Option-Based Management of Technology Investment Risk

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Abstract
Real operating (flexibility) options embedded in a technology investment are valuable because they allow management to take rational, value-adding actions that could favorably affect operational traits of the investment (timing, scale, scope, etc.). These options, however, are not inherent in technology investments. Rather, they usually must be carefully planned and designed to fit each investment differently. Building on concepts from the area of financial risk management, this paper presents a methodology for planning the creation of specific operating options designed to maximize the value of a technology investment in light of the risks underlying that investment. The paper also illustrates the use of the methodology in the context of a Web-based information technology investment.

Index Terms: technology investment, real options, risk management, investment risk, investment structure, project management.

1. Introduction

Firms invest in two types of technology options -- growth options and operating options (Kogut & Kulatilaka, 1994). *Growth options* are usually the product of strategic platform (infrastructure) investments that produce indirect, long-term payoffs in the form of future business opportunities. These options are spawned by investments that aim at developing core technologies and/or building experience with promising technologies that could become the drivers of future organizational capabilities. By contrast, *operating options* are common to all kinds of technology investments, and especially ones that yield direct measurable payoffs. Operating options (defer, abandon, lease, etc.) offer management the flexibility to adapt traits (timing, scope, scale, etc.) of a technology investment to unforeseen conditions. In this paper, our interest is mainly in technology investments embedding operating options.

Much work on operating options aims at the correct evaluation of technology investments embedding managerial flexibility (see our review in Section 2.2). For example, take the case of a utility firm facing the choice of investing in a power plant that burns only oil or a plant that can burn oil and coal. Trigeorgis (1996) describes a model that balances the higher cost of a dual-fuel plant against the "switch inputs" option it embeds. This option grants the flexibility to switch between fuels whenever beneficial fluctuations in fuel prices occur. Like in this example, most of the literature focuses on technology investments that are *a-priori assumed* to embed a *single* operating option.

In reality, however, operating options are not inherent in technology investments -- they usually must be planned and designed to fit each investment differently. As a small example, consider an investment in the production of a new consumer good. To mitigate the risk of customer rejection, the investment can be structured to include a pilot stage and a contingent follow-up stage. Structuring the investment in this way is analogous to acquiring a call option – only if the pilot succeeds, which would indicate that the risk of customer rejection has been resolved, would the cost of a full-scale investment be justified. Of course, oftentimes multiple options could be used

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to structure an investment in more intricate ways that can make the investment more valuable and less risky. Unfortunately, the real options literature offers no explicit guidance on how to plan, design and create operating options for the purpose of structuring an investment in a way that maximally contributes to its value.

This paper presents an option-based methodology that enables management to optimally structure a technology investment by creating a set of operating options that maximally contributes to the investment value. The methodology includes steps for addressing three investment management complexities.

1. *Typical technology investments could embed multiple "shadow" operating options*. Respectively, one step uses the risks present in an investment to drive the recognition of shadow options the investment potentially embeds. This step relies on the notion that operating options can be used to control risk.
2. *Creating a specific subset of the shadow options embedded in an investment corresponds to just one way to structure the investment*. In accordance with this notion, another step first identifies which of the recognized shadow options are worth creating, and then maps those options to relevant investment-structuring alternatives. Each structuring alternative may control a different subset of the risks present, by using the options it embeds to adapt specific traits of the investment (timing, scale, etc.).
3. *Different investment-structuring alternatives affect the investment value differently*. Consequently, a third step evaluates all identified investment-structuring alternatives in order to find the one that maximally contributes to the investment value. In so doing, three issues are considered. First, tradeoffs could exist between structuring alternatives that can't control all the risks present in the investment. Second, multiple interacting options form compound options, whose value could be different than the sum of values of the individual options they comprise. Finally, bringing any shadow option into existence could involve a cost in excess of the option value. In light of these issues, structuring alternatives are evaluated using an option-pricing method that is both intuitive and easy to apply using spreadsheet technology.

Because our methodology builds on financial risk management concepts, it can also be said to support the management of technology investment risk.

The rest of the paper is organized as follows. Section 2 offers background material on real options and how they relate to technology investments. Section 3 presents our option-based methodology for managing technology investment risk as well as explains the concept underlying the methodology. Section 4 applies the methodology to a sample information technology investment involving the creation of a Web-based sales channel. Section 5 offers concluding remarks and directions for future research.

2. Real Options in Hedging Technology Project Investment Risk

This section offers a brief introduction to real options. It reviews basic financial option concepts and then expands these concepts to the types of real options that technology investments could embed. The concepts covered help to understand the methodology we present in Section 3.

2.1. Option Concepts

The fundamental options are financial *calls* and *puts*. A *European call* (*put*) option on some underlying asset, *V*, gives its holder the right to buy (sell) the asset for an agreed upon exercise price, *I*, at some fixed expiration date. For example, a "June 98 call" on Microsoft stock with a $120 exercise price allows its holder to buy Microsoft shares for $120 on June 15, 1998. This call is worth exercising only if the value of a Microsoft share on June 15 exceeds $120. In this case, the option is said to be *in-the-money*. Hence, the values of a call and a put on expiration are C=max(0,$V-I$) and P=max(0,$I-V$), respectively. An *American option* is like a European option, except that it can be exercised any time before it expires.

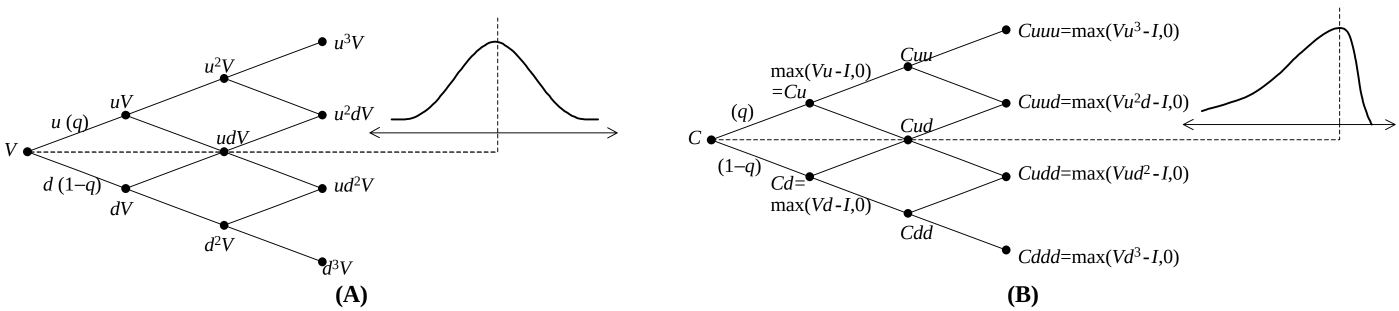
Two fundamental methods for pricing financial options are the *binomial method* and the *Black-Scholes method* (Hull, 1993). To understand the intuition behind the formal valuation of options, suffice to look at how the binomial method prices European calls. The *binomial method* assumes that *V*, the value of a risky underlying asset, follows a binomial distribution. Starting at t_0, in one time period *Dt*, *V* may rise to *uV* with probability *q* or fall to *dV* with probability 1–*q*, where d<1, u>1 and $d<r<u$, with *r* being 1+r_f and r_f is the risk-free interest rate. For the multi-period case, *V* ends up being modeled using a binomial tree (see Figure 1A). Respectively, it can be shown that the value of an option has an asymmetric distribution (see Figure 1B). Where *I* is the option's exercise price, the terminal value of a call option on *V* that matures in *Dt* is C_u=max(0,*uV*–*I*)*q* or C_d=max(0,*dV*–*I*)(1–*q*). For a call that matures in *n* time periods, where *Dt*=*T/n* and *T* is the option's time to maturity, the option value can be written as:

$$C = V\,\mathrm{B}(a; n, p') - Ir^{-n}\,\mathrm{B}(a; n, p) \qquad \mathbf{(1)}$$

In this equation, B(·) is the complementary binomial distribution, or the probability that V would make a or more up moves out of n moves, with $p \equiv (r-d)/(u-d)$ and $p' \equiv (u/r)p$. (p is called the risk-neutral, certainty-equivalent of probability q.) When $n \to \infty$, whereby $Dt \to 0$, equation 1 converges to:

$$C = V\,\mathrm{N}(d_1) - e^{-r_f T}\, I\,\mathrm{N}(d_2), \qquad d_1 = \frac{\ln(V/I)\; r_f\, T}{s\sqrt{T}} + \frac{1}{2}\, s\sqrt{T}, \qquad d_2 = d_1 - s\sqrt{T}, \tag{2}$$

where N(·) is the cumulative normal distribution and s is the variability (volatility) of the expected rate of return on V. Equation 2 is also the option value derived by the *Black-Scholes method*.



(A) Binomial tree modeling the probability distribution of *V*, the value of the underlying asset of an option.
(B) The value of a call option on *V* has an asymmetric probability distribution.

Figure 1: modeling the value of an underlying asset and of a call option on that asset

The value of an option, C, feeds on s, the variability of V, and on T, the option's time to maturity. If the underlying asset is a security (e.g., stock), V could go down only to zero or up to infinity. This asymmetrical distribution of V means that, the higher is s and/or the longer is T, the more likely it is that V will climb above I before the option expires, and so the higher is C.

2.2. Real Options and Technology Investments

The analogy between financial and real options is straightforward, although it depends on the type of real option in question. For example, consider a deferral option that confers the right to postpone investment for T periods. Holding the option is akin to holding an investment opportunity, whose V and s are the present value of expected payoffs and their variability, respectively. Exercising the option amounts to making cost outlay I in order to convert the investment opportunity into an operational project. Like with a financial call, the value of a deferral option depends on the variability (uncertainty) of V, or on how much management expects to learn during the deferral period about the way V could evolve in response to changes occurring within the firm or in its environment. This analogy shows that the fundamental option pricing methods are readily adapted to real options.

