is introduced through real options that include the possibility of change that one develops in the planning and design stage, allowing the infrastructure (and service) to cope with future uncertainty. This paper intends to provide an overview of the current literature on real options, thereby fulfilling a gap in current academic literature. It addresses the main types of options and valuation mechanisms and provides an extensive overview of their application to the infrastructure sector. **DOI: 10.1061/(ASCE)IS.1943-555X.0000188.**

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Introduction

The realm of infrastructure investment analysis has been an active field of research in the last several decades. The discounted cash flow (DCF) method was used to calculate the value of a project. The critical variable was the choice of the discount rate that would "transform" future cash flow into present values. This method was seen as the most adequate and suitable to capture the project's real value, although other alternatives existed; e.g., capital cash flow, which is more suitable to large investments with variable debt structures (Esty 1999).

Large infrastructure investments, like roads, airports, dams, and hospitals, are long-term projects with large sunk costs. Moreover, the context involving these projects is frequently highly uncertain, particularly regarding demand, capital costs, and even construction costs (Cruz and Marques 2013). This uncertainty has been acknowledged by the academic literature (Skamris and Flyvbjerg 2003), but only recently has the subject been truly addressed by academics. The proposed alternative is the design of flexible infrastructure projects (i.e., to incorporate flexible options into the projects).

The rationale for incorporating flexibility in infrastructure projects is rather simple, unlike the empirical application, which can be extremely complex. The principle is that the project should have the necessary flexibility to adapt to future changes; i.e., at the design stage, it is necessary to incorporate flexible options (real options) that allow the infrastructure and/or the service to be adapted to a certain change (Wang and de Neufville 2005). A casebook example is the 25th of April Bridge over the Tagus River in Lisbon, Portugal. The initial project included only one road deck for cars, but the substructure was reinforced to accommodate a future second deck. A second deck was added some decades later, but instead of a road deck, the new deck offers rail services (de Neufville et al. 2008).

How should one value this flexibility when calculating the economic value of the project? Simple DCF techniques take into account the cost of building this flexibility, but not the benefit of using the flexibility according to an adaptable timing.

Emerging from the financial market, real options (ROs) have their origins in the seminal work of Black and Scholes (1973) and Merton (1973), who provided the theoretical formulation to evaluate financial assets—options.

ROs are, nowadays, a growing valuation tool for infrastructure investments. Their growth in the last two decades meets the needs of new methods to evaluate project value since DCF do not allow capturing the inherent value of flexibility (Frayer and Uludere 2001).

In the medium and long term, market fluctuations will evolve, and what is unknown now will become known in the future. This is why projects should be designed to accommodate those changes. Because this is the case. Some of the managerial choices cannot, or should not, be taken into account during preproject planning to increase the project's value. This requires profound changes in the forecast paradigm. Project designers and managers must understand the range of uncertainties, and projects should be designed to deal effectively with a large number of possible scenarios. Understanding the difficulties associated with the *flow of averages* is the key to addressing risk and uncertainties properly.

The expansion into several areas arose naturally. Just over a decade after being put into practice, ROs have been used in many fields [e.g., natural resources investment, corporate

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governance, research and development (R&D) and business strategy; Triantis (2005)].

Their application in infrastructure began in 1991, in a theoretical example concerning the Sydney airport (de Neufville 1991). Since the beginning of the 21st century, the use of ROs applied to infrastructure projects has grown large, both in number of authors and of articles published. There is a clear tendency toward growth, and since this is a relatively recent field in infrastructure studies, it will probably remain so over the next decade.

Incorporating flexibility into design is a core issue as far as facing future uncertainty is concerned. Despite all the adjacent benefits when projects are designed carefully, there are still several other aspects that must be addressed. Because this is so, incorporating flexibility in design is only part of the solution, not the solution by itself.

The present paper aims to provide an overview on the academic literature of ROs in infrastructure, highlighting the importance of this approach to project design, not only because it maximizes the project value, but also because it represents a paradigm shift on how infrastructures will be built in the future. To the authors' knowledge, this is the first paper to provide such an overview, thus allowing academics to understand quickly the main drivers of the research alongside the main critical issues and main contributions.

After this introduction, section "Beginning of ROs from Financial to Real Options" explains how and why ROs appeared, along with their main features. Thereafter, in section "Valuation Tools: Techniques to Value ROs", five valuation techniques are described and their pros and cons are emphasized. Section "Comparison between Models" focuses on real options applied to infrastructure, while in the last section, the major conclusions and future research are discussed.

Beginning of ROs from Financial to Real Options

ROs: From Financial to Real Options

The Beginning

The foundation of financial options (FO) theory was established in 1900 by the French mathematician Louis Bacheliers—"The theory of speculation," as argued by Chiara et al. (2007). Around 1960, Samuelson recognized the need to bring the value of the uncertain payoffs back to the present. Nevertheless, this work did not solve the discount rate problem. The field of capital budgeting remained stagnant for several decades until recent developments in RO theory that provided new tools and unlocked the possibilities of revolutionizing the field. RO roots have their origin in financial stock option pricing. These financial options are contracts sold against a certain premium, giving the buyer the right, but not the obligation, to buy a stock against a predetermined price (Ammerlaan 2010).

