

Technology Competition and Optimal Investment Timing: A Real Options Perspective

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Abstract—Companies often choose to defer irreversible investments to maintain valuable managerial flexibility in an uncertain world. For some technology-intensive projects, technology uncertainty plays a dominant role in affecting investment timing. This article analyzes the investment timing strategy for a firm that is deciding about whether to adopt one or the other of two incompatible and competing technologies. We develop a continuous-time stochastic model that aids in the determination of optimal timing for managerial adoption within the framework of real options theory. The model captures the elements of the decision-making process in such a way so as to provide managerial guidance in light of expectations associated with future technology competition. The results of this paper suggest that a technology adopter should defer its investment until one technology's probability to win out in the marketplace and achieve critical mass reaches a critical threshold. The optimal timing strategy for adoption that we propose can also be used in markets that are subject to positive network feedback. Although network effects usually tend to make the market equilibrium less stable and shorten the process of technology competition, we show why technology adopters may require more technology uncertainties to be resolved before widespread adoption can occur.

Index Terms—Capital budgeting, decision analysis, investment timing, network externalities, option pricing, real options, stochastic processes, technology adoption.

I. INTRODUCTION

THE RECENTLY unprecedented development of new technological innovations has yielded many investment opportunities for firms. However, such innovations are usually associated with significant uncertainties that derive from the nature of the technology itself, the consistency of investor perceptions about the quality of its solution capabilities, and competition that is occurring in the market around similar kinds of innovations. As a result, adopting the right technology at the right time becomes a challenging issue that many managers must face head on, if they are to achieve effective decisionmaking on behalf of their firms. In this paper, we propose a new model based on the theory of real options that is intended to provide senior managers with a tool to address this issue in a manner that balances effective managerial intuition with a depth of insight that is only possible with the application of rigorous methods. At the core of our perspective—and the theory of real options, in a larger

sense—is the idea that every successful business manager must understand the fundamental tradeoff between risk and reward [2], [7]. Recent efforts have been made to understand potential benefits associated with real options in multiple information systems (IS) contexts, including software development and enterprise systems module adoption [71], [72], banking IT infrastructures [62], software development project portfolios [9], and decision support systems [48]. All these papers, however, deal with investment evaluation problems in the absence of technology competition.

A. Investment Decisions for Competing Technologies

Very often, however, senior managers must consider *whether* and *when* to adopt one of two incompatible competing technologies. Leading examples in our time include Sun Microsystems' Java and J2EE software development environment versus the Visual Basic, Visual Studio and the Net development environments of Microsoft. In addition, there are many cases of intratechnology competition in which somewhat different, and somewhat compatible technologies compete within a technology standard [14], increasing the anxiety of the marketplace as to how fast it will shift to embrace the new technological innovations. We need look no farther than recent developments around the IEEE standards for Wi-Fi fixed location wireless computing. Although many hardware and software vendors have been working to create compliant products for the 802.11b standard, the market has recently been shaken up by indications that the 802.11g standard offers faster throughput and greater effective range.

A typical technology investment project requires a significant initial outlay of capital and is generally either partially or wholly irreversible. In addition, technology investment projects usually bear significant business and technological uncertainties, especially in terms of the variance of future cash flows. Moreover, it is typical that some of the uncertainties will be resolved as time passes, changing future period expected values to future period realized values. The “surprise value” of this information that is revealed to a decisionmaker in the future has the potential to change the perceived value of a project and to shift the sentiments that senior managers express about willingness to invest [24].

B. Real Options and Technology Adoption

The characteristics that we have just described—risk expressed in variance terms, and the value of new information—make the financial economic *theory of real options* an appropriate theoretical perspective for evaluating technology investment projects under uncertainty and risk [10]. For example, some authors have recently written that the theory of

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real options has the potential to play a role in the assessment of technology investments, business strategies and strategic alliances in the highly uncertain and technology-driven digital economy [11], [12], [34], [48]. Although other authors have written about some of the shortcomings of applying real option investment evaluation methods [70], its advantages over other capital budgeting methods [such as static discounted cash flow or distributed coordination function (DCF) analysis] have been widely recognized for the analysis of strategic investment decisions under uncertainty [1], [53], [54], [73]. (For readers who are not familiar with the real options theory, we provide a brief and nontechnical introduction in Appendix A.)

Although option pricing theory has been extended beyond the evaluation of financial instruments, it is important that we caution the reader to recognize that there are some technical issues lurking just below the surface of the intuition that deserve our comment. First, option pricing theory is founded on the *market tradability* of the asset on which the option has been created. Unfortunately though, most knowledgeable observers and option pricing theorists will point out that technology investment projects are not subject to the valuation of the market. Moreover, technology projects are often *specific assets* for the firms that invest in them, and as a result, it is unlikely that another identical project would ever be available in the market on which to base a comparison. In financial economics terms and to comply with the requirements of the underlying theory—senior managers who wish to find a traded portfolio that can completely duplicate the risk characteristics of the underlying nontraded asset are likely to be frustrated. Without this *twin security*, as it is often referred to in the literature, risk-neutral valuation is difficult to justify [67], [68]. The result is that the standard “methods toolkit” for option pricing may be inappropriate to apply.

Second, the business value of a potential investment project is assumed to follow a *symmetric* stochastic process. The stochastic process that is most commonly used in real option analysis is *geometric Brownian motion*, as illustrated in [57], but models that incorporate the Brownian geometric motion stochastic process assume that there are no competitive impacts on the cash flows and future payoffs of the project. The essence of the concern is the possibility of competition affecting a technology project investment’s future cash flows. Why? Because competition is likely to cause the distribution of future project values to become *asymmetric*: higher project values are less likely to occur because of the potential competitive erosion of value (e.g., [64]).

As Kulatilaka and Perotti [45] and other business innovators have pointed out, the benefits of early preemptive investment may strategically dominate the benefits of waiting when the competition is very intense. These problems associated with traditional real option modeling motivate us to model technology investments from a new perspective. Instead of stochastically modeling the investment project value—as might be the case for traditional assessment of technology projects using real option methods—our insight is that the standard Brownian motion can be used to directly model the technology competition process. Like Grenadier and Weiss [31], our paper uses the first passage time of a stochastic process to characterize a random time in the future. The *first passage time* is a technical term frequently used in stochastic analysis. It is the first time for a Brownian mo-

tion to reach a predetermined threshold. See Domine [23] and Ross [63] for its statistical properties. Grenadier and Weiss [31] use the first passage time of a geometric Brownian motion to characterize the random arrival time of a future innovation. Our paper uses the first passage time of a standard Brownian motion to characterize the random time at which one technology wins the competition. The appropriateness of this modeling approach depends on whether each state of the stochastic process can be easily and precisely interpreted. In Grenadier and Weiss [31], each state of the stochastic process corresponds to a certain expected arrival time of the future innovation. Here, each state of the stochastic process corresponds to a certain expected probability for a technology to win the competition. Therefore, the Brownian motion used in our model can be linked to decisionmakers’ expectations of the outcome of the technology competition.