Option pricing methods are suitable for the evaluation of technology investments embedding real options. Unlike in net present value (NPV) analysis, option pricing methods compute the value of an investment as:

$$\mathrm{NPV}^A = \mathrm{NPV}^P + \text{value of managerial flexibility afforded by embedded real options} \tag{3}$$

NPV^P, the *passive NPV* of an investment, is the present value of net direct cash flows from the investment. Since the value of managerial flexibility is not a tangible cash-flow, it does not enter NPV^P. Therefore, option pricing methods compute this value separately and then add it to NPV^P. NPV^A, the *active NPV*, thus recognizes that real options enable management to flexibly change traits of the investment in order to add value. In this light, it should be clear that an evaluation based NPV^A can sometimes accept investments that an evaluation based on (conventional) NPV^P might reject. Benaroch and Kauffman (2000) offer a case study that illustrates this point in the context of deploying electronic banking point-of-sale debit technology.

On this ground, many studies use real option methods to evaluate technology investments embedding different types of real options (see Table 1). A few of these studies go a step further by offering guidelines for managing certain classes of investments in accordance with the real options they embed. For example, McDonald and Siegel (1986) derive the value for an option to stage investment and subsequently identify conditions under which it is optimal to stop and then resume the construction of a project investment embedding such an option.

Option	Features of Project Investment (and sample references)
Defer	Project that can be postponed allows learning more about potential project outcomes, as a function of stochastic output prices and/or stochastic production costs, before making a commitment (McDonald & Siegel, 1986). For example, the flexibility associated with project initiation timing can be valuable for the purchaser of an offshore oil lease who can choose when, if at all, to develop the property during the lease period (Paddock, Siegel and Smith, 1988).
Stage *(Stop-Resume)*	A multi-stage project whose construction involves a series of cost outlays could be shutdown temporarily and resumed, or even killed in midstream (if new information is unfavorable), where project payoffs arrive only after the project is complete (Majad & Pindyck, 1987; Carr, 1988). Examples include projects in R&D intensive industries (e.g., pharmaceuticals), long development capital intensive projects, and start-up ventures.
Outsource	Project development can be sub-contracted to a third party, to transfer the risk of "in-house" failure. Sometimes this option can be likened to a stage option, expect that breaking an outsourcing contract in midstream could carry a cancellation penalty.
Explore *(Pilot / Prototype)*	Start with a pilot (or prototype) project and follow-up with a full-scale project if the pilot succeed. For example, it may pay to explore in high production cost areas in order to gain the option to produce if the price of the product (or natural resource) produced at some later date is higher than is expected today.
Alter Operating Scale – Contract Expand Shutdown Restart	A project whose operating scale can be expanded or contracted, depending on market conditions, with the extreme case of shutting down temporarily and restarting when conditions become favorable. For example, when it is not optimal to keep "alive" a production facility whose stochastic revenues are not expected to cover variable costs, management may have the option to shut down the project for a certain period until higher revenues are expected (Brennen & Schwartz, 1985; McDonald & Siegel, 1985; Andreou, 1990). This type of managerial flexibility is important when choosing among alternative production technologies with different ratios of variable to fixed costs. Changes in a project's total output can be achieved by changing the output rate per unit time, by accelerating resource utilization, or by changing the total length of time the project is kept alive. Choosing to build production capacity in excess of the uncertain expected demand provides the flexibility to produce more. Similarly, choosing to build a plant with higher maintenance costs relative to initial construction costs provides the flexibility to reduce the life of the plant and contract the project's scale by reducing maintenance expenditures. This type of option is relevant to natural resource industries (e.g., mining), to facilities planning and construction in cyclical industries (e.g., fashion apparel, consumer goods, and commercial real estate).
Switch-Use (*Abandon*)	Project can be abandoned permanently if market conditions worsen severely, so that project resources could be sold or put to other more valuable uses (Myers & Majad, 1990). The abandonment flexibility is important, for example, when choosing among alternative production technologies with different purchase-cost to resell-cost ratios. This option is especially relevant in capital intensive industries (airlines, railroads, etc.), financial services, and new product introductions in uncertain markets.
Lease	Project resources can be leased, so that if project payoffs are too low, the project could be cut at a minimal cost. Unlike in the case of abandonment, breaking a lease (by failing to make the next lease payment) could carry a pre-specified penalty term.
Switch Input/Output	The project permits changing its output mix, or producing the same outputs using different inputs, in response to changes in the price of inputs and/or outputs. This option is especially relevant to the utilization of flexible manufacturing systems (Kulatilaka, 1993). Examples where the output can shift include industries in which the goods sough are in small batches or subject to volatile demand (e.g. consumer electronics, toys, machine parts, autos). Examples where inputs can shift include all feedstock-dependent facilities (e.g., oil, electric power, and chemicals).
Compound	Real-world projects involve two or more of the above options, where the value of an earlier option can be effected by the value of later options (Trigeorgis, 1993, 1996; Kulatilaka, 1993; Brennen & Schwartz, 1985).
Strategic Growth	A project that is a prerequisite or a link in a chain of inter-related projects, whereby it spawns future project opportunities (Kester, 1984). Examples include infrastructure-based projects in industries with multiple product generations, industries exploring new generation products or processes, industries involving entries into new markets, or industries where the strengthening of core technological capabilities is of strategic importance.

Table 1: types of real options that technology project investments could embed

In sum, however, the real options literature has given little attention to the methodological issues involved in applying real option concepts to technology investments. Most notably, the majority of the existing studies overlook the fact that real-world technology investments usually embed multiple interacting options, not just one option. Managers are hence left without answers to questions like:

- What is a principled way to identify all the operating options potentially embedded in a technology investment?
- What alternative paths can the investment value take given that not all these options are worth considering? and,
- Which subset of these options can potentially lead to a value-maximizing investment management behavior?

These questions are at the heart of the methodology we present shortly.

The answers to such questions are not trivial because of several unique traits of real options. These traits appear from the way we can classify real options along the three dimensions depicted in Figure 2. The dimension labeled *existence form* recognizes that an investment could embed *shadow options*, which usually can be converted into *real options* upon making some small additional investment. For example, the option to lease investment resources becomes real only once the firm makes the investment necessary to solicit and process bids from potential counter parties to a leasing contract. The next dimension, *source of value*, makes an important distinction between operating options and (strategic) growth options. *Operating options* are found mainly in operational investments, whose value follows from direct cash flows and/or cost savings that they generate. *Growth options* are usually found in infrastructure investments, whose value is derived mainly from new investment opportunities that they open. Finally, the *type* dimension separates between simple options and compound options. A *compound option* is a series of simple options. An *intra-project compound option* involves simple options that are all embedded in the same investment (e.g., options to defer and abandon). An *inter-project compound option* involves simple options that are embedded in different investments (e.g., a growth option spawned by one investment and the option to stage a follow-up investment that builds on the technological capabilities yielded by the first investment). Simple options can add value to the compound option comprising them in a substitutive, additive or synergetic fashion. By substitutive, additive and synergetic we mean that the value of compound option A&B is smaller than, equal to, or greater than the sum of values of option A and option B, respectively (Trigeorgis, 1996).[2]

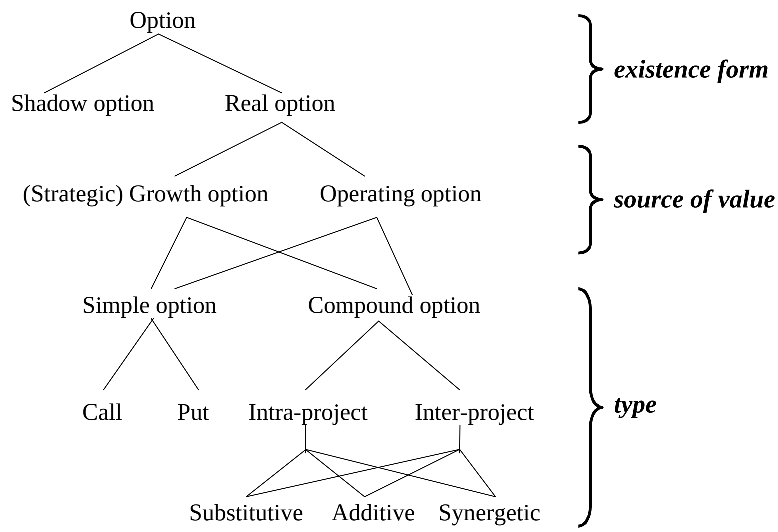


Figure 2: classifying real options along multiple dimensions

3. Option-Based Methodology for Managing Technology Investment Risk

The methodology we present next helps to address the question: *What operating options potentially embedded in a technology investment can and ought to be created in order to maximize the investment value*?

Like with most methodologies, the value of our methodology arises from the fusion of several simple yet powerful real option concepts. Moreover, as we show throughout this section, the concepts our methodology fuses have received little explicit attention in the real options literature. When applied together, these concepts enable management to control the balance between the risk and reward characteristics of technology investments.

Before we elaborate on these concepts and how they fit into our methodology, let us first summarize the three main steps in the methodology (see Figure 3).

(1) *Define the investment and its risk profile*. State the investment goals, requirements and assumptions (technological, organizational, economic, etc.), and then identify the risks present in the investment.

(2) *Recognize shadow embedded options and use them to identify investment-structuring alternatives*. Start by mapping each of the identified investment risks to shadow embedded options that can control them. It may be necessary to reiterate this step to gradually identify compound options, because some options can be the pre-requisites or the payoff of some other options. Upon recognizing the shadow embedded options, use different subsets of these options to generate alternative ways to restructure the investment.

(3) *Evaluate investment-structuring alternatives to find a subset of recognized options that maximally contribute to the investment value*. To choose which of the recognized shadow options to create in order to increase the investment value, assess the value of each shadow in relations to how it interact with other options, in relation to the risks it controls, and in relation to the cost of converting it into a real options.

[2] Generally, the degree of additivity of options depends on: (1) whether they are of the same type (e.g., two call options) or opposite types (e.g., a call and a put), (2) the separation between their exercise times, (3) whether they are "deep", "out" or "in-the-money", and (4) their sequence.