The Need for a New Approach

Myers (1984) and Trigeorgis and Mason (1987) pointed out the main problems and limitations of the DCF method, concluding that it could lead to wrong investment decisions. The main problems regarding the DCF method are the fact that expected future cash flows do not adequately reflect the flexibility within the investment and the operation of the assets; and that the cash flows at different points in time usually require different discount rates to reflect their risk appropriately. Furthermore, DCF techniques favor short-term projects in certain markets over long-term and relatively uncertain projects (Lint and Pennings 1999).

The idea of ROs comes from corporate finance and provides a way to think more rationally about capital investment decisions when there is significant uncertainty related to the potential benefits.

The Gap between Finance Theory and Strategic Planning

The concept of incorporating flexible options into infrastructure requires a strategic planning of the system. In the late 1980s, several reviews stated that there was no link between financial theory and strategic planning. What can the future bring? What types of services or changes in current services might be necessary? The answers to these questions were given by Myers (1984), who discussed this apparent disconnection and reached the conclusion that strategic planning would benefit from tools provided by the finance theory, as long as properly applied. RO analysis presents an important step bridging the gap between these two themes (see more in Myers 1984). Trigeorgis and Mason (1987) clarified that option valuation can be seen operationally as a special, economically corrected version of decision-tree analysis that is better suited for valuing a variety of corporate operating and strategic options. Ford et al. (2004) stated that "Competitive advantage comes from the creation of valuable resources through long-term investment in value-creating activities. So, real options are used somewhat metaphorically to denote the opportunities that result from a particular set of path-dependent investments."

Myers's argument was supported by Barwise et al. (1989), and during the next decade and the beginning of the 21st century, several books regarding these topics were published (e.g., Amram and Kulatilaka 1999; Copeland and Antikarov 2003). Myers (1984) acknowledged that "Finance theory and strategic planning could be viewed as two cultures looking at the same problem."

Similarities between Options

In 1969, Black developed the partial equation and, together with Scholes, found a single equation that provided the option value. The equation came to be called the Black-Scholes Option Pricing Model (BSOPM). Some years later, Merton added the missing piece—arbitrage (Myers 1977). But it was not until 1973 that Black and Scholes (1973) published the equation able to quantify the value of a European financial option. The Black, Merton, and Scholes formula uses an entirely different approach to working around the discount rate dilemma. They established the value of an option by constructing a portfolio of traded securities, known as a *tracking portfolio*, which has the same payoffs as the option. This work awarded them a Nobel Prize in economics in 1997.

Myers (1977), who first coined the term *RO*, observed that future investment by corporations is discretionary; thus, it is analogous to a financial option where an investor holds a claim to buy or sell an underlying financial asset at a potentially favorable price and has the right to make this trade only if it is profitable. He established the term *RO* to emphasize that investment opportunities are (or involve) options on real assets, as opposed to financial assets (Triantis 2003). One year later, Ross (1978) was already discussing the theory of RO valuation based on an analysis that he had made regarding risky projects. He considered the inherent potential investment opportunities as a real option. However, there are several analogies between FOs and ROs, as shown in Table 1.

As Ross (1978) claims, considering investments as options, the emphasis of the analysis goes from the choice of discount and interest rates toward discussing risks and how to deal with them. In the field of infrastructure, this changes the traditional paradigm. Like FOs, the value of ROs depends on five main variables, plus an indirect variable—the dividends (Copeland and Antikarov 2003; Leslie and Michaels 1997):

Table 1. Analogy between Financial and ROs

Financial options	Real options
Time to maturity	Time until the investment opportunity disappears
Exercise price	Costs of irreversible follow-on investment
Volatility of stock return	Variability of growth in project value
Share price	Present value of expected CFs
Risk-free rate of return	Risk-free rate of return
Dividend	Value lost by waiting to invest

Note: Data from Lint and Pennings (1999).

1. Value of the underlying risk asset—The project, investment, or acquisition in the RO case. An important difference between FOs and ROs is that the owner of FOs cannot affect the value of the underlying asset. At the same time, managers operating a real asset can increase its value.
2. Exercise price—Money invested to exercise the option of buying the asset; otherwise, the money that will be received if the company is selling the asset.
3. The time until the option expires—An investment opportunity is only valid until the expiration date (depends on both technology and contracts).
4. Standard deviation of the value of the underlying risk asset/uncertainty—The unpredictability of future cash flows that is related to the asset.
5. Risk-free rate of interest over the life of the option—The theoretical interest rate returned in the case of an investment that is risk-free.
6. Dividends—The cash outflows and inflows over the asset's life. These cash flows are similar to dividends on a stock.