C. Process View of Technology Competition

To effectively make our general argument about the appropriateness of representing the competitive process that occurs around a technology investment project, we first bring into clearer focus what we mean by the “typical process” of technology competition. Grenadier and Weiss [31] present a model to describe the IT investment behavior of a company facing sequential technology innovation. In their model, they identify four potential technology migration strategies:

- *compulsive strategy*: purchasing every innovation;
- *leapfrog strategy*: skipping the earliest version, but adopting the next generation of an innovation;
- *buy-and-hold strategy*: only purchasing the early innovation;
- *laggard strategy*: waiting for the arrival of new innovation and then buying the previous innovation.

Using the option pricing approach, they give an analytical solution from which the probability for a company to pursue any of the four strategies can be derived. In today’s dynamic business environment, the process of technology development is usually both *parallel* and *serial*. Therefore, investors not only care about serial technology migration, but also about the kind of parallel technology competition that is our focus here. We note four basic elements of the process of technology competition that may affect the real option valuation of technology investment projects. They include the following.

- *Problem identification*. An important business problem that the firm faces is identified and new technology solutions are sought to solve it.
- *Proposed technology solutions*. Technology developers and vendors make proposals to the firm for different approaches that they believe will solve the problem.
- *Solution testing and comparison*. The firm observes different technologies competing in the market and managers evaluate and test their effectiveness and draw conclusions based on the appropriate comparisons.
- *Technology standardization*. Over time, the marketplace will reveal which technology or technology solution is the best. As a result, one can expect to see the application of the technology to solve the problem to become increasingly standardized.

As a company plans a technology investment when a two-technology standards battle is present, it usually will face two questions. Which technology is likely to eventually win the standards battle? How long will it take for the technology competition process to end? We will show why the answers to these two related questions play important roles in a firm's technology investment decisionmaking. More specifically, our model suggests that a firm should defer technology adoption and let some of the relevant uncertainties in the world be resolved before the technology competition process reaches an *investment viability threshold*. We will shortly lay out the characteristics of this threshold. The managerial guidance that we offer is that firm should adopt a technology immediately if the current state of technology competition reaches this threshold. We also consider the drivers of competition that affect the market's ability to permit this threshold to be reached.

Although our greater focus is on the competition between incompatible technologies, we also address the more general issue of compatibility. We will demonstrate how significant switching costs and possible technology lock-in may give technology adopters the incentive to wait. Our approach to understanding this problem is especially accommodating of scenarios under which strong network effects exist. It turns out, based on our modeling efforts to develop this theory, that strong network feedback has the potential to shorten the technology competition process by increasing the observed volatility of adopter preferences. The reason why technology adopters usually will act much more quickly in the presence of strong network externalities is not because that they can tolerate the greater uncertainty. Instead, the self-reinforcing network feedback effects make technology adopters' expectations reach the optimal threshold more quickly.

D. Plan of this Paper

The rest of this paper is structured to communicate the analysis details of the story behind this theory-based interpretation, and to provide an effective basis for the acceptance of the ways that we will use the theory of real options to create a new evaluative methodology. In Section II, we begin with a formal presentation of an option-based investment timing model, and show how we reach a closed-form analytical solution. In Section III, we show the linear relationship between investors' expectations and the optimal timing solution generated by our investment viability proposition. We also explore the roles of technology switching costs and network effects in affecting technology investors' decisions. In Section IV, we present the results of numerical analyses and simulations that are aimed at showing the robustness of our modeling approach. Section V concludes the paper with a discussion of the primary findings and some consideration of the next steps in developing this stream of research.

II. REAL OPTIONS MODEL FOR ADOPTING OF COMPETING TECHNOLOGIES

We next discuss the setup of an option valuation model for the adoption of competing technologies. The model is designed to capture the technology competition that leads to an established technological standard as a stochastic process, whose drift over time presents technology evaluation issues that can be

addressed via the specification of a real option pricing model. Our modeling choices permit us to assess the appropriate timing for adoption, based on the use of a *ratio metric* that helps a firm to know whether it has reached a threshold beyond which investment deferral no longer makes sense. (For ease of reading, our modeling development, we include the modeling notation and construct definitions in Table I.)

A. Modeling Preliminaries

Consider a risk-neutral firm that faces a technology investment opportunity. Setting aside the potential outcome of technology competition for a moment, we will assume that the expected payoff of the technology investment project is a positive constant V as of the time the technology investment is made. To implement the technology project, the firm must adopt one of two competing technologies, called Technology S_1 and Technology S_2 . We use a standard Brownian motion $w(t)$ with $dw = \sigma dz$ to characterize the dynamics of competition between Technology S_1 and Technology S_2 . The continuous-time stochastic process $w(t)$ denotes the *state of technology competition* and σ is the variance parameter that affects the volatility of $w(t)$. In $dw = \sigma dz$, dz is a Wiener increment that has two properties: 1) $dz = \epsilon \sqrt{dt}$ with ϵ_t drawn from the normal distribution $N(0, 1)$ and 2) $E(\epsilon_t, \epsilon_s) = 0$ for all $t \neq s$.¹

In many continuous-time real options models (e.g., [13], [57]), deterministic drift parameters are included, in addition to the stochastic parameter. Most of these models use geometric Brownian motions to model investment project values that stochastically increase over time. The drift term is used to characterize the deterministic part of the value increment, and the Wiener process (standard Brownian motion) is used to characterize the stochastic project value increment. Unlike these studies, we use Brownian motion to model the technology competition process, instead of the investment project value. Therefore, our model does not need the drift term to quantify the instantaneous project value increment. All it needs is the Wiener increment (standard Brownian motion) that characterizes the uncertainties surrounding the technology competition process.²

After a random time T , one of the two technologies S_1 and S_2 will prevail and become the standard solution. To model the time T at which the standard emerges, we use an upper boundary $+W$ and a lower boundary $-W$ with $-W < w(t=0) < +W$. The technology competition will finish and one technology will emerge as the standard solution when the stochastic technology

¹Two problems arise when Brownian motion is used to model technology competition. First, it is appropriate to question whether a typical technology competition process meets the mathematical conditions that define Brownian motion. Second, it is hard to find managerially observable variables that can be used to represent a technology competition process. So, it may be difficult to interpret the results of the model. To solve these problems, we will provide a proof that there is a linear mapping between each Brownian motion state and the probability that a technology will become a standard.