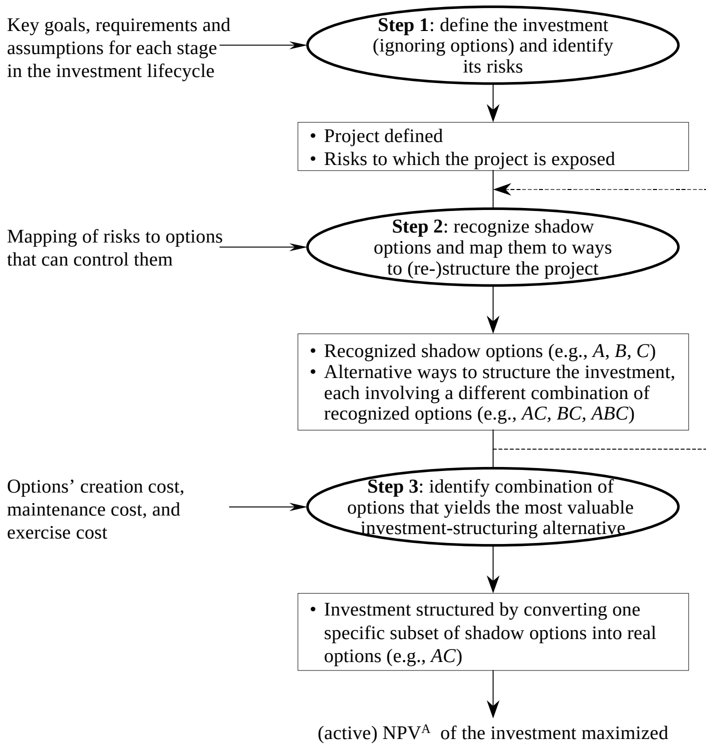


Figure 3: option-based methodology for managing technology investment risk

The key concept underlying our methodology is that *the specific real options used to beneficially structure an investment ought to be chosen based on the investment-specific risks that they can control*. Recall that real options build into an investment flexibility that permits management to take rational, value-adding actions (e.g., defer, abandon) throughout the life of the investment. Because such actions are essentially aimed at controlling (downside and upside) investment risks, they must be designed to fit the risks specific to each investment. This notion that the embedding of real options in a capital investment must be motivated by the desire to control investment-specific risks has received little practical attention in the literature. Our methodology builds on this notion, to facilitate the planning and design of investment-specific real options, the same way that the area of financial risk management uses carefully chosen options to manage differently the risks specific to each financial investment. (Relatedly, we show shortly that most real options are put options that permit mitigating risk, contrary to the way the real options literature often refers to some of them as call options.)

Another concept underlying our methodology is that *different risks and different real options arise at different stages in the investment lifecycle*. This concept is the basis for how we operationalize the first concept. As we show in section 3.2, it is possible to develop for each class of technology investments a mapping between risks and real options that can control them. Such a mapping permits carrying out step 2 in our methodology, whereby the risks specific to a target investment are used to identify the shadow options potentially embedded in that investment.

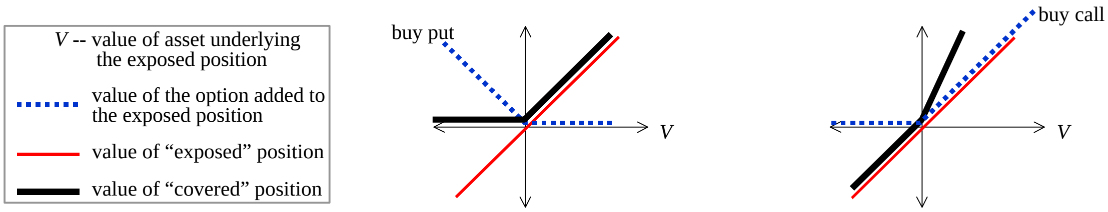
The last concept is that *real options analysis is valuable only if it is intuitive and easy to apply* (see business survey in the *Economist*, 22 April 2000, p. 64). Since real-world technology investments are exposed to multiple types of risk (discussed in section 3.2), they usually embed complex series of cascading options (i.e., compound options). Such options are difficult to evaluate using common options pricing methods such as the Black-Scholes method. It is not enough to compute individually the value of each option in a series of cascading options, as this value may be enhanced or lowered by interactions with other options. One option pricing method that simplifies the evaluation of cascading options is the log-transformed binomial method (Trigeorgis, 1991). As we show in section 3.3, in the context of our methodology, this method is really a natural extension of decision tree analysis.

The rest of this section elaborates on the above real option concepts and how they facilitate deployment of the three steps in our methodology.

3.1. Controlling Risk with Real Options

The notion that real options can be used to control risks inherent in capital investments directly follows from the way the area of financial risk management has been using equity options and commodity options to control financial investment risks.

Financial *risk management* aims at designing investment positions that protect the investor against losses due to, and/or generate profits from exploiting, well-defined risks (Hull, 1993).[3] In the case of option-based risk management, given an "exposed" position containing underlying asset *V* (e.g., stock), the goal is to buy and/or sell options on *V* and then add them to the position in order to form a "covered" position. Figure 4 shows the payoff functions of the most fundamental covered positions created by purchasing a call or a put option on *V*. These covered positions limit risk by canceling out bad, or leverage opportunities by enhancing good, fluctuations in *V*. Other types of covered positions are created by selling a call option, selling a put option, or simultaneously buying and selling multiple calls and puts. The way options in all covered positions work is simple: the buyer and the seller of an option hold different beliefs about the direction and size of future fluctuations in *V*, and so they create a side-bet on the future value of *V* by trading an option on *V*. Hence, options are vehicles that allow trading specific risks across investors that perceive those risk differently.



(A) **(B)**

(A) A purchased put option on *V* cancels out bad, but is insensitive to good, fluctuations in value of *V*.

(B) A purchased call option on *V* enhances good, but is insensitive to bad, fluctuations in value of *V*.

Figure 4: two fundamental option-based risk management strategies

The analogy with managing capital investment risk is apparent. The value of an exposed financial position parallels the (passive) NPV^P of a capital investment, the options added to the position parallel real options embedded in the investment, and the value of the covered position parallels the (active) NPV^A of the investment. However, there is one important difference. With capital investments, risk management is mainly about controlling risk "internally", through exploitation of owned operating options that are already embedded in the investment. Only the options to outsource and lease allow trading risk with other parties.

To see what controlling risk internally means, consider an investment with uncertain value *V*, where the probability distribution of *V* is modeled using a binomial tree. A real put option allows responding to risky events that lead to poor investment outcomes, using actions (e.g., abandon investment) that cut out bad branches in the binomial tree (see Figure 5A). In contrast, a real call option permits taking advantage of risky events that give rise to good investment outcomes, using actions (e.g., expand investment) that enhance good branches in the binomial tree (see Figure 5B). In both cases, real options control risk by favorably changing the probability distribution of *V*.

In light of the above observation, it is interesting to see which of the real options listed in Table 1 are calls and which are puts. If most real options are put options, contrary to the way the literature often refers to them as call options, then we can see why risk ought to drive the recognition of shadow embedded options. As in the case of financial risk management, since financial puts can mitigate financial investment risk, so can real operating options mitigate capital investment risk. This is the key concept underlying our methodology.

To find out which real options are indeed put options, we can derive the payoff function characterizing the value contribution of each type of option to the NPV^A of an investment. Specifically, based on equation (3), if $NPV^P=V-I$, where *V* and *I* are the investment value and cost, respectively, the payoff function of an option can be derived by isolating its effect on NPV^A. For example, consider the case of a deferrable investment (see Figure 6A). We know from the literature (e.g., Trigeorgis, 1996) that the NPV^A of the investment has the form $\max(V-I, 0)$. Since this NPV^A can also be written as

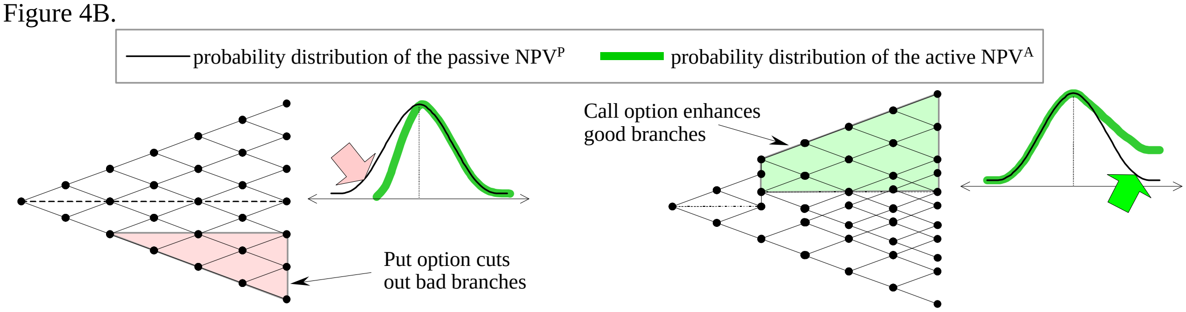
[3] Traditionally, risk management is aimed at protecting a financial position against the devaluative effects of risk (e.g., changes in foreign exchange rates). Under this view, actions (trades) that increase the risk of a position are considered speculative. In recent years, however, it has been recognized that rational and economically sound actions (trades) can sometimes increase the expected return on a position by more than the risk they add to the position. Respectively, risk management is now more broadly viewed as a way to control the balance between the risk and return characteristics of a financial position.

$$\text{NPV}^A = (V - I) + \textit{defer}\text{ option} = \max(V - I, 0),$$

the value of the embedded deferral option can be written as

$$\textit{defer}\text{ option} = \max(V - I, 0) - (V - I) = \max(0, I - V).$$

So, we see that the payoff function of a deferral option really resembles that of a purchased put option, similar to what is seen in Figure 4A. Applying the same algebraic exercise to other operating options reveals that, except for the option to expand, all other real options are put options. For the option to expand (see Figure 6B), the above algebraic exercise derives a payoff function that resembles the one of a purchased call option, similar to what is seen in Figure 4B.