Two types of options are commonly traded in the financial stock market: call and put options. In call options, the owner of the contract holds the right, but not the obligation, to buy a stock at a predetermined price within a predetermined time. In put options, the exact opposite happens: the owner has the right to sell a stock against a predetermined price at a predetermined time (D'Amico et al. 2009). Table 2 illustrates how call and put option values change when each of the variables increases.

Two types of FO should be highlighted: European options (options that can be exercised only at their maturity date) and American options (options that can be exercised at any time until the maturity date) (He 2007). The difference with American options is the time in which the owner of the contract can exercise the option (which is variable)—he or she is not tied to a one-time event (i.e., the maturity date) as in European options.

Beyond FOs

In the late 1970s and beginning of the 1980s, the field of ROs experienced successive developments: the expansion of the areas of application and the emergence of diverse options. Margrabe (1978) valued a compound option (the option to acquire another option; i.e., the ability to exchange one asset for another within a certain period). This is relevant in financial markets, but it has only limited application to the field of physical assets. Furthermore, Carr (1988) valued sequential exchange options, involving an option to acquire a subsequent option to exchange the underlying asset for another risky alternative. Mason and Merton (1985) and Kasanen and Trigeorgis (1994) maintained that ROs may be valued similar to FOs, even though they may not be traded, since in capital budgeting the main objective is to determine the value of the project's cash flow (CF) if it was traded in the market (Trigeorgis 1996).

Table 2. RO Value Characteristics (Data from Brealey and Myers 1992)

Increase in variable	Call option value	Put option value
Asset value	Increases	Decreases
Exercise price	Decreases	Increases
Interest rate	Increases	Increases
Time to expiration	Increases	Increases
Volatility	Increases	Decreases
Dividends	Decreases	Increases

Note: Data from Brealey and Myers (1992).

Luehrman (1998) linked the variables of a call option to the variables of an investment opportunity. A change in any of the variables will alter the value of the option in the respective investment (e.g., a higher expenditure lowers the option value; greater uncertainty increases the volatility rate, which leads to potential higher values achievable, which in turn leads to increased option value).

RO and investment opportunities present several similarities. Fig. 1 illustrates the mapping of an investment opportunity onto a call option. The example described is relative to a European call option, which is easier to understand since it can be exercised only on the maturity (or expiration) date (He 2007).

Infrastructure investments are similar to exercising an option or a share of stock. First, the investment is a certain fixed amount of money, which in this case corresponds to the exercise price (X) of the option. Second, the present value of the asset to acquire corresponds to the stock price (S). Third, the time for which each investment can be deferred without losing the opportunity resembles the option's time to expiration (t). The uncertainty concerning the future value of project CF corresponds to the standard deviation (σ^2). Finally, the value of money is represented by the risk-free rate of return in both cases. The following Fig. 1 sums up this information.

Mapping an investment opportunity as a call option helps managers to understand the role played by uncertainty when it comes to decision making, as well as recognizing the asymmetry in the options net payoff (Ross 1978).

Since other approaches failed to capture managerial flexibility, the RO framework was extended to different fields, and the theory was tested to validate and evaluate the association between physical investment and flexibility (Yeo and Qiu 2003). Amram and Kulatilaka (1999) helped managers to use their own option right to make management decisions in areas such as project selection, strategic investment, and infrastructure. They managed to do so by applying option pricing theory and the financial market rules to the evaluation of nontrading assets. Two main reasons explain why the RO framework is suited for real asset applications: the payoffs of the contingent investment decision can be tailored to every situation, and the RO framework illuminates the nature of risk

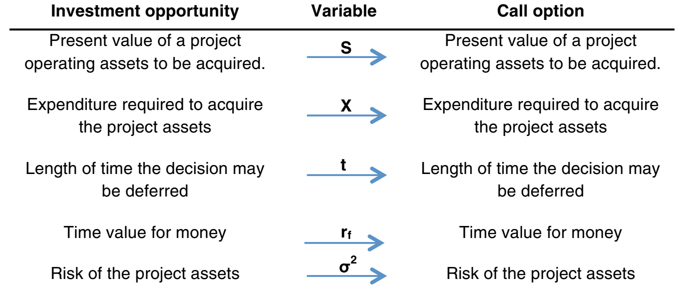

Fig. 1. Mapping an investment opportunity onto a call option [adopted from data from Luehrman (1998)]

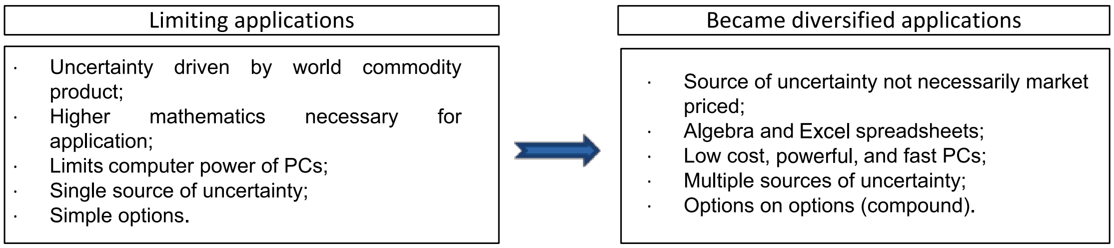

Fig. 2. Bypassing limitations [data from Copeland and Antikarov (2003)]

embedded in real assets. As this is the case, the RO approach incorporates the effects of market-priced risk and private risk when it comes to valuing strategic investment opportunities (Amram and Kulatilaka 1999).