²A standard Brownian motion without the drift term is a *martingale*. The *martingale property* is well known in financial economics related to the informational efficiency of stock prices [50]. Adding the drift term destroys the property. However, the *law of iterated expectations* implies that well-behaved expectations should possess the martingale property. Therefore, we intentionally suppressed the drift term to preserve the martingale property, which allows us to interpret our analytical results in terms of decisionmakers' expectations of the future technology competition.

TABLE I
MODELING NOTATION AND CONSTRUCT DEFINITIONS

MODEL NOTATION	DEFINITION	COMMENT
V	Portion of expected technology payoff that does not depend on standardization	Total payoff is the sum of V and an exogenous bonus
$w(t)$	Brownian motion stochastic process used to model technology competition process	Models technology uncertainties of competition and standardization
$-W, +W$	Lower, upper bounds of $w(t)$ used to model technology standard outcome	Determines time when technology standard is reached
w^*	Optimal investment point for $w(t)$	Technology investment should be deferred when $-w^* < w(t) < w^*$
S_1, S_2	Competing incompatible technologies, 1 and 2	High switching costs for S_1 and S_2
T	Random variable characterizing time at which a technology becomes standard in the marketplace	T depends on $w(t)$, W and the initial state, $w(t=0)$
σ	Variance parameter affecting volatility of $w(t)$	Affects speed of change in technology competition process
dz	Wiener increment to characterize instantaneous changes in $w(t)$	Defines standard Brownian motion
r	Cost of capital for the risk-neutral firm	Affects the costs of waiting
Z	Exogenous gain in investment payoff if the technology adopted becomes the standard	Works as a bonus to a firm that adopts the “right” technology
η	Investment deferral tradeoff threshold ratio between Z and V	If $Z/V > \eta$, optimal investment strategy is to defer investing till one technology becomes standard

competition, $w(t)$, reaches either $+W$ or $-W$. If the stochastic process, $w(t)$, reaches $+W$ first, then Technology S_1 will dominate Technology S_2 to become the standard technology at time T . The result will be opposite if $w(t)$ reaches $-W$ first. So an increase in $w(t)$ will make Technology S_1 more likely to prevail in the market and a decrease in $w(t)$ will make Technology S_1 less likely to beat Technology S_2 in the competition.

The approach that we use to determine the uncertain technology standardization time T is similar to the modeling technique used in Black and Cox [16], Leland [49], and Grenadier and Weiss [31]. The outcomes of the technology competition will affect the payoff of a technology investment project that adopts either Technology S_1 or Technology S_2 . To quantify this, we assume that there is an exogenous gain in investment payoff Z at time T if the technology adopted becomes the standard. If the solution adopted fails in the competition, then the value gain will be 0. We also can assume that there is an exogenous value loss in this case, but this assumption will not enhance the generality of our model since we can easily adjust V to normalize this value loss to 0. It may be more helpful for the reader to think of Z as a *bonus* for adopting the “right” technology. The reader should also note that we assume that the switching costs between the two incompatible technologies are prohibitively high. This technology lock-in situation gives the firm little flexibility to switch once it has adopted one technology.

Let the cost of capital for the technology investment project be $r > 0$. Since we assumed that V is constant over time, the firm’s technology investment strategy is very simple if no consideration is given to the effect of technology competition between S_1 and S_2 . The firm should invest immediately if $V \geq 0$, and never invest otherwise. However, the decisionmaking

problem becomes more complicated when we consider the competitive dynamics that may occur between Technology S_1 and Technology S_2 . The expected total payoff from the technology investment with technology competition may be greater than the baseline expected payoff V . Why? Because the firm can gain Z if the technology solution it adopts wins the standards race at time T . More importantly—and a factor that makes the theory of real options especially relevant for our analysis, is that it may be valuable to defer the investment to resolve the uncertainty surrounding the two competing technologies.

To derive the firm’s optimal investment strategy, it is necessary to quantify the value of the options that are embedded in the technology investment opportunity. Before committing to the investment, the firm has an option to choose one of the two competing technologies. When it decides to invest, the firm exercises its adoption option, selecting the technology that it believes to be more promising. The expected investment payoff can be derived by dynamic optimization.

Let $F(w)$ denote the expected value gain through the standardization bonus Z if the company decides to invest, where w is the state of technology competition. So the expected investment payoff at $w(t)$ is $V + F(w)$. Note that the company can adopt either S_1 or S_2 at the time of the investment. Let $F_1(w)$ and $F_2(w)$ denote the expected value gain if the company decides to adopt S_1 and S_2 at w , respectively. For a rational risk-neutral company that always maximizes its expected investment payoff, we know that $F(w) = \text{Max}[F_1(w), F_2(w)]$. So, to calculate the expected investment payoff, we need to derive values for $F_1(w)$ and $F_2(w)$.

We first derive $F_1(w)$. $F_2(w)$ then can be found in a similar way. Since $F_1(w)$ generates no interim cash flows when w is

between $-W$ and $+W$, *Bellman's principle* suggests that the instantaneous return on $F_1(w)$ should be equal to its expected capital gain. So $F_1(w)$ must satisfy the equilibrium equation $rF_1dt = E(dF_1)$.

Expanding dF_1 using *Ito's Lemma*³ yields $dF_1 = (1/2)F_1''(w)(dw)^2$. By plugging $dw = \sigma dz$ into this equation, we obtain $dF_1 = (1/2)\sigma^2 F_1''(w)(dz)^2$. Now, since $E[(dz)^2] = dtE(\varepsilon^2) = dt$, we can rewrite the equilibrium equation $rF_1dt = E(dF_1)$ as $rF_1dt = (\sigma^2/2)F_1''(w)E[(dz)^2] = (\sigma^2/2)F_1''(w)dt$ or simply $(1/2)\sigma^2 F_1''(w) - rF_1 = 0$.