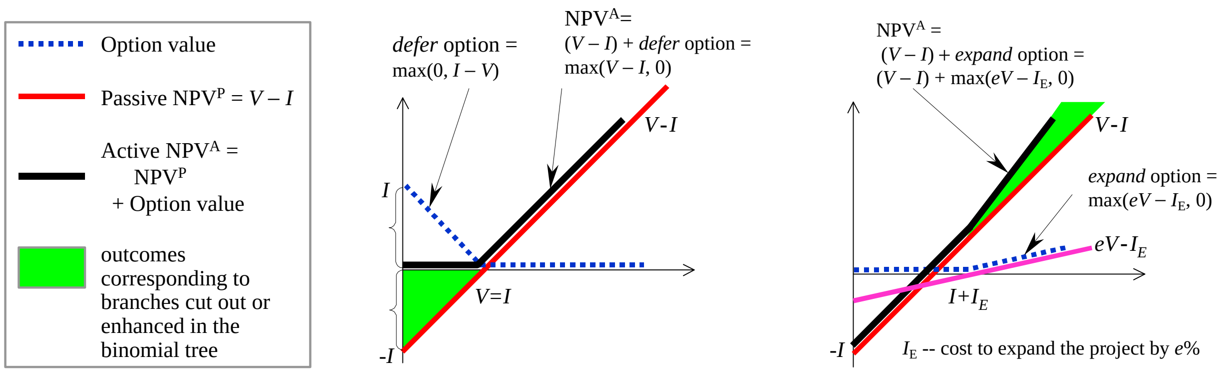


(A) **(B)**

(A) Put options cut out bad branches in the tree modeling the symmetric uncertain behavior of V (the investment value), thereby reducing the downside risk and pushing downwards the left tail of the probability distribution of V.

(B) Call options enhance good branches in the tree modeling the symmetric uncertain behavior of V (the investment value), thereby enhancing the upside potential and pushing upwards the right tail of the probability distribution of V.

Figure 5: effects of call and put options on the probability distribution of the investment value



(A) ***Defer*** option **(B)** ***Expand*** option

Figure 6: graphical depiction of the value of options and its effect on the active NPV^A

The above discussion suggests an important principle – the recognition of embedded shadow options could be driven by the identification of specific risks that they can control. This principle applies even to the option to expand, for which risk can be defined as: "failure to react to favorable outcomes that justify investment expansion" (e.g., favorable market reaction to a new product, indicating higher demand than expected).

3.2. Recognizing Real Embedded Options

Operationalizing the concept that risk can drive the recognition of embedded options requires reliance on a mapping of risks to options that can control them. We develop such a mapping based on the notion that different real options and different technology investment risks arise at different stages in the lifecycle of an investment (see Figure 7). The lifecycle of an investment starts at the *inception* stage, where the investment exists as an implicit opportunity that was probably facilitated by earlier investments. At the *recognition* stage the investment is seen to be a viable opportunity. The *building* stage follows upon a decision to undertake the investment opportunity. In the *operation* stage, the investment produces direct, measurable payoffs. Upon *retirement*, the investment continues to produce indirect payoffs, in the form of spawned investment opportunities that build on the technological assets and capabilities it has yielded. When these assets and capabilities no longer can be reused, the investment reaches the *obsoleteness* stage.

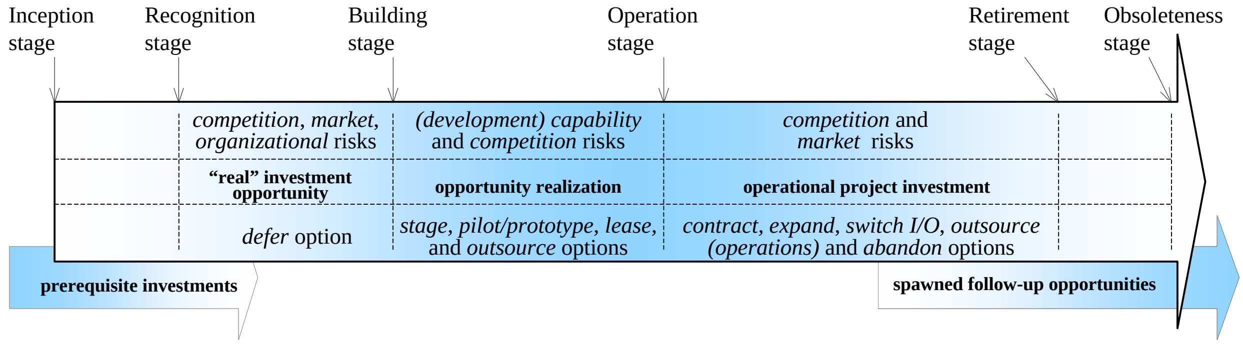


Figure 7: types of risks and real options arising at different stages in the investment lifecycle

As seen in Figure 7, different stages in the investment lifecycle give rise to different risks. These risks fall into three generic categories.

- *Firm-specific risk* is due to uncertain factors endogenous to the firm. It could be the result of uncertainty about the ability of the firm to fully fund a long-term capital-intensive investment, uncertainty about the adequacy of the firm's existing development capabilities (e.g., infrastructure, technical skills, experience with a target technology), uncertainty about the cooperation (or resistance) of various organizational units, etc. These factors contribute to the chance that the firm might not be able to realize an investment opportunity successfully.
- *Competition risk* is due to factors in the control of competitors. It could be the result of uncertainty about whether a competitor will make a preemptive move, or simply copy the investment and improve on it. These factors give rise to the possibility that the firm might loss part or all of the investment opportunity.
- *Market risk* is due to uncertain factors that effect every firm considering the same investment. These factors pertain to uncertainty about customer demand for the products or services a target investment yields, uncertainty about potential regulatory changes, uncertainty about unproven capabilities of a target technology, uncertainty about the emergence of a cheaper or superior substitute technology, and so on. These factors can effect the ability of the firm to obtain the payoffs expected from a realized investment opportunity.

Ac can also be seen in Figure 7, the different real options listed in Table 1 are relevant at different stages in the investment lifecycle. The reason is that each type of real option essentially enables the deployment of specific responses to threats and/or enhancement steps, under one of four different investment modes.

1. **Defer investment** to learn about risk in the investment recognition stage. If we don't know exactly how serious some risk is, we could *defer* investment and learn about the risk by acquiring information passively (e.g., observe) or actively (e.g., market research, lobbying). Here, *learning-by-waiting* helps to resolve market risk, competition risk, and organizational risk.
2. **Partial investment** with active risk exploration in the building stage. If we don't know exactly how serious some risk is, we could actively explore it by investing on a smaller scale. Here, three options facilitate *learning-by-doing*, for the purpose of gathering information about the firm's ability to realize the investment. The option to *stage* investment supports learning via a sequential development effort, and the options to *pilot* and *prototype* support learning through the production of a scaled down operational investment. The last two options compress the investment lifecycle, thus allowing to learn early how competitors, customers, regulatory bodies and internal parties will react to the investment initiative. Put another way, these options permit market risk, development risk and organizational risk to be transferred to earlier stages. Similarly, the option to stage investment divides the investment realization effort into parts, thus permitting to transfer risk within the building stage. For example, implementing the riskiest parts of the realization effort as early as possible helps to reveal very early whether the entire realization effort can be completed successfully.
3. **Full investment** with reduction of the expected monetary value of risk in the building and operation stages. Here, options help to lower the value consequences of some risk and/or reduce the probability of its occurrence. An example of the former is the option to *switch inputs/outputs*, which through use of a more flexible technology permits mitigating market risk, by changing the inputs-outputs mix of the operational investment. Somewhat differently, the option to *lease* development resources protects against development and market risks, by allowing to kill an investment in midstream and save the residual cost of investment resources. An option that lowers the probability of risk occurrence is the option to *outsource* development. This option lowers the risk of development failure, by subcontracting (part or all of) the realization effort to a third party that has

the necessary development capabilities and experience. In essence, both the options to lease and outsource *transfer risk* (partially or fully) to a third party.

4. **Dis-investment/Re-investment** with risk avoidance in the operation stage. If we accept the fact that some risk cannot be actively controlled, we can prepare contingency plans for the case it will occur. Two options permit doing so. The option to *abandon* allows planning to redirect resources if competition, market and organizational risks materialize. The option to *alter scale* allows planning to contract (partially dis-invest) or expand (re-invest) the operational investment in response to unfolding market uncertainties.

Based on the logic of these four investment modes, the mapping of specific risks to specific options that control them can be refined to fit any target class of technology investments. In the next section we show a sample mapping designed to fit common information technology investments. Note that, independent of the target class of investments, the mapping from risks to options is not necessarily one-to-one. This means that, while a particular risk might map to several options that can control it, not every investment exposed to that risk would necessarily embed all those options. For example, shadow options to contract and abandon an operational investment can help mitigate market risk; yet, if regulatory constraints prohibit abandoning a certain investment once it becomes operational, the shadow abandonment option cannot be converted into a real option. Clearly, the only way to identify which shadow options an investment really embeds is to closely examine the investment requirements and assumptions.

3.3. Assessing the Value Contribution of Real Options

Different subsets of the recognized shadow options permit structuring an investment differently, by changing differently the timing and size of cash outflows and cash inflows occurring throughout the investment lifecycle. Therefore, the third step in our methodology seeks to identify the most valuable investment-structuring alternative among all plausible structuring alternatives.

Evaluating investment-structuring alternatives is complex because they usually embed cascading (compound) options. The difficulty in computing the value contribution of options to the investment NPV^A is due to three reasons.

- *Interaction among options*. The value of intra-investment cascading options is non-additive when they cut out the same bad branches, or enhance the same good branches, in the binomial tree modeling the uncertain investment value (Trigeorgis, 1996). In this sense, we can talk about substitute and complementary options. For substitute options, a later option reduces the value of a former option (e.g., defer and abandon). For complementary options, a later option increases the value of a former option (e.g., contract and expand).
- *Cost of a real option*. There is a cost associated with converting a shadow option into a real option, keeping the real option alive, and exercising the real option. For example, consider a shadow option to lease investment resources. Creating the lease option involves the cost of soliciting and evaluating lease proposals from vendors, and exercising the option usually involves a penalty term that must be paid to break the lease. Hence, it is necessary to weigh the value each option contributes to the investment against the cost of converting the option into a real option.
- *Tradeoffs among different cascading options*. It is possible that no single series of cascading options (involving a specific subset of the recognized shadow options) can control all the risks present. In such cases, risks may have to be traded off against each other, where one series of cascading options can lower one risk and at the same time increase other risks (e.g., deferral can lower market risk but it can increase competition risk).