With the entrance to the new millenium, huge advances in computational processes enabled bypassing the limitations presented in Fig. 2.

RO Framework

Baldwin and Trigeorgis ("Toward remedying the underinvestment problem: Competitiveness, real options, capabilities, and TQM," working paper, Harvard Business School, Boston, Massachusetts) proposed a solution to bypass the underinvestment problem and simultaneously restore competitiveness by developing specific adaptive capabilities—viewed as an infrastructure—for acquiring and managing corporate RO. This became known as the *RO framework*.

A company's need to behave more proactively contrasts with the paradigm "The future is to be predicted, not chosen or created" (Meadows 1991). Instead of forecasting, the RO approach encourages managers to create opportunities to be used something else in the future as uncertainty is resolved.

The main questions that RO theory attempts to answer are (Johnson et al. 2006):

- What are the future alternative actions?
- When should one choose between these actions to maximize value, based on the evolution of the key variables?
- How much is the right to choose an alternative worth at any given time?

The ability to map out future actions is the key issue regarding ROs. By mapping both uncertainties and decisions over time, ROs provide an appropriate way to track not only value creation, but also the risk profile of a project or a portfolio of projects.

The RO framework is characterized as follows (Triantis 2005):

- It focuses corporate managers' attention on the value of flexibility;
- It raises awareness to answer to new information over time;
- It affects both present and future decisions;
- It increases the effectiveness of areas such as planning investment and operating strategies;
- It makes management more reactive (in the sense of responding effectively as uncertainties are resolved over time) and more proactive (building flexibility into projects).

Ford et al. (2002) recognized the need for a new approach when they claimed that "successfully managing dynamic, uncertain project conditions require a proactive approach."

Taxonomy of ROs

Types of ROs

Trigeorgis (1993) focused explicitly on the nature of RO interactions, pointing out that the presence of subsequent options can increase the value of the effective underlying asset for earlier options, while the exercise of prior ROs may alter the underlying asset itself, hence the value of subsequent options. Thus, the combined value of a collection of ROs may differ from the sum of separate option values (Trigeorgis 1996). The author distinguished several types of options, taking into account differences in flexibility, dividing them into seven categories:

- The option to defer;
- The staged investment option;
- The option to alter operating scale;
- The option to abandon;
- The option to switch;
- The growth option;
- The interacting option.

These categories belong to four groups of options: growth, contraction, switching, and contractual. A detailed description, the main fields of application, the type of flexibility they grant, and a guide to the related literature can be found in Table 3.

Growth Options

These options, which are similar to financial call options, are the most frequent type of ROs. The investment made (either today or in the past) is the *cost* of the option. This positions the company in a scenario where future investments can be made to grow its earnings. Like FOs, some growth options have a limited horizon.

However, most of these options do not have a fixed maturity and are exercised only when the cost of waiting for additional uncertainty to be resolved is higher than the benefit. Growth option also differs from FOs because most growth opportunities involve a sequence of investments over time. Options are created upon exercising early options—compound options. Pindyck (1988) suggests that growth options should account for at least half of a company's value.

Contraction Options

These options (contract or abandon) can have an impact on shareholder value. Production at a mine or refinery plant can be scaled down to answer to the decline in output prices; e.g., it allows the minimizing of losses (Triantis 2003).

The costs of contraction and abandonment are related to the degree to which the company invested upfront in flexibility. In the majority of cases, abandoning a production can be staged due to environmental issues.

Switching Options

A company is able to make several adjustments in order to take maximum advantage of market conditions by designing flexibility into the production system. Using only one production line can be inefficient if that product value is increasing, and the company could produce more units by altering the form of involvement (Ford and Sobek 2005). Therefore, having the flexibility to switch to two production lines will allow the system to improve its performance.