In addition, $F_1(w)$ must satisfy two boundary conditions at $w = -W$ and $w = +W$: $f_1(+W) = Z$ and $f_2(-W) = 0$. The first boundary condition says that the firm that adopts Technology S_1 will gain payoff Z when the state of technology competition, w , reaches $+W$ first, but if the state of technology, w , reaches $-W$ first, then the firm will gain nothing. So the solution to this second order differential equation is $F_1(w) = Ae^{(w\sqrt{2r}/\sigma)} + Be^{-(w\sqrt{2r}/\sigma)}$, where

$$A = Z \left(e^{(W\sqrt{2r}/\sigma)} - e^{-(3W\sqrt{2r}/\sigma)} \right)^{-1} > 0$$

and

$$B = Z \left(e^{-(W\sqrt{2r}/\sigma)} - e^{(3W\sqrt{2r}/\sigma)} \right)^{-1} < 0.$$

For $F_2(W)$, the solution will also satisfy the Bellman equilibrium equation, but the two boundary conditions are $F_2(w) = 0$ and $F_2(-W) = Z$. The solution is $F_2(w) = Be^{(w\sqrt{2r}/\sigma)} + Ae^{-(w\sqrt{2r}/\sigma)}$. Since $F_1(w)$ is monotonically increasing in w and $F_1(w) = F_2(-w)$, we can prove that

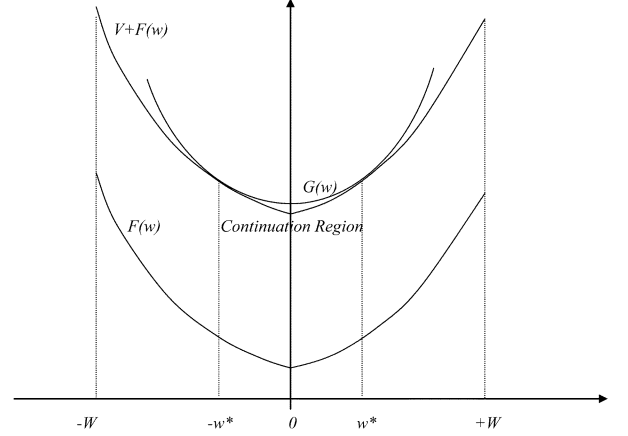
$$F(w) = \begin{cases} Ae^{(w\sqrt{2r}/\sigma)} + Be^{-(w\sqrt{2r}/\sigma)}, & \text{for } 0 \leq w \leq W \\ Be^{(w\sqrt{2r}/\sigma)} + Ae^{-(w\sqrt{2r}/\sigma)}, & \text{for } -W \leq w < 0 \end{cases}.$$

Since we know the expected investment payoff at the time of investment, we are able to find the optimal timing to make the investment. There are both benefits and costs associated with the option to defer the investment. Waiting will erode the expected investment payoff V in terms of its present value at time 0. However, waiting longer will resolve more uncertainties about the competition between Technology S_1 and Technology S_2 .

Consider two extreme cases. In the first one, the firm invests at time 0. So it will maximize the present value of V but faces uncertainties in the technology competition. In the other, the firm waits until one of the two competing technologies becomes the standard. At that time, the firm's expected investment payoff will be $V+Z$, but the waiting time also will erode this composite payoff in terms of its present value at time 0. Therefore, the optimal investment timing strategy must balance the benefits and costs associated with investment deferral. One may guess that a firm will invest at some threshold of $w(t)$. We prove this in the first theorem.

Theorem 1—Optimal Investment Timing Strategy Theorem: There are two thresholds w^* and $-w^*$, where $w^* \in [0, +W]$.

³*Ito's Lemma* is a well-known theorem in stochastic calculus that is used to take the derivatives of a stochastic process. Its primary result is that the second order differential terms of a Wiener process become deterministic when they are integrated over time. The interested reader should see Merton [59] for additional details.



Note: This figure depicts: (1) the value, $F(w)$, if the firm decides to invest when the state of the technology competition is w , (2) the expected payoff of the technology at the time of investment, $V + F(w)$, (3) the value of the option to invest in the technology, $G(w)$, and (4) the two optimal investment thresholds, $+w^*$ and $-w^*$.

Fig. 1. Symmetric payoffs from firm adoption with competing technologies.

Given $w \in [-W, +W]$, the firm will invest immediately if w is outside of $[-w^*, +w^*]$. Otherwise, it will defer the investment until $w(t)$ reaches either $+w^*$ or $-w^*$. If $w(t)$ reaches $+w^*$ first, the firm will adopt Technology S_1 . If $w(t)$ reaches $-w^*$ first, it will adopt Technology S_2 .

(See Appendix B for the proof.) Fig. 1 depicts $F(w)$, $G(w)$ and the continuation region between the optimal thresholds $+w^*$ and $-w^*$.

We can this apply the optimal timing strategy analysis to several special cases. When there is no gain associated with selecting the right technology $Z = 0$, it turns out that $w^* = 0$. So there will be no need to defer the technology investment. Waiting in this case has a single impact: it decreases the present value of the technology payoff, V . When $\sigma = 0$, however, we will see that $w^* = 0$. In this case, $w(t)$ will degrade to a constant and the optimal strategy for the firm will be to invest immediately in the technology project. More generally, the optimal strategy suggests that the firm will be more willing to defer the technology investment when V is getting smaller or Z is getting larger.

We also find that there is a critical ratio between Z and V in Proposition 1 that can guide investment decisionmaking. The firm will defer the technology investment until $w(t)$ reaches $+W$ or $-W$ when Z/V is greater than or equal to the critical ratio.

Proposition 1—Investment Deferral Tradeoff Threshold Ratio Proposition: There is a critical ratio, the investment deferral tradeoff threshold ratio η , between Z and V . If the ratio Z/V is greater than or equal to η , the optimal investment timing strategy is to defer the investment until one technology becomes the standard. The optimal timing solution w^* depends only on Z/V , and not on the separate values of either V or Z .

See the proof in Appendix B.

The Investment Deferral Tradeoff Threshold Ratio Proposition suggests that the adopting firm's optimal investment strategy is to defer the investment until *all* of the relevant uncertainties associated with technology competition are resolved if $Z/V \geq \eta$. In other words, the firm should defer the investment

until one technology becomes the standard, if the outcome of the standards battle appears likely to have a significant impact on the technology investment's expected payoff. This proposition also says that the actual values of V or Z are irrelevant to the timing decision as long as we know the ratio between Z and V , which is intuitively plausible.

For the optimal investment thresholds found in our model, it is important to show how they are affected by the model parameters. Because of the symmetry of our model, we only need to conduct a comparative static analysis on the positive threshold w^* . This leads to Proposition 2.

Proposition 2—Comparative Statics Proposition: For a positive investment threshold $w^* \in (0, W)$, the following comparative static results must hold: $\partial w^*/\partial \sigma > 0$, $\partial w^*/\partial r < 0$, $\partial w^*/\partial V < 0$, $\partial w^*/\partial Z > 0$, and $\partial w^*/\partial W < 0$.

See Appendix B for this proof also.

The results of the comparative static analysis are readily interpreted. First, if the gain Z from adopting the right technology is large compared to V , the firm will wish to wait for more uncertainty to be resolved with respect to the technology. Second, because increases in W and decreases in σ will tend to prolong the technology competition process, the firm will tend to adopt sooner because the present value of Z will be smaller. Finally, increasing the discount rate r will make waiting more costly and, as a result, the firm will tend to shorten its time to adopt.⁴

We next interpret the results of our model from another perspective and demonstrate the significance of technology adopters' expectations in technology investment timing.