In light of the above complexities, what kind of method can evaluate investment-structuring alternatives embedding compound options? Decision tree analysis (DTA) may seem one candidate. In essence, our methodology helps to design a risk-centered decision tree that allows management to choose which risks to avoid or exploit in order to increase the investment value. Step 1 yields a plain tree showing the possible cash outflows and inflows occurring in the building stage and the operation stage. Step 2 tracks through the tree to identify risks that bring about poor or good outcomes, and then adds decision nodes (i.e., contingent managerial actions) that permit diminishing or enhancing the value consequences of these risks. In other words, step 2 identifies risks at different investment stages and then maps each risk to the type of options that can control it. Considering all potential risks and relevant options, the tree that step 2 produces is essentially a map of the incremental cash-flows occurring under all possible scenarios. Each path through this tree encompasses a different subset of the decision nodes (options) in the tree, and so it corresponds to one plausible investment-restructuring alternative.

However, DTA has two problems that make it inadequate for the evaluation of investment-structuring alternatives. First, the tree tends to grow fast when more cash flow contingencies are considered. This problem is aggravated when decision nodes correspond to American options (that can be exercised at multiple time points), because entire subtrees must be duplicated. The second problem of DTA is finding a proper risk-adjusted discount rate for each investment-structuring alternative. The options embedded in each structuring alternative prune different bad tree branches and/or enhance different good tree branches. Thus, each structuring alternative changes the dispersion (risk) of expected investment outcomes differently, complicating the estimation of a proper risk-adjusted discount rate.[4] This last problem has been widely recognized in the capital budgeting literature (e.g., Trigeorgis, 1996; Amram & Kulatilaka, 1999; Dixit & Pindyck, 1994). Some non-trivial enhancements to DTA resolve this problem, for example, through incorporation of the decision-maker's utility function (Smith & Nau, 1995). In sum, the core issue is that DTA is not geared towards computing the NPV^A of an investment as the sum of two value-adding terms: the passive NPV^P and the embedded options.

Common option pricing methods can compute the value of embedded options separately, by using two means to avoid the above problems of DTA. One means is to model all cash flow contingencies using an explicit probability distribution (e.g., binomial, log-normal) of the gross investment value, *V*. This means prevents a decision tree from growing fast. However, it also requires estimating, s, the variability of *V* (see section 2.1). The next estimation technique naturally follows from our methodology. When the sources of value uncertainty are known (competition risk, market risk, etc.), s can be broken down into its components. Where R_i is one of the risks contributing to the uncertainty of *V*, s_{R_i} is the contribution of R_i to the variability of *V*, and $r_{R_iR_j}$ is the correlation coefficient between risk factors R_i and R_j, s can be written as:

$$s = \sum_i s_{R_i} + \sqrt{\sum_{j \neq i} 2 s_{R_i} s_{R_j} r_{R_i R_j}} \qquad (1 \leq i, j \leq n) \qquad \textbf{(4)}$$

When risks are not correlated, equation 4 is a simple sum of independent elements, each of which can be estimated using generic techniques described in the literature (Benaroch, 2000, Amram & Kulatilaka, 1999; Luehrman, 1998). Our technique is rigorous and it enables a simpler piecewise estimation of s.

The other means option pricing methods use is to replace the actual probabilities of contingent cash flow by risk-neutral probabilities, and then use the risk-free (not a risk-adjusted) discount rate. In this sense, real options analysis is an adjusted version of DTA. It redistributes probability masses such that risk is reallocated in a way that allows for discounting by the risk-free rate. This adjustment relies on economic arguments that permit for the appropriate discount rate to be extracted from market information, indirectly through revision of probabilities. This means poses no problem for options whose underlying assets are traded (e.g., oil, gas, minerals) or are highly correlated with other traded assets. But, for real options on non-traded assets, some people question the validity of risk-free discounting. Amram and Kulatilaka (1999) rightfully explain that this issue is becoming less critical: as more and more investment risks are nowadays being scrutinized by the financial markets (shareholders), decision-makers can draw on financial market techniques, benchmarks and information in order to align their investment decisions with those of the market.[5]

This brief discussion of option pricing methods indicates their suitability to the evaluation of investment-structuring alternatives embedding options. However, of the existing option pricing methods, our methodology uses Trigeorgis' (1991) log-transformed binomial method (see Appendix A). This method simplifies the evaluation of compound options of the kind likely to be embedded in technology investments. Moreover, this method is intuitive because it is a natural extension of DTA. This is apparent from the similarity of the evaluation rules used to assess tree branches embodying decision nodes (options) to the evaluation rules that the log-transformed binomial method uses to measure the value of embedded options. These two points are clearly illustrated in the example we present shortly.

We summarize the methodology by making two additional observations. First, ignoring options can seriously undervalue an investment, whereas simply summing up the value of individual options can overvalue the investment. Second, recognizing all embedded options, not just key ones, is critical to a correct investment evaluation. Ignoring some embedded options can undervalue those options that we do consider (because the presence of later options increases the effective underlying asset for prior options, and exercise of a prior option may alter the underlying asset and the value of later options on it). At the same time, considering more and more options increases the evaluation complexity without necessarily adding much value. Recall that most real options are put options, and so there is a higher chance that more embedded options would be substitute options. Thus, the marginal contribution of each additional option is likely to get smaller and smaller. Ignoring some options therefore makes the error negligible, especially if the options we choose to consider minimize substitutive relations. These two points are demonstrated in the next illustrative application of the methodology.

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[4]In DTA, since a decision at any stage can be optimal only if all subsequent decisions are themselves optimal, the optimal initial decision must be determined by starting from the end of the tree and working backwards to the beginning. This dynamic programming, roll-back procedure involves determining at each stage, as we move backwards, the expected risk-adjusted discounted NPV by multiplying all the NPV values calculated at the previous stage with their respective probabilities of occurrence and summing up.

[5]A good example is Netscape's earlier launching of its browser as a totally new product. Netscape's potential range of outcomes could have been estimated by examining the volatility of a stock index of new public (Internet-based) firms in the technology sector (Amram & Kulatilaka, 1999).

4. Application in Information Systems Engineering

This section illustrates how our option-based methodology for managing technology investment risk is applied to an information technology (IT) investment involving the establishment of Web-based sales channel. Our exposition traces the three steps in the methodology: (1) *Define the investment and its risk profile*; (2) *Recognize shadow options and use them to identify investment-structuring alternatives*; and, (3) *Evaluate investment-structuring alternatives to find a subset of the recognized options that maximally contributes to the investment value*.

4.1. Web-Based Sales Channel – Investment Requirements and Assumptions

Consider a simple investment opportunity involving the establishment of a Web-based sales channel. The investment goals, requirements, assumptions and risks are summarized below, along the main stages in the investment lifecycle.

- *Recognition* stage. An opportunity exists to create a Website for selling products A and B to e-shoppers. The Website would enable e-shoppers to obtain product information, to order products and pay for them, and to track their orders. However, there is uncertainty about how much demand this new sales channel can generate.
- *Building* stage. Developing the Website entails building a core front-end application (using HTML and/or Java) and linking it to legacy sales systems in the back-office. This stage, too, involves risks. First, because the IT organization has no experienced with building Web-based applications, especially ones linked to back-office systems, it is unclear whether the investment opportunity can be successfully realized. Second, some parties (e.g., sales force, retail vendors) might hold the view that the new sales channel would cannibalize the traditional sales channels, raising the possibility that these parties will be reluctant to contribute their valuable knowledge and experience to the investment realization effort.
- *Operation* stage. The Website is to be used to offer sales-related services to customers. The risk here is that customer use of the new sales channel might be too low or significantly higher than expected. Regardless of the level of use, there is also the possibility that the competition will react by launching a similar Website, thereby eroding the extra customer demand produced by the new sales channel.

Given these investment requirements, assumptions and risks, the goal is to maximize the investment value by identifying a good way to structure the investment using carefully chosen real options.

4.2. Mapping Investment Risks to Real Options

Recall that the key to identifying shadow embedded options is the risks that these options can control. Clemons and Weber (1990) and Clemons (1991) identified the key risk factors common to many IT investments. These risk factors naturally fall into the three risk categories we discussed earlier: (1) firm-specific risks – monetary risk, project risk, functionality risk, and organizational risk; (2) competition risk; and (3) market risks – environmental risk and technological risk. Table 2 lists these risk factors and shows how they map to specific real options that can control them. Of course, this list of risk factors could be revised and expanded to fit the profile of any specific firm, IT organization, and/or type of IT investments.

Table 3 summarizes part of the outcome of the second step in our methodology. Of all the risks listed in Table 2, the risks in the target investment are mainly due to uncertain market factors and software development capability factors. In this respect, the example makes explicit two earlier observations. First, the identification of risks is anchored in the investment requirements and assumptions; e.g., the presence of project risk P1 (Table 3) is tied to the need for linkages with legacy sales systems. Second, steps 1 and 2 are somewhat intertwined; e.g., identifying environmental risk E3 in step 2 requires returning to step 1 to clarify assumptions about how the investment might be expanded in the future (Table 3).

Having recognized the relevant shadow options, we proceed to identify subsets of these options that permit structuring the investment in ways that mitigate the identified risks. Recall that sometimes not all the risks present can be controlled by any single investment-structuring alternatives, in which case risks must be traded off against each other. Moreover, not every recognized shadow option is necessarily worth considering. For example, the option to outsource can mitigate project risk P1 (Table 3), but it may not be relevant for various reasons. If the Web-based application is also expected to spawn (strategic) growth options that could open new E-Commerce opportunities, outsourcing may undesirably suppress these options. Additionally, outsourcing may not be the best way to address project risk P1, because legacy sales systems are linked to core business processes.