Table 3. Taxonomy of Real Options

Option	Description	Main fields of application	Type of flexibility	Guide to literature
Defer	Regards profitability on investing. Possible future conditions may be preferable compared to the present situation. This option exists when management is able to leave itself open to investment opportunities, for a certain period. American call-like option	Natural resources industries, real estate development, farming	Upside potential	Tourinho (1979); Titman (1985) ; McDonald and Siegel (1986); Paddock et al. (1988); Ingersoll and Ross (1992); Dixit (1992)
Staged investment	Some investments can be staged in order to create growth and abandonment options. This allows for viewing each stage as an option on the value of subsequent stages (compound option)	R&D intensive industries, capital-intensive projects and start-up ventures	Upside potential and downside protection	Brennan and Schwartz (1985); Majd and Pindyck (1987); Carr (1988); Trigeorgis (1993)
Alter operating scale	Regards changes in market conditions in order to make the most of them (either increase profits or minimize losses). If market conditions are favorable, the company will want to increase the output level by making an investment to scale up the production plant. On the other hand, if market conditions are unfavorable, the company must have the ability to shut down production. Similar to call options	Natural resource industries, commercial real estate, and other cyclical industries	Upside potential and downside protection	Brennan and Schwartz (1985); McDonald and Siegel (1985); Trigeorgis and Mason (1987); Pindyck (1988)
Abandon	Management's ability to abandon a current operation permanently and recover the salvage value of the asset. Similar to American put options	Capital-intensive industries (e.g., airline industry, railroad, and financial services)	Upside potential	Myers and Majd (1990); Sachdeva and Vanderberg (1993)
Switch	Options that create both process and product flexibility. By combining call and put options, the owner is able to switch between two or more modes of operation	Facilities highly dependent on one input (e.g., oil or any other commodity)	Downside protection	Margrabe (1978); Trigeorgis (1993)
Growth	Exist when early investments (e.g., in R&D) create the opportunity for future revenues. Compound Options whose value depends on a preexisting option. Similar to European or American call	R&D	Upside potential and downside protection	Myers (1977); Kester (1984); Trigeorgis (1988); Pindyck (1988); Brealey and Myers (1992); Chung and Charoenwong (1991)
Interacting	Combination of the previous options	Combination of the previous options	Depends	NA

Note: Data from Triantis (2003).

Likewise, if the value of a service is decreasing, the system can reduce the number of production lines, or even change to another product with a higher market value. These options should be within reach of the most competitive companies. Unlike FOs, which offer a binary choice most of the time, ROs typically involve a choice among several available alternatives.

Contractual ROs

Contractual ROs are options embedded in contracts (e.g., locking in prices and lead times for delivery). Contraction and switching options also may appear in contractual form. In these types of options, flexibility is traded through options in contracts—only firms that have invested in flexibility and that can deal with a diversity of customers and products can take profitable advantage of this type of flexibility (Triantis 2003).

ROs on Projects and in Projects

ROs can be categorized as *on* and *in* the projects (de Neufville 2002; Wang and de Neufville 2005). The options that deal with technology as a *black box* are ROs on projects, which are FOs taken on technical items. On the other hand, options created by changing the design of a technical system are options in projects. ROs in projects are the latest expansion of RO theory into physical systems design (Greden et al. 2005).

ROs on Projects

ROs on projects regard flexibility associated with uncertainty (Greden et al. 2005). This type of RO deals with the entire infrastructure as one single system. The options are applied over this system. These options are generally applied if the source of uncertainty is related to market factors (e.g., changes in demand).

ROs in Projects

ROs in projects are options that can be created within the design of the system or projects. The infrastructure is no longer a single system; it is divided into several subsystems. The options are applied within these systems. The data available for this type of RO are far less accurate than what is available to ROs on projects. Moreover, there is a need for an appropriate analysis framework due to the specific features of these types of options (i.e., in projects). ROs in systems also require a profound understanding of technology. Project managers must have technical understanding and be strategically ready for the project to make the most of these options (de Neufville 2002). Then managers will be able to manage both risks and uncertainties. A really simple example is the spare tire on a car—the car owner has the right, but not the obligation to change

Table 4. Main Differences between ROs on and in Projects

ROs on projects	ROs in projects
Value opportunities	Design flexibility
Valuation important	Decision important (go or no go)
Relatively easy to define	Difficult to define
Interdependency/path dependency a less important issue	Interdependency/path dependency an important issue

Note: Data from Wang and de Neufville (2005).

the tire whenever he or she decides to do so. Table 4 summarizes the comparison between ROs 'on' and 'in' projects.

Contractual Options in Projects

Contractual options in projects were created to address the problem of flexibility in particular cases of infrastructure or in particular cases of infrastructure delivery models: i.e., public-private partnerships (PPPs).

When it comes to infrastructure development, PPPs are considered relation-specific investment since both the public and private sectors are better off handling the project together than by themselves (Dong and Chiara 2010).

This type of relationship carries a critical issue when it comes to the transaction cost. Every party wants to take advantage of the slightest opportunity available, and their greed might ruin the project. Until recently, long-term, rigid contracts were the best way to reduce as much as possible the transaction cost (De Bettignies and Ross 2004).

Infrastructure projects have a high uncertainty associated with them, particularly due to their long life cycles and vulnerability to the macroeconomic context. There is no accurate way to predict future downside risks at a preproject planning phase since these projects require a long-term commitment. A proactive approach to uncertainty management is the solution because it allows for incorporating flexibility into the contracts.

Chiara and Kokkaew (2009) presented a new approach to address the concerns highlighted previously. The process, contractual flexibility analysis (CFA), is a way to evaluate endogenous flexibility at a project level since it refers to the endogenous interdependent flexibility within a contractual structure of many shareholders. Failing to incorporate flexibility in long-term contracts has damaged both the public and the private sectors. Thus, with CFA, it is now possible to adjust the allocation of risk during the life cycle of the project.