III. SWITCHING COSTS, ADOPTER EXPECTATIONS, AND NETWORK EFFECTS

We next consider the problems of switching costs and lock-in, and the role of adopter expectations and network externalities in technology adoption decisionmaking.

A. Switching Costs and Lock-In

An assumption that we make in this model is that the switching costs between the two technologies are very high. Although this assumption may seem restrictive at first, significant switching costs are common in technology-intensive industries and often lead to a situation known as *technology lock-in* [26], [43], [74]. Based on the comparative statics results, we can relax this assumption and examine how decreases in switching costs affect the optimal investment strategy [52]. In our model, a decrease in switching costs will affect two parameters. The switching costs will dwarf the uncertain exogenous value gain, Z , because firms that have adopted the nonstandard technology may later choose to switch to the standard one at the expense of some switching costs. Also, the switching costs increase the investment payoff V because a part of Z becomes certain. Since the derivatives, $\partial w^*/\partial V < 0$ and $\partial w^*/\partial Z < 0$, decrease in switching costs, this implies that waiting is less attractive, but clearly, technology adopters are willing to wait because they are afraid of getting locked into the nonstandard

technology. Without proper coordination, significant switching costs may lead to Pareto-inferior equilibria, and possibly unacceptably slow, inertial adoption. Consequently, some technology vendors may voluntarily promote open standards or technology interoperability to reduce switching costs and to boost potential adopters' confidence about the future benefits stream from the technology.

B. Role of Expectations

As we mentioned earlier, one difficulty that managers will face in interpreting our model is that the Brownian motion process $w(t)$ that represents the technology competition process will be hard to define in practice. In Proposition 3, we show that $w(t)$ can be interpreted as the technology adopter's expectations of the outcome of the technology competition.

Proposition 3—Expected Technology Standard Proposition: At point $w(t)$, where $-W < w(t) < +W$, the probability for Technology S_1 to defeat Technology S_2 and to become the future standard is given by $P_1 = (W + w(t))/2W$. At the same point in time t , the probability for Technology S_2 to defeat Technology S_1 and to become the future standard is given by $P_2 = 1 - P_1 = (W - w(t))/2W$.

The proof is omitted.⁵ This proposition basically says that there is a linear mapping between each point of $w(t)$ and the expected probability for a technology to win the competition. This mathematic property, coupled with the martingale property of the Brownian motion, establishes a direct link between each decisionmaker's expectations and the technology competition process $w(t)$ defined in this paper. With knowledge of the relationship between $w(t)$ and the firm's expectations, we are able to provide a more precise interpretation of the Optimal Investment Timing Strategy Theorem.

The optimal timing strategy for the risk-neutral firm is to defer the technology investment until it expects that either Technology S_1 or Technology S_2 will win the competition with a probability of $(W + w^*)/2W$. Rational decisionmakers will always adopt the technology that is expected to have a higher probability to win. So if $w(t)$ hits w^* first, Technology S_1 is expected to win the competition with a probability of $(W + w^*)/2W > 1/2$. But if $w(t)$ hits $-w^*$ first, Technology S_2 ought to win with a probability of $(W + w^*)/2W$. Note that P_1 and P_2 only depend on σ/W , and not on the separate values of either W or σ . This interpretation clearly indicates that the technology adopter's expectations of future technology competition outcomes play a crucial role in its investment timing decision.

An important question here is: How can managers observe the probability of one technology defeating the other? In business, decisionmakers cannot observe the state of the stochastic process directly. Instead, they must rely on their expectations formed through adaptive learning. Therefore, managers who want to apply our model need to rely on their subjective expectations of the future technology competition. Similarly, Grenadier and Weiss [31] use a geometric Brownian motion to depict the technological progress. To interpret the stochastic

⁴All else equal, the expected time for $w(t)$ to reach $+w^*$ increases in w^* . So here we interpret the comparative statics results in terms of the expected investment deferral time rather than the actual investment deferral time.

⁵The proposition directly follows from the fact that $w(t)$ is a martingale. For more details about the *hitting probabilities* of a martingale upon which the proof is based, we refer the interested reader to Durrett [25].

process in their model, decisionmakers also need to rely on their subjective expectations to come up with a reasonable guess of the expected arrival time of the future innovation. The quality of managers' technology adoption decisions depends on how close their subjective expectations are from the "true" state, which is generally unobservable. This is not a big problem for those who believe Muth's [60] rational expectations theory (such as Au and Kauffman [4], which offers a first assessment of the use of rational expectations theory related to IT adoption). In this theory, economic agents' subjective expectations that are formed through adaptive learning should be informed predictions of future events. However, boundedly rational managers also may sometimes form erroneous subjective expectations that may negatively affect the quality of their decisions. Indeed, in some cases, even rational decisionmakers have difficulties in making informed predictions of future events because of various informational or incentive problems [39].

As far as the technology vendors are concerned, their abilities to effectively manage their potential customers' expectations are also critical. A commonly used strategy in technology competition is *penetration pricing*, where one technology vendor unilaterally and aggressively cuts prices to gain market share or preempt its competitors at an early stage in the technology competition. This strategy not only makes a firm's technology more attractive because of the lower price. The vendor also affects other potential adopters' expectations by showing its own determination to win the standards battle. A similar strategy is *survival pricing*, where a weak competitor cuts its product's price defensively to escape a defeat in a battle involving standards. A survival strategy is hard to make work, according to Shapiro and Varian [65], because it negatively affects potential adopters' expectations by signaling the product's weakness.

It is worth noting that our model does not analyze the two pricing strategies. Instead, our discussion of the strategic pricing issue serves two purposes. First, managers' expectations play a significant role in technology adoption decisionmaking. The opposite effects of the two similar pricing strategies further underscore the importance of potential adopters' expectations in technology competition. Second, technology pricing is an example of many strategic issues of expectations management in technology competition. Our discussion here aims to suggest that many of these issues should be studied in general equilibrium models that consider the dynamic interaction between the adopters and technology vendors. In fact, some recent real options studies advocate using real options games for general equilibrium analyzes of firms' investment strategies [32], [34], [66].

C. Technology Competition With Network Effects

We use continuous-time Brownian motion to directly model a technology adopter's expectations that also are subject to continuous changes. Although we have proved that expectations are linear in $w(t)$, there is another question that we have not yet fully addressed. Is it appropriate to assume that the adopter's expectations can be characterized by Brownian motion? As long as the adopter's expectations are rational and consistent, the martingale property of $w(t)$ is justified by the *law of iterated*

expectations.⁶ Since only unpredictable new information can change the adopter's expectations, $w(t)$ should have a *memoryless property*.