Investment Life Cycle			Recognition	Building				Operation			
	Risk	**Typical Risk Factors** / **Option**	*Defer*	*Stop-Resume*	*Explore (Pilot)*	*Outsource*	*Lease*	*Abandon*	*Contract*	*Expand*	*Outsource*
Firm-Specific Risks	*Monetary (Financial)*	• **M1** -- firm cannot afford the project – financial exposure is not acceptable	+				+				
		• **M2** -- expected costs are not in line with projected benefits	+		+	+	+				
		• **M3** -- costs are no longer in line with projected benefits						+	+		+
	Project	• **P1** -- staff lacks needed technical skills	+	+	+	+	+				
		• **P2** -- project is too complex		+	+	+	+				
	Functionality	• **F1** -- wrong design (e.g., analysis failed to assess correct requirements)		+	+		+	+			
	Organizational	• **O1** -- uncooperative internal parties	+	+	+			+			
		• **O2** -- parties slow to adopt system			+			+	+		
	Competition	• **C1** -- competition could act before the firm (since it has necessary resources)			+				+		
		• **C2** -- response of competition could eliminate the firm's strategic advantage	+		+		+	+	+		
Market Risks	*Environmental*	• **E1** -- action of regulatory body	+		+		+	+	+		
		• **E2** -- customers may bypass or threaten to develop their own system			+			+	+		
		• **E3** -- failure to react to demand in excess of expectations			+					+	
		• **E4** -- customer response may overwhelm the system			+		+	+	+	+	+
		• **E5** -- customer demand is (or could be) lower than expected	+		+		+	+	+		+
		• **E6** -- environment changed requirements			+			+			
	Technological	• **T1** -- system may be infeasible with current IT	+	+	+	+	+	+	+		
		• **T2** -- system might not remain feasible if current IT becomes obsolete	+				+	+	+		+

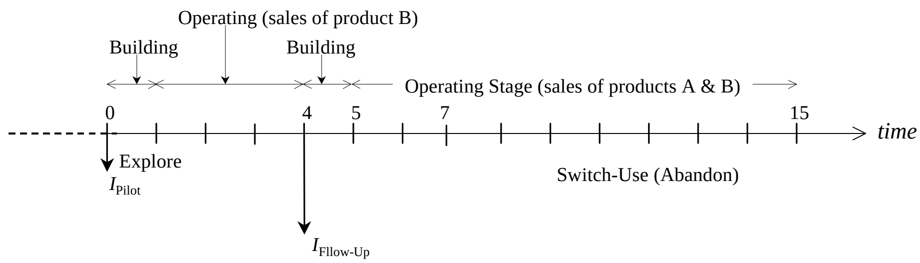
Table 2: risk factors inherent in IT investments mapped to operating options that can control them

Stage	Key Risks / Opportunities	Potential Shadow Options
Recognition	• environment (E5) – low customer demand	• defer • explore (pilot)
Building	• technical (T2) – HTML development is cheaper but it could be limited (so, use Java instead)	• stop-resume (start building linkages to legacy sales systems, to give time to build Java skills)
	• project (P1) – staff lacks needed Java skills • project (P1) – staff lacks experience with linking Web applications to conventional back-office systems	• explore • outsource • stop-resume (start with building linkages to back-office sales systems)
	• organizational (O1) – non cooperative parties	• explore (support only product B) • defer (build good project team)
Operation	• environmental (E5) – low customer demand	• switch-use (e.g., reuse as Intranet) • contract (support sales only of product B, or support only e-ordering and e-payment)
	• environmental (E3) – high customer demand (failure to react to demand in excess of expectations)	• expand (support sales of additional products, or add "push technology" features for products A and B) • strategic growth options (not considered hereafter)
	• competition (C2) – response of competition might erode firm's strategic advantage	• contract (scale down) • switch-use (abandon)

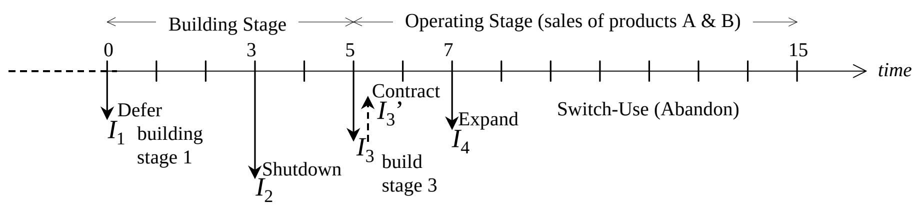
Table 3: first two steps of the methodology applied to the Internet sales presence investment

Suppose that further analysis of the information in Table 3 identifies the two investment-structuring alternatives summarized in Figure 8. (Other alternatives are not considered here.) The first alternative (Figure 8a) considers two of the recognized shadow options. The option to explore would facilitate learning-by-doing, through a pilot effort that supports sales of only product B. This option could help to: (1) lower risk E5 (low customer use) by allowing the firm to learn more about the e-shopping habits of potential customers; (2) partially resolve risk P1 because it will be less risky to establish linkages with legacy sales systems on a prototype basis; (3) hedge organizational risk O1 by giving non-cooperative parties a chance to see that the Web-based sales channel attracts new customers (rather than cannibalizes existing channels); (4) resolve risk E3 because, if the pilot succeeds, the full follow-up implementation could be done using Java, which provides the flexibility needed to support any necessary expansion; and, (5) resolve competition risk C2 by allowing to find out early (after 1-2 time periods) what the competition's reaction might be. In addition to the explore option, should competition risk C2 materialize, the switch-use option would permit abandoning the operational investment and switching its resources to an alternate use.

The second structuring alternative (Figure 8b) considers a larger subset of the recognized shadow options. The most important one is the option to stage the investment into three cost outlays. The first construction stage would provide the learning-by-doing necessary to resolve project risk P1 (establishing linkages with legacy sales systems). If this stage fails, construction can be shutdown permanently by foregoing subsequent cost outlays, with no recovery of the first outlay. Staging can also buy the time needed to work on getting the cooperation of all involved parties, so as to avoid organizational risk O1. In addition, an option to defer the first stage facilitates learning-by-waiting, in support of hedging environmental risk E5 (low customer demand). The third option allows contracting the project by lowering the third planned cost outlay, also in support of hedging environmental risk E5. A fourth option permits expanding the investment by making an additional cost outlay. This option could exploit environmental risk (opportunity) E3, especially if the variable costs of the operational investment have a diminishing growth rate. Last, a switch-use option supports abandoning the operational investment, like in the first structuring alternative.



(A) Two of the shadow options listed in Table 3 are considered: an “explore” option facilitates learning-by-doing, through a pilot project that initially supports sales of only product B and then following-up with a full scale implementation; and, should poor investment outcomes be encountered, a “
abandoning the operational project and putting its resources to a best alternate use.



(B) A larger subset of the shadow options listed in Table 3 is considered: a “
staging the investment into 3 cost outlays during the building stage; an option to “defer” the first stage facilitates learning-by-waiting; and option to “contract” the project’s operating scale by lowering the third planned cost outlay; an option to “expand” the project by making a fourth cost outlay; and, a “switch-use” option that supports abandoning the operational project, like in the first structuring alternative.

Figure 8: two structuring alternatives of the Web-based sales channel investment

The logic behind these two investment-structuring alternatives re-emphasizes the importance of clarifying all the relevant investment requirements, assumptions, risks and their tradeoffs. While both the pilot and the stage options could hedge organizational risk O1 (non-cooperative parties), the picture is different with respect to other risks. For example, the pilot option could hedge competition risk C2 for reasons explained above, whereas the stage option cannot hedge this risk because the firm cannot know how competition will react before the investment becomes operational upon completion of all three stages (in time period 5).

4.3. Evaluating Investment-Structuring Alternatives

Having isolated plausible investment-structuring alternatives, the next step is to evaluate these alternatives. We next illustrate how the second investment-structuring alternative shown in Figure 8b is evaluated using Trigeorgis’ (1991) log-transformed binomial method. This method allows computing the incremental value contribution of each shadow option to the active NPV^A of this alternative, while considering intra-project relations of the option with other options and the cost of converting it into a real option.

Of the all-encompassing risk-centered decision tree for the Web-based sales channel investment, Figure 9 shows only the portion the tree that reflects the options considered under the second investment-structuring alternative. Data pertaining to this alternative is shown in Figure 10. This data may not necessarily correspond to realistic costs and revenues. It was borrowed from the generic example that Trigeorgis (1991) uses to illustrate the log-transformed technique, so that the reader can easily get details on how the value of options is derived. Regardless, we stress that our focus here is primarily on how to interpret the derived option values in relation to the target investment.

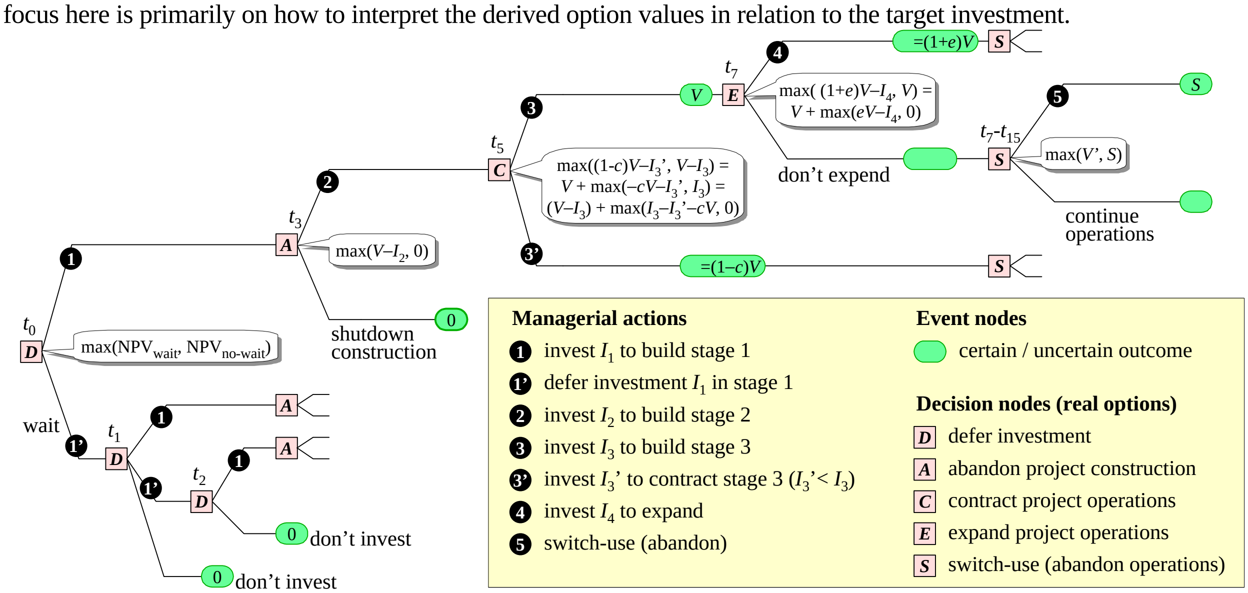
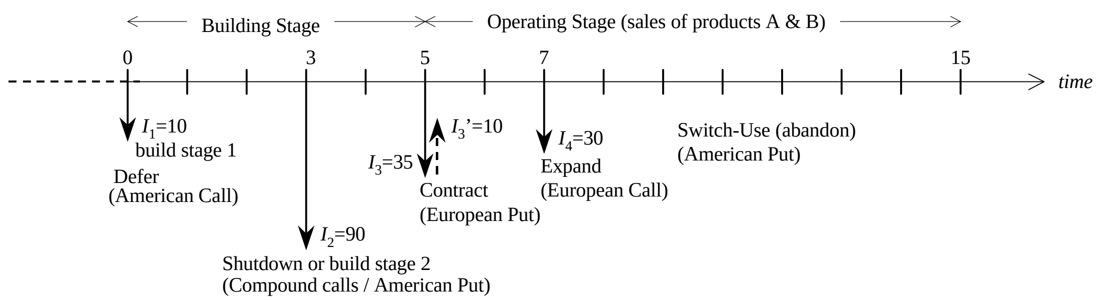