Table 5 presents a summary of the literature review of the application of ROs to several infrastructure sectors.

Valuation Tools: Techniques to Value ROs

Valuation Tools: Overview

There are five main techniques to valuing options: the BSOPM, the Binomial Option Pricing Model (BOPM), the Risk-Adjusted Decision Trees (RADT), the Monte Carlo Simulation (MSC), and finally, Hybrid Real Options (HRO).

The main specifications, advantages and disadvantages, are briefly addressed next, along with a comparison of the five valuation tools.

Black-Scholes Option Pricing Model (BSOPM)

The model developed in 1973 by Fischer Black and Myron Scholes requires several assumptions to become applicable. First, this model can be implemented only if the options are of the European (call and put) kind, since it requires a fixed decision date. Second, the limiting distribution has to be the normal distribution. This is one of the main limitations of the model, since most variables do not behave under a normal distribution function (e.g., cost overruns). Furthermore, the price process needs to be continuous. It is important to highlight the fact that this model is not an alternative to the BOPM but a limiting case of that model (Damodaran, "The promise and peril of real options," working paper, Stern School of Business, New York University, New York). When constructing a tracking portfolio, the value of the option is established. The portfolio has the same payoff as the option.

Table 5. Summary of Literature Review on ROs

Authors	Fields of application
2003	
Smit	Airport
2004	
Zhao and Tseng	Parking garage
Ford; Lander and Voyer	Large engineering projects
Bowea and Leeb	High-speed rail
Garvin and Cheah	Toll road
Cui et al.	Highway
Wang and de Neufville	Hydropower station
Law, Mackay, and Nolan	Rail line
Zhao; Sundararajan and Tseng	Highway
2006	
Michailidis and Mattas	Irrigation dam
Cheah and Liu	Bridge
Do Couto	Production unit
Pereira, "The optimal timing for the construction of an international airport: A real options approach with multiple stochastic factors and shocks." Draft, Universidade do Minho, Portugal; Rodrigues and Armada	Airport
De Neufville	Large-scale projects
Weihua and Dashuang	Tolled expressway
Haung and Chou	High-speed rail project
2007	
Alonso-Conde; Brown and Rojo-Suarez	Toll road
Ohama	Airport
Rivey	Airport
Chiara; Garvin and Vecer	Toll road
Gil	Airport
Pimentel, Azevedo-Pereira, and do Couto, "High speed rail transport valuation." Working paper	Rail transport
Chambers	Airport
De Neufville	Airport
De Neufville; Lee and Scholtes	Hospital
Zhao and Tseng	Facility
Masek	Airport
2008	
Ohama	Tokyo Bay aqua line
Kwakkel	Airport
Maseda	Hospital
Brandão and Saraiva	Toll road
De Neufville	Airport
2009	
Blank; Baidya and Dias	Toll road
Chalmers et al.	Power plant
Huber	Airport
Park and Lim	Power plant
Bulan; Mayer and Somerville	Hospital
Zhang and Babovic	Water supply system
Muche	Pump storage plants

Table 5. (*Continued*.)

Authors	Fields of application
2010	
Ammerlaan	Gas plant
Mestre	Real estate
Dong and Chiara	Highway
Sitruk	Railway
Kwakkel; Walker and Marchau	Airport
Athias and Saussier, "Contractual flexibility or rigidity for public private partnerships? Theory and evidence from infrastructure concession contracts." working paper, University of Lausanne	Infrastructure concession
Shan; Garvin and Kumar	Toll highway concession
Cardin et al., "Minimizing the cost of innovative nuclear technology through flexibility: The case of a demonstration accelerator-driven subcritical reactor park," working paper, Massachusetts Institute of Technology, Cambridge	Reactor park
Doan and Patel, "Investment with government subsidies and cost contingency: The case of build-operate-transfer (BOT) toll road," working paper, University of Cambridge, U.K.	Toll road
Suttinon and Nasu	Industrial water infrastructure
Cabral and Júnior	Football stadiums
Lawryshyn and Jaimungal	Wastewater plant
2011	
Grimes, "Building bridges: Treating a new transport link as a real option." working paper, Centre for Advanced Engineering New Zealand	Bridge
Ashuri; Lu and Kashani	Toll road
Morgado et al.	Steel industry
Zambujal-Oliveira and Duque	Asset replacement
Corato and Moretto	Biogas plant
Vajdić and Damnjanović	Highway
Herder et al.	Infrastructure planning
Padhy and Sahu	Petrochemical industry
Zhang and Babovic	Maritime domain protection
Rohlfs and Madlener	Power plant
Mao and Wub	Real estate
Li and Zhang	Real estate
2012	
Cruz and Marques	Hospital
Alexander and Chen	Real estate
Bednyagin and Gnansounou	Thermonuclear infrastructure
Clapp; Bardos and Wong	Residential development
Zhu	Nuclear power
Brandao et al.	Metro
Ozorio et al.	Steel plants
Garvin and Ford	Theorethical/general
Nishihara	Farmland
Pinon; Garcia and Mavris	Airport
Madlener and Stoverink	Power plant
Zhang and Babovic	Water supply systems
Shing; Kheon and Chung	Build-then-sell properties
2013	
Jain; Roelofs and Oosterlee	Nuclear power plants
N.A.	
Miller and Clarke	Airport