However, if we use $w(t)$ to model some directly observable variables like each technology's market share, these two properties are actually much harder to justify.⁷ One reason is that many technology competition processes are subject to positive network feedback that makes a strong technology grow stronger [18], [38], [40]. *Network effects* stem from the efficiencies associated with a user base for compatible products. Consequently, the technology with a larger market share can be expected to gain more market share from its competitor in our model. But note that this directly violates the martingale property and can result in *dependent increments* (in lieu of memoryless increments) of the market share. Although network effects do not undermine our modeling assumptions since we directly model adopter's expectations, their relationships with our model should not be ignored.

In our model, network effects affect the technology adoption dynamics through two channels: through the technology adopter and through the market. The externalities created by network effects usually make it more beneficial to adopt the winning technology. In our model, the investment threshold ratio $\eta = Z/V$ can become larger due to strong network effects. As a result, the optimal timing threshold w^* will increase. According to our comparative static results, the technology adopter will require more certainty about the outcome of the standards battle before making an investment decision. This effect requires that the technology adopter be more patient and wait longer to let more uncertainties in the market be resolved.

But strong network effects usually also result in "tippy" markets that can significantly shorten the technology competition process. In markets subject to strong network externalities, any market equilibrium will be highly unstable and the expected winning technology may be able to obtain a commanding market share even in a very short period of time [27], [28]. We have recently seen this occur with some of the new wireless technologies and instant messaging services [39]. So network effects can reduce the expected duration of the technology competition process in our model by increasing the volatility of $w(t)$. This also will occur because the expectation of the random variable representing the time at which a technology becomes standard in the marketplace T monotonically decreases in σ .

To sum up, our model suggests that network externalities either cause a delay or expedite technology adoption, but this depends on adopter and market-related factors. In general, strong

⁶The *law of iterated expectations* states that today's expectation of what will be expected tomorrow for some variable in a latter period, is simply today's expectation for the variable's value in the latter period. For additional details, the reader should see Walpole *et al.* [75].

⁷Issues of this sort frequently arise in the midst of efforts to bring a theoretical perspective into more practical uses for analysis and evaluation. The reader should recognize this as inevitable, just as the application of agency theory for contract formation and managerial incentives development (e.g., [5] and [8]), or the theory of incomplete contracts for interorganizational IS investments and governance (e.g., [6] and [33]) is founded on relatively strict assumptions. In spite of this, the theoretical perspectives and the modeling approaches that complement them still offer rich and meaningful managerial insights.

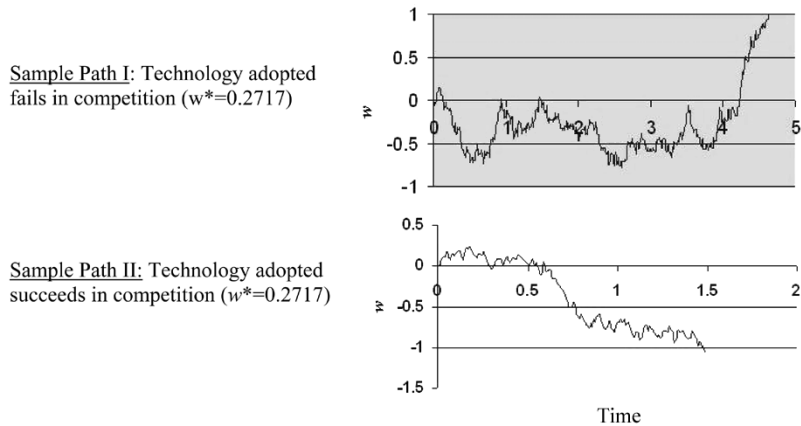


Fig. 2. Optimal timing strategy: no guarantee technology adopted becomes standard.

network effects tend to result in very fast adoption of the technology that adopters believe will be most likely to win the standards competition. In some cases, however, network externalities will make people adopt a technology too early, even though waiting is Pareto-preferred [3], [20]. A final point suggested by our model is that technology adopters actually require more assurance about the future technology standard outcome when they make technology investment decisions, although network effects usually speed up their decisions to adopt.

IV. SIMULATION, NUMERICAL EXPERIMENTS, AND INTERPRETATION

This section discusses a firm-level decisionmaking simulation for technology adoption in the presence of a standards battle between two technologies.

A. Simulation Setup and Outcome

Entry Conditions: We assume that the investment decision will be irreversible. Once it is made, the firm will be locked into the costs and benefits stream associated with the adopted technology. Our goal is to determine the firm's optimal technology adoption timing strategy w^* . To initiate this simulation, we require that the decisionmaker who is contemplating adopting the technology at the firm will know the following information.

- The decisionmaker's current expectations of each technology's probability to win the standards battle will determine $w(t=0)$, the initial state of technology competition.
- The decisionmaker's current estimate of the duration of the technology competition process will determine the appropriate values of W and σ .
- The decisionmaker should be able to make a reasonable estimate of Z/V , the ratio between the bonus for adopting the technology that becomes the standards battle winner, and the firm's baseline payoff from investing in the technology project, regardless of the technology choice.
- The decisionmaker should know the discount rate r that affects the costs of waiting.

We normalize V and W to 1 for the numerical analysis. The discount rate r is assumed to be 10%. The likelihood that either technology will become the standard is 0.50, from which follows that $w = 0$ at time 0. The firm also expects that one of

the two technologies will emerge as the winner in four years. This assumption causes the numerical value of the standard deviation, σ , to be around 0.50. We also set the value of Z , the exogenous gain in business value if the technology becomes a standard at 0.5 V .

Optimal Timing Results. With these specified parameter values, we find that the optimal investment threshold w^* is 0.2717. Thus, the optimal timing strategy in this case is to adopt the new technology when the firm expects that the technology's probability to win is greater than or equal to $(1 + 0.2717)/2 = 0.64$. The optimal timing strategy helps the firm to maximize its expected total investment payoff, but it does not guarantee that the technology adopted will eventually become the standards battle winner. Fig. 2 shows two sample paths that illustrate that the technology adopted at the optimal thresholds $+w^*$ or $-w^*$ can either succeed or fail in the standards competition. (See Fig. 2.)