Figure 9: decision tree for the second investment-structuring alternative
(and rules for evaluating decision nodes in the tree)



Assumptions:

1. Present value of the initial gross revenues from the investment opportunity is V=100.
2. Annual risk-free interest rate is r=5%.
3. Volatility of the investment's initial gross value is s=50%.
4. Expected life of the project, T, is 15 years.
5. Project begins with cost outlay I_1=10 in the first stage used to try to establish linkages with legacy sales systems, where this stage is deferrable for t_1=2 years (or less).
6. Construction can be abandoned, with no recovery, by foregoing in year 3 cost outlay I_2=90 used to develop the Internet application using Java. (I_2=70 if the application is developed solely using HTML scripts.)
7. Where the third initially planned cost outlay I_3=35 is needed to complete the building stage in year 5, the project scale can be contracted by c=25% by not adding the order tracking functionality and investing only I_3'=10.
8. If the Internet application is developed using Java, the project scale can be expanded by e=50%, by making in year 7 a forth cost outlay I_4=30, which would allow the application to support sales of other products.
9. Project's salvage value, S, is 50% of the cumulative investment costs (i.e., it "jumps" upward 50% of each cost outlay incurred), and it declines exponentially at a rate of 10% per year between cost outlays.

Figure 10: data and underlying assumptions for the second investment-structuring alternative (Figure 8b)

Evaluation of the second investment-structuring alternative based on the data in Figure 10 yields the following results. First, the passive NPV^{P} of this alternative is negative:

$$\mathrm{NPV}^{\mathrm{P}} = V - I = V - (I_1 e^{-r_f \cdot 0} - I_2 e^{-r_f \cdot 3} - I_3 e^{-r_f \cdot 5}) = 100 - 114.7 = -14.7\,,$$

where $e^{-r_f \cdot t}$ is the operator for continues-time discounting by the risk-free rate, r_f. The picture changes drastically once we consider the embedded options: defer (D), staging with abandonment (A), contract (C), expand (E), and switch-use (S). Figure 11 shows the value contribution of all option combinations to the active NPV^{A}, as calculated by the log-transformed binomial method. At this point, a key result is that, ignoring the cost associated with converting shadow options into real options, the active NPV^A is significantly higher than the passive NPV^P:

$$NPV^A = NPV^P + \text{value of all operating options} = -14.7 + 86.6 = 71.9.$$

But, is it still sensible to create all the options once we consider their associated costs? We address this issue next, based on the results in Figure 11. (Appendix B offers material that helps to trace our discussion with greater ease.)

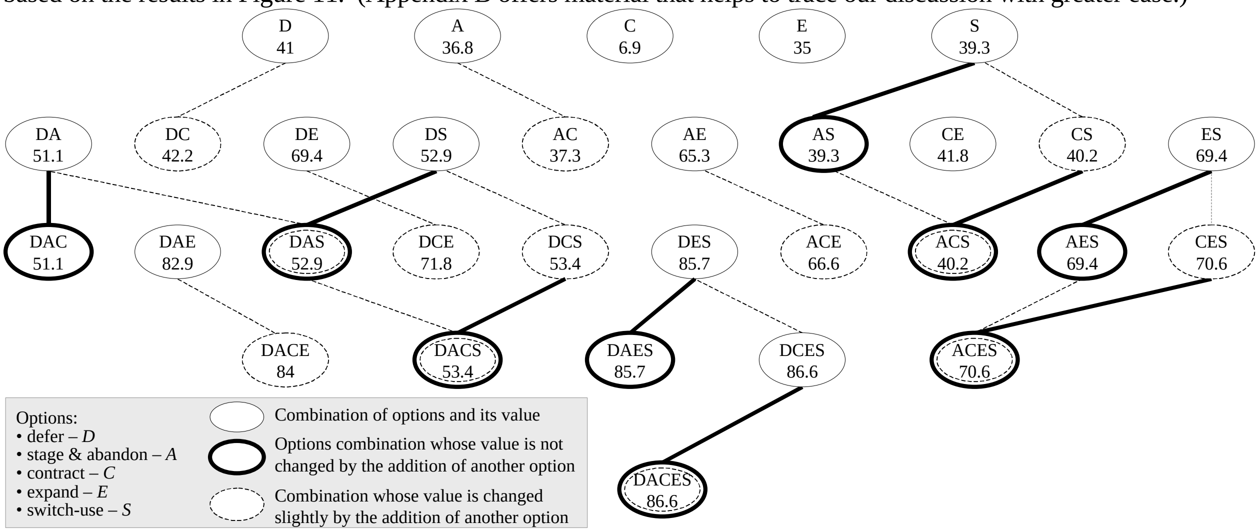


Figure 11: value of all option combinations for the second investment-structuring alternative

The first shadow option to stand out is option *E*. Its value alone is 35, and the least value it contributes to any combination is 28.4 (see Appendix B, Table B1). Being the only call option considered (see Figure 5), it is the only one to enhance good investment outcomes (or tree branches). In this sense, we can say that option *E* has a complementary relation with all other options. Finally, knowing that option *E* costs only 20 to create (see assumptions 6 and 8 in Figure 10), the conclusion is that it makes economic sense to create this option.

Having seen why option *E* ought to be created, we use the same logic to find the value contribution of other shadow options to combinations that include *E*. Of the remaining options, *D* also contributes considerable value to all these combinations. It is worth 41 on its own, and it adds at least 16 to these combinations (see Appendix B, Table B2). Even if this suggests that option *D* has a substitutive relation with some of the other options, it is not a strong one. As to the cost side, the project assumptions indicate that option *D* can be created at no cost (i.e., during deferral, no cash flows are foregone and no market share is lost). Overall, this suggests that option *D* should be created as well.

The remaining shadow options present a more interesting case. Options *A*, *C* and *S* combined increase the active NPV^A from 69.4 (combination *DE*) to 86.4 (combination *DACES*). Yet, because combinations *AES*, *DAES* and *ACES* indicate that a strong substitutive relation exists between these options, we may not want to create all of them. Starting with option *A*, it adds no value to combinations *AES*, *DAES*, *ACES*, and *DACES*. Ignoring the fact that this result is intended by design, to show that some options could add no value, the question is: should option *A* be created? We need to look at its cost as well. When we decide to stage project construction, the option to abandon construction is obtained at no cost. (This would not be the case if a staged construction makes the project more costly.) Additionally, options *A* and *S* seem to have an especially strong substitutive relation, where *S* adds a little bit more value but *A* costs much less. Under the project assumptions, using Java gives the flexibility to expand and to switch-use with salvage value. Since the use of Java adds 20 to the project cost (see assumption 6 in Figure 10), the switch-use option is created by default when the expand option is created. Therefore, it is still worth considering option *S* even though it adds only 2.60 to combination *DACES*. Finally, apparent from combination *DACES*, option *C* adds at least 0.90 to the investment value. Hence, unless the cost associated with option *C* exceeds 0.90, this option should also be created.

Let us summarize how our methodology works in the Web-based sales channel investment. Steps 1 and 2 showed how two plausible investment-structuring alternatives are revealed, through the identification of risks present in the investment and their mapping to options that can control them. Then, step 3 showed how option pricing analysis is used to evaluate one of these investment-structuring alternatives, where the derived value contribution of options determined which of the options should be created so as to maximize the active NPV^A of that alternative.

5. Conclusion and Directions for Future Research

This paper expands the literature on the application of real options theory to technology investments. Previous research in this area has focused primarily on two issues. One is the motivation behind applying real options theory to such investments. Another is the evaluation of investments that are a-priori assumed to embed a single operating option. In practice, however, operating options are not inherent in technology investments, but rather must be carefully planned and designed to fit each investment. Respectively, the present paper focused on issues pertaining to how to apply this theory to investments that possibly embed multiple (compound) operating options.

In particular, the paper presented a methodology that helps to use real operating options to structure technology investments in ways that increase the value of these investments. Managers can always consider different ways to structure technology investments using different forms of flexibility (e.g., prototyping), without even thinking in terms of real options. Nevertheless, our methodology helps managers in two ways. It supports the systematic identification of investment-structuring alternatives, by framing operating flexibility in terms of the risks that real options can control. In turn, it supports the evaluation of these alternatives on an adequate economic ground; it allows evaluating different possible option combinations, or investment-structuring alternatives, for the purpose of identifying the most economically valuable one.

The paper also presented an example of how the methodology is applied in practice. A by-product of this example is a clear illustration of two important points. First, ignoring embedded options can seriously understate the value of an investment, while simply summing up the value of individual options can overstate the investment value. Second, recognizing all embedded options, not just one or two key options, could be critical to the correct evaluation of an investment, because ignoring some options can understate the value of those options that we do consider.

The example also helped to surface an important research question that requires further investigation. The question pertains to how we can isolate the value contribution of each option in a series of cascading options. The state-of-the-art scheme that the real options literature (Trigeorgis, 1996) uses is: calculate the value contribution of all option combinations and then compare the values of "adjacent" combinations to find the marginal contribution of each option. As we saw in our example, this ad-hoc scheme could render the evaluation of multiple investment-structuring alternatives both complex and time consuming, especially since the cost of options is considered only after the marginal contribution of each option has been calculated. A more logical scheme might be one that builds on decision tree analysis. Given that a decision tree models the flexibility borne by operating options using decision nodes, is it valid to isolate the value contribution of options (in light of their cost) using the roll-back procedure of decision tree analysis (explained in Footnote 3)? With an adequate scheme for analyzing the value of cascading options, it would be possible to build a computer-based support system that can automatically screen out inferior investment-structuring alternatives, identify tradeoffs based on traits of the options involved, etc.