The main advantage of this model is the simplicity required to calculate the value of the option, as it is only needed to plug six variables into the formula: initial value of the underlying asset, time until maturity, exercise price, difference between capitalization rate and the percentage of expected change in the value of the underlying asset, continuous compound risk-free rate of return, and the volatility in the underlying asset (Triantis 2003).

The more relevant disadvantages involve some of the assumptions (e.g., price, volatility, and duration), as they limit the use of this approach as well as advanced financial knowledge. Moreover, the formula lacks in transparency and intuition, which comes across as a black box (Triantis 2003). Therefore, it becomes really difficult to apply this approach to large-scale complex engineering projects such as an airport, which is the focus of this project.

Binomial Option Pricing Model (BOPM)

The Binomial Model allows the creation of a simple representation regarding the evolution of the underlying asset, and it is based on a risk-neutral argument. The multiplicative Binomial Model of uncertainty is described as follows: the asset has an initial value X. In the next time period, its value either moves upward, being multiplied by u with a probability of $p(Xu)$, or downward, being multiplied by d with a probability of $1 - p(Xd)$; the underlying asset can take only one of two possible values (binomial). In the following period, the value may have one of the following values: Xu^2, Xud, or Xd^2. By allowing a sequence of periods with such binomial movements, a large set of paths (a binomial *tree*—see Fig. 3) can be generated and will closely approximate all the possible value changes that would occur to the underlying asset during the life of the option (Arnold et al. 2007).

The main advantage of the Binomial Model is the effectiveness of the model if there is only one uncertainty. Moreover, it allows for estimating the value of several option futures, including the early exercise of an American option.

However, this model is not easy to use, as it also requires advanced financial knowledge, like the BSOPM. It is difficult to conduct if there are several uncertainties at the same time.

Comparing these two models, the Binomial Model can be defined as a simplified discrete-time approach to the valuation of options compared to the BSOPM (Cox et al. 1979). Triantis (2003) stated that "the Black-Scholes and binomial option valuation models are widely used in practice for valuing growth options."

Decision Analysis (DA)—Risk-Adjusted Decision Trees (RADT) Model

Decision analysis (DA) is a more subjective methodology since it relies on the subjective assessment of probabilities, discount rates, and decision makers' preferences concerning a specific objective that is aligned to maximize shareholder wealth (Oren 1981).

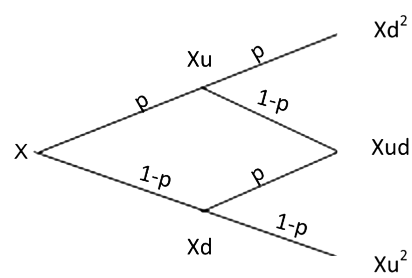

Fig. 3. Example of a binomial tree

This approach is able to map more complex problems better. Resorting to DA has become an appealing alternative because in addition to being able to deal with multiple uncertainties, it also enables decision makers to develop insights about ROs and to estimate the approximate value of flexibility, especially those projects with sequential decision opportunity and variable outcomes over time (de Neufville 1990).

DA becomes a really useful methodology when a drastic change in the system occurs, and it is not necessary to possess as much financial knowledge. These are the key advantages when compared to both of the previously mentioned models.

When developing several branches, it becomes too complicated to interpret the results. This is the main disadvantage. Moreover, this methodology does not provide the true value of projects.

When compared with the BOPM, the RADT valuation model has two major advantages: the ability to take into account the risk from the shareholders' point of view and a simpler layout, since at each event node in the tree, the decision node is implicit (Triantis 2003).

Monte Carlo Simulation (MCS)

Like DA, the MCS methodology is able to deal with several uncertainties. A number of different values for the underlying uncertainties are generated based on distributions that are adjusted for systematic risk. The expected value of the option is then calculated, and a risk-free rate is used to discount this expected value back to the initial date (Triantis 2003). The optimal strategy investment is determined at the end of each path, where the payoff is calculated.

As opposed to the previous models, MCS is a simulation model. Because of this, the key advantages to take into account are, in addition to the ability to deal with multiple uncertainties, the fact that it becomes quite helpful for problems with *path-dependency* [i.e., future outcomes or decisions depend on decisions made at earlier points in time (Baldwin and Clark 2000)]. Furthermore, with recent computer technology developments, it is now possible to construct large computer simulations easily using available commercial software. These main advantages make this model user-friendly, as well as making it really simple to explain the results graphically to the decision maker. The last, but not the least important, advantage lies in the use of spreadsheet software, such as Microsoft Excel, to conduct MCS (Clemen 1996).