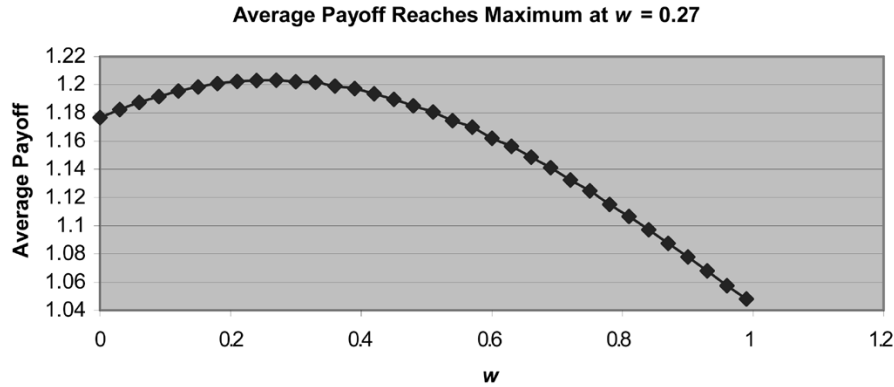
According to the derivation of η given in the Investment Deferral Tradeoff Threshold Ratio Proposition, we find that $\eta = 2.075$. So, in this case, if the exogenous gain in business value when the technology becomes a standard Z is larger than 2.075 V , the result is that the optimal investment strategy is to wait until one technology emerges as the winner.

B. Model Robustness

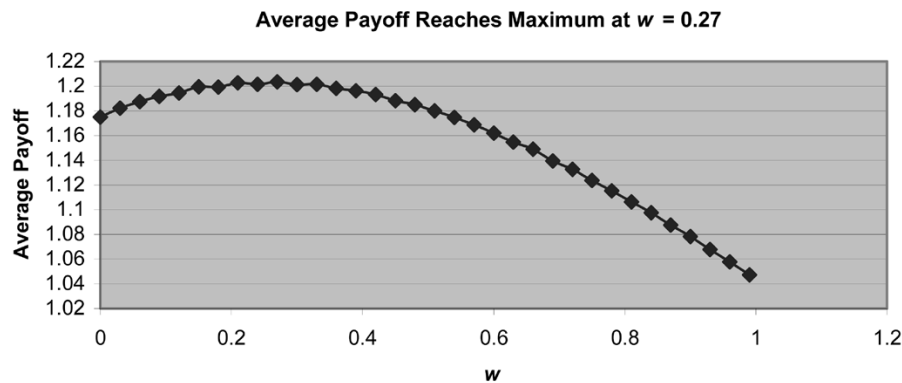
We also use computer simulation to obtain some Monte Carlo results. Because a closed form solution is given in our model, the primary goal of computer simulation is to test its robustness rather than to generate numeric solutions. We used *ANSI C* to code the simulation. With 0.03 as an increment in w , we draw the 100 000 sample average investment payoffs as a function of w in Fig. 3. We set the number of sample paths used in our simulation to be sufficiently large to make sure that these sample average payoffs are very close to the expected investment payoffs.

Fig. 3(a) is a benchmark simulation where no parameter noise has been introduced. It shows that the sample average payoff function achieves its maximum at $w = 0.27$, which is very close to the closed-form solution $w^* = 0.2717$, given that the increment in w is 0.03 in the simulation. Fig. 3(b) shows the average sample payoffs when Z is uniformly distributed between 0 and 1. Again, the payoff function achieves its maximum at $w = 0.27$. We let Z and σ both be uniformly distributed and

a) Benchmark simulation when no parameter noise is introduced.



b) Simulation result when Z is uniformly distributed within $[0,1]$.



c) Simulation result when Z is uniformly distributed within $[0,1]$ and σ is uniformly distributed within $[0.4, 0.6]$.

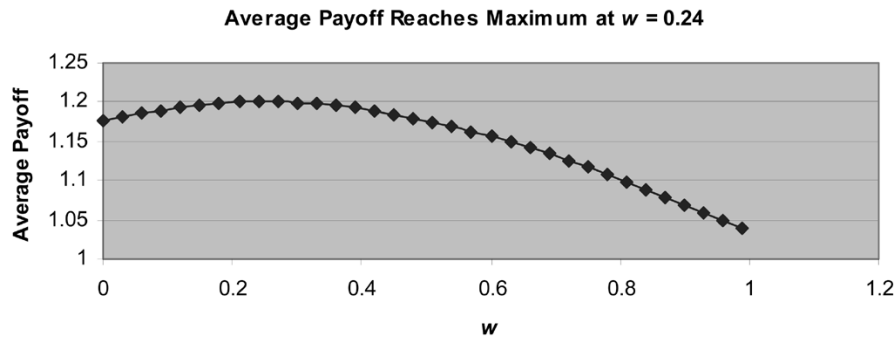


Fig. 3. 100 000 sample average investment payoff as a function of w .

draw the sample average payoff function in Fig. 3(c). Here, we also let σ be randomly drawn between 0.4 and 0.6: so the expected duration of technology competition could range from 2.8 years to 6.3 years in our simulation. We intentionally set this wide range to test the limits of our model's robustness. The payoff curve reaches its peak at $w = 2.4$. The second highest payoff is reached at $w = 2.7$, which is only 0.017% less than the highest payoff.

V. DISCUSSION, IMPLICATIONS, AND CONCLUSION

Since the dynamics of the technology competition process play an important role in technology adoption, we proposed a continuous-time real options model to explore this issue. We next provide a managerial interpretation of the main findings of

this research, as a basis for assessing the usefulness of the ideas in a variety of technology competition and adoption contexts. We also will discuss the limitations of our approach, and the agenda they prompt for future research.

A. Interpretation and Applicability of the Main Findings

Interpretation of the Managerial Contribution. Unlike traditional real options models that stochastically model an investment project's value, our model uses a Brownian motion stochastic process to simulate changes over time in a technology adopter's expectations. This modeling approach enjoys several distinctive advantages. First, decisionmakers' expectations are continuously changing in the presence of new information from the environment in which decisionmaking

occurs. Unfortunately, multistage discrete-time models usually cannot accommodate this feature of the decisionmaking process. Second, the information that arrives typically does so in random fashion. But so long as managerial expectations are rational and consistent, the memoryless and martingale properties of the stochastic process that we discussed turn out to be not too hard to justify. So, in spite of some initial concerns that we pointed out, we believe that our use of the standard Brownian motion representation is a suitable modeling tool. Third, many observers believe that managerial decisionmakers' expectations play a fundamental role in many strategic decisionmaking processes. By characterizing managers' expectations directly, and incorporating them into a decisionmaking model for competing technologies, the modeling approach that we used may create power to analyze other decisionmaking problems under uncertainty.

A major implication of our model is that a firm's technology adoption decisions are directly affected by what senior management decisionmakers expect to happen in the future. Since waiting is usually expensive in a competitive environment, a technology adopter needs an investment timing strategy to balance the tradeoff between waiting and preemption. Our model shows that in a partial equilibrium setting the optimal investment time can be directly expressed as a function of the decisionmaker's expectations about the outcome of the standards battle.