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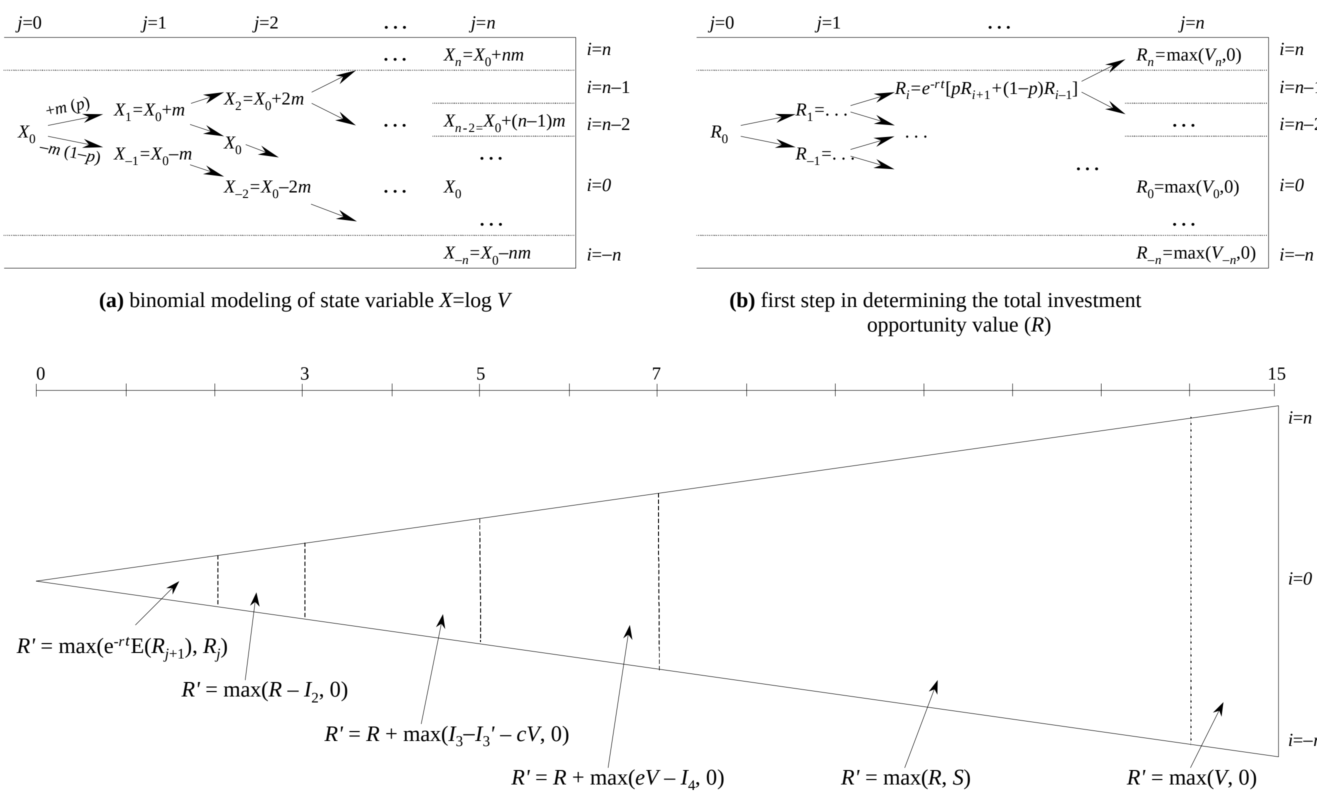
Appendix A: Log-Transformed Option Pricing Method

While the binomial method models the behavior of *V*, the underlying asset (project) value, using a multiplicative diffusion process, the log-transformed method transforms this process into an additive one (Trigeorgis, 1991). The log-transformed method does so in order to simplify the valuation of investments embedding complex compound options.

Suppose that the behavior of *V* is modeled using a standard binomial tree with *n* time steps, each of length $k = s^2 T/n$ (also denoted $t = T/n = k/s^2$). Define state variable *X* as the log-transformed version of *V*, $X = \log V$, which can make up and down moves of magnitude $m = \sqrt{k + (mk)^2}$, where $m = r/s^2 - 1/2$, with the probabilities $p = 1/2(1 + mk/m)$ and $1-p$, respectively. Let *i*, $-n \le i \le n$, be the index of state variable *X* corresponding to the net number of up less down moves, so that $X_i = X_0 + im$ (see Figure A1a). Also, let R_i denote the total investment opportunity value, including embedded real options (i.e., active NPV[A]), at state *i*. Where index *j* denotes the number of time steps, each of length *k*, determine R_i as follows (see Figure A1b). For each state *i*, set the terminal boundary value of the investment at *j*=*n* to be $R_i = \max(V_i, 0) = \max(e^{X_i}, 0) = \max(e^{X_0 + im}, 0)$. Thereafter, for *j*<*n*, work backwards to determine R_i, and adjust for real options at appropriate time steps. First, for a time step where no option can be exercised, let $R_i = e^{-r_f t}[pR_{i+1} + (1-p)R_{i-1}]$, with r_f being the risk-free discount rate and t being the discounting period length. Then, adjust R_i for each *j* where an embedded real options can be exercised. In the Web-based sales channel investment discussed in Section 4, the adjustment is done using the following rules (see Figure A1c): [6]

1. Defer – $R' = \max(e^{-rt}E(R_{j+1}), R_j)$, where E() is the expectation operator.
2. Stop-resume (Abandon) – $R' = \max(R - I_2, 0)$, where I_2 is the cost outlay being defaulted.
3. Contract – $R' = R + \max(I_3 - I_3' - cV, 0)$, where $I_3 - I_3'$ is the reduction in cost outlay used to contract by *c*%.
4. Expand – $R' = R + \max(eV - I_4, 0)$, where I_4 is the cost outlay needed to expand by *e*%.
5. Switch Use – $R' = \max(R, S)$, where *S* is the salvage (or alternate use) value.



(a) binomial modeling of state variable *X*=log *V*

(b) first step in determining the total investment opportunity value (*R*)

(c) second step in determining *R* – adjusting for embedded options (in the Internet Presence example)

Figure A1: evaluating an investment embedding multiple real options using the log-transformed binomial technique

[6] These option adjustment rules resemble the rules used to evaluate decision nodes in the decision tree seen in Figure 9. Only rule 3 differs from the corresponding one in Figure 9, because the log-transformed method includes I_3 in I (i.e., $I = I_1 + I_2 + I_3$). Also, these option adjustment rules apply only to European options, but they can be easily extended to the case of American options like in the standard binomial technique.

Appendix B: Option Values Calculated for the Web-Based Sales Channel Example

Table B1: All option combinations.

Value of Option Combinations		Contribution of Option to each Combination				
		D	***A***	***C***	***E***	***S***
D	41.00	41.00				
A	36.80		36.80			
C	6.90			6.90		
E	35.00				35.00	
S	39.30					39.30
DA	51.10	14.30	10.10			
DC	42.20	35.30		1.20		
DE	69.40	34.40			**28.40**	
DS	52.90	13.60				11.90
AC	37.30		30.40	0.50		
AE	65.30				28.50	30.30
AS	39.30		0.00			2.50
CE	41.80			6.80	34.90	
CS	40.20			.90		33.30
ES	69.40				30.10	34.40
DAC	51.50	14.20	9.30	0.40		
DAE	82.90	17.60	13.50		31.80	
DAS	52.90	13.60	0.00			1.80
DCE	71.80	30.00		2.40	29.60	
DCS	53.40	13.20		0.50		11.20
DES	85.70	16.30			32.80	16.30
ACE	66.60		24.80	1.30	29.30	
ACS	40.20		0.00	0.90		2.90
AES	69.40		0.00		30.10	4.10
CES	70.60			1.20	30.40	28.80
DACE	84.00	17.40	12.20	1.10	32.50	
DACS	53.40	13.20	0.00	0.50		1.90
DAES	85.70	16.30	0.00		32.80	2.80
DCES	86.60	16.00		0.90	33.20	14.80
ACES	70.60		0.00	1.20	30.40	4.00
DACES	86.60	16.00	0.00	0.90	33.20	2.60
	Min	13.20	0.00	0.40	28.40	1.90
	Max	35.30	30.40	6.80	34.90	34.40

Table B2: Option combinations that include option *E*.

Value of Option Combinations		Contribution of Option to each Combination				
		D	***A***	***C***	***E***	***S***
DE	69.40	34.40			28.40	
AE	65.30				28.50	30.30
CE	41.80			6.80	34.90	
ES	69.40				30.10	34.40
DAE	82.90	17.60	13.50		31.80	
DCE	71.80	30.00		2.40	29.60	
DES	85.70	16.30			32.80	16.30
ACE	66.60		24.80	1.30	29.30	
AES	69.40		0.00		30.10	4.10
CES	70.60			1.20	30.40	28.80
DACE	84.00	17.40	12.20	1.10	32.50	
DAES	85.70	16.30	0.00		32.80	2.80
DCES	86.60	**16.00**		0.90	33.20	14.80
ACES	70.60		0.00	1.20	30.40	4.00
DACES	86.60	**16.00**	0.00	0.90	33.20	2.60
	min	16.00	0.00	0.90	28.40	2.60
	max	34.40	24.80	6.80	34.90	34.40

Table B3: Option combinations that include options *D* and *E*.

Value of Option Combinations		Contribution of Option to each Combination				
		D	***A***	***C***	***E***	***S***
DE	69.40	34.40			28.40	
DAE	82.90	17.60	13.50		31.80	
DCE	71.80	30.00		2.40	29.60	
DES	85.70	16.30			32.80	16.30
DACE	84.00	17.40	12.20	1.10	32.50	
DAES	85.70	16.30	0.00		32.80	2.80
DCES	86.60	16.00		**0.90**	33.20	14.80
DACES	86.60	16.00	0.00	**0.90**	33.20	2.60
	min	16.00	0.00	0.90	28.40	2.60
	max	34.40	13.50	2.40	33.20	14.80