As for disadvantages, this model may lack some transparency to management when compared with the BOPM or RADT. In addition, it is a hard methodology to implement since simulation models use a subjective discount rate (as referred to previously) and do not incorporate financial market information (Clemen 1996).

HROs

New projects or products with both inherent technological and financial risks need solid methods for valuing prospective investments so that they can justify their development strategies. Traditional methods are mechanically (because they assume a single CF and assume that the value of this average CF equals the average value of a range of CFs) and conceptually (because they ignore the reality of management control) inadequate for risky projects. This valuation model is more effective for large, risky projects (Neely and de Neufville 2001).

By considering two distinct types of risk (project and market), Neely (1998) developed a different approach to this type of problem. As per his definition, project risks regard uncertainty associated with the project under study, and market risks concern the market price of the product. This distinction is crucial since each of these two types of risk have different implications concerning the discount rate.

Project risks, which are unique to the project by definition, do not require an adjusted discount rate to reflect risk since managers can diversify their investments to compensate for losses. Since this is true, a DA is used to analyze these risks with a constant discount rate.

In contrast, market risks cannot be avoided by appealing to diversification. Only options analysis can cope with these types of risks once the level of market risk changes when a project is actively managed (Neely and de Neufville 2001). A risk-neutral valuation is a process whose net effect is to adjust the project outcomes so that the risk-free rate can be applied (Hull 1989). The combination of options methods for market risks with DA for project risks is seen as a practical approach to value ROs.

Table 6. Valuation Methods

Methodologies	Advantages	Disadvantages
BSOPM	Simple to calculate the option value	Only applicable to European options Only works with normal distributions Require advanced financial knowledge Required assumptions limit the use of the model (price, volatility, duration) Able to deal with only one factor of uncertainty
BOPM	Effective when dealing with one factor of uncertainty Provides project managers with an appropriate evolution of the underlying asset Estimates the value of several option futures	Require advanced financial knowledge Able to deal with only one factor of uncertainty
RADT	Allows mapping complex problems Able to deal with multiple uncertainties Enables decision makers to develop insights into ROs Useful in the case of a possible drastic change in systems	Does not provide the true value of the project If the number of branches is high, it becomes too complicated and unclear
MCS	Demonstrates graphically the analysis results Able to deal with multiple uncertainties Not required to understand financial theory Helpful for problems with path-dependency User-friendly multiple document interface	Lacks transparency Hard methodology to implement with American options
HROs	Able to deal with multiple uncertainties Combining the best of decision analysis and options analysis Independent handling of technical and financial parts	Hard methodology to implement (it requires highly sophisticated mathematical modeling skills)

The main advantages of this unusual method are (1) it combines the best of DA and options analysis into a practical means of accurate valuation; and (2) it offers the possibility of choosing the discount rate for the valuation. Moreover, by dividing the valuation process into technical and financial parts, experts can handle each of them independently. This facilitates the implementation of a systems approach to project valuation (Neely and de Neufville 2001).

The only negative aspect of this valuation method concerns the lack of elegance from a theoretical point of view.

Comparison between Models

Each of the models has advantages and disadvantages, which are summarized in Table 6. To obtain the most detailed qualitative analysis possible, there is not just one choice of validation tool. The BSOPM and the BOPM were excluded from the outset since they cannot handle more than one type of uncertainty. On the other hand, RADT, MCS, and HRO are the best candidates to apply to infrastructure projects. These three tools allow not only to compare the value of the RO incorporation in the projects, but also to measure different gains depending on the valuation tool used.

Summary and Conclusions

ROs arise due to the need for a new approach to infrastructure management and valuation, since the DCF method does not allow for capturing the value of flexibility, which preferably should be incorporated into any infrastructure project. This failure is solved by introducing ROs since many decisions are made with initial wrong assumptions—not incorporating flexibility can alter the value of a project significantly. ROs emerged as a financial market development.

Prior to this approach, all projects were seen as taking into account a single decision—go or no go. The incorporation of ROs into projects increased the range of decisions, thus becoming possible to defer, stage investments, alter the operating scale, abandon, switch, grow, and interact.

The many similarities between ROs and investment opportunities allowed expansion of the scope for many different areas such as R&D, engineering, and the focus of this paper, infrastructure. Concepts such as uncertainty and management flexibility are explained to understand how to make the most of RO analysis.

In subsequent years, the number of fields appropriate for RO application increased, since managers quickly realized that this methodology deals with uncertainty in a way that never had been used before. The application of ROs in infrastructure began at the very start of the 21st century. The main reason for resorting to this tool lies in the possibility of incorporating flexibility from the design phase of the project, following de Neufville's five-step methodology, to estimate the distribution of future possibilities. As flexibility has the ability to manage uncertainty, this concept has gained much importance, both academically and professionally.

Its significance in the field of infrastructure is arousing the interest of many managers who aim to determine the real value of their project, as well as take advantage of as many options as possible.

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