We also addressed the issues of technology switching costs and lock-in within the context of technology investment timing. If competing technologies are more compatible or they compete within an open standard, the technology uncertainties may be significantly reduced and firms may become more aggressive in adopting new technologies. The major results of our model are especially applicable to technology competition processes subject to strong network externalities. We have argued that technology adopters' expectations may become more volatile in a "tippy" market, and that this is caused by positive network feedback. Consequently, waiting may be more beneficial to adopters because the technological uncertainties will be resolved sooner due to the increase in the volatility of expectations. The actual waiting time, as a result, may be significantly shortened because the competition process itself usually ends much more quickly.

Breadth of Application. This approach to thinking about technology competition and adoption has ready application in a number of interesting new business environments involving IT. For example, in the domain of digital wireless phone technologies, we currently see a proliferation of technology standards around the world. Kauffman and Techatassanasoontorn [41], [42] report empirical results at the national level of adoption among countries throughout the world to show that the presence of multiple wireless standards slows down diffusion. In this context, there are problems that exist at the level of the firm, where the kind of managerial decisionmaking issues arise that we have described. However, there is another aspect: technology policymaking by regulators and government administrators may affect the technology economy. In the presence of uncertainty about the outcome of technology competition, these decisionmakers will be faced with the possibility of creating technology adoption distortions through policymaking

that lead to inefficient growth and diffusion, as the information they tap into and their expectations blend together. The primary fear is that inappropriate expectations, possibly amplified by the regulator's distance from the actual process of firm-level decisionmaking, may drive inefficient economic outcomes.

The same can be said for what may happen when firm-level decisionmakers are unable to effectively process information about competing technologies, and end up with inappropriate expectations about the likely outcome. Kauffman and Li [39] argue that there is a risk of *rational herding*, when decisionmakers at potential technology adopting firms misinterpret the signals that are sent and received in the marketplace. Au and Kauffman [4] further argue that this is a problem of *rational expectations*, in which the information for technology adoption decisionmaking is not able to be assembled all at once. Instead, decisionmakers obtain impressions that are later weakened or consolidated, based on their interactions with other potential adopters in the marketplace, as well as vendors and other third parties that may play an important role in the outcome. They point out that the problem of gauging the potential of competing technologies to achieve the status of *de facto* standard has occurred with electronic bill payment and presentment technologies diffusion in the United States, slowing diffusion in the absence of an acknowledged standard.

A similar problem has been occurring with the diffusion of fixed location wireless telephony, the so-called "Wi-Fi" technologies, but here also, we see an environment in the United States characterized by the near simultaneous emergence in time of multiple standards (including 802.11b, 802.11a, and 802.11g, etc.). The difficulties arise for manufacturers of electronics products who wish to embed compatible wireless technologies into their products, including handheld computers and PDAs, sound electronics, electronic shelf management technologies, computer peripherals, and wireless routers and network equipment. They are faced with making uncertain decisions about two aspects of the wireless standards: which ones will become widely accepted by potential consumers of the products they make, and how long the standards will be in use before they are supplanted by the next innovation. Although our model does not directly address this issue of "standards stability," the reader should recognize that the value of the real options that an adopter possesses by making a commitment to a current version of a standard is affected by a variety of market, vendor, and technology innovation issues that are beyond the managerial control of adopting firms. Indeed, this is generally true in many technology adoption settings.

B. Limitations and Future Research

Limitations. We note three limitations of this research that deserve comment before we close out our discussion. First, even though the underlying mathematics of the competing technologies analysis that we present are fairly complex, the concepts that we have presented are relatively straightforward in conceptual terms for use by senior managers. Some may argue that our first concerns should be with the technical details of the modeling formulation—in particular, ensuring that the assumptions that go along with a standard Brownian motion stochastic process with martingale features are precisely met. We chose a

different approach though. Our goal was to find a way to make an analogy between the technical details of the decision model and the exigencies of its application in an appropriate managerial context. We offered a technical argument to assuage the reader's fears that some of our model's assumptions are too stringent. However, we believe that the single best way to think about our approach is in terms of the new capabilities it opens up in support of managerial decisionmaking.

Second, although we have done some initial numerical analysis with our model to gauge its robustness across a number of parameter values, there is a higher level test for robustness that our model still has not measured up to: *construct robustness* in various applied settings. Even though additional analysis work is beyond the scope of the present work, it will be appropriate to conduct additional tests to see whether other issues involving uncertainty that affect adoption decisionmaking can be incorporated. Several related questions immediately come to mind. What will happen when signals on the state of the technology relative to its becoming a standard in the market are filtered or garbled or misread by an adopter, or are misrepresented by a technology vendor? How can the model handle changes in the key parameters, such as changed estimates of volatility, or shifting perceptions of the adoption time line that firms face, over the duration of the adoption period? Clearly, there is additional evaluative work to be done with respect to the general aspects of the modeling approach that we have presented.

Third, we have not yet fully validated this approach with a real world test—something which also is beyond the scope of the present work. This is desirable because we will need to find ways to simplify the approach so that senior management decisionmakers can work with the modeling parameters and concepts. In prior work on the application of real options, for example, Benaroch and Kauffman [12] found that managers did not understand the concept of risk variances and the distributional mechanics that represent stochastic outcomes. This puts a limitation on the application of the methods, since senior management decisionmakers need to be able to work within the modeling constructs of a recommended evaluation approach to represent their understanding of the technology adoption valuation issues in an applied, real world context. Understanding risks and variances is critical to successful use of the approach that we propose.

Future Research. Since technology vendors can proactively influence adopters' timing decisions, an interesting direction for future research is to address the timing issue in a general equilibrium model, to determine policies for adopting firms in a multipartite (i.e., with multiple vendors and adopters) competitive context. In such a model, game theory is arguably the ideal tool, as suggested by Huisman [34], Grenadier [32], and Zhu [76], and the role of strategic expectations should be the focal point. Once vendors' strategies become endogenous to a decisionmaking model, the information asymmetry between technology adopters and vendors will emerge, affecting the manner in which each approaches a decision about when to adopt and when to push toward the next standard. In most cases, technology vendors will hold private information about their firms' plans with the technology, the schedule for releasing the next-generation versions, the speed of development, and so on. As a

result, informational asymmetry should be built into adopters' expectations. Game-theoretic real options analysis can also be applied to situations where the competitive dynamics between technology adopters significantly impact their equilibrium investment strategies. For example, the technological innovation investment model in Grenadier and Weiss [31] is generalized by Huisman and Kort [35] to a duopolistic real options game. Huisman and Kort [36] further extend their duopolistic game to scenarios where the future technology arrives stochastically. Their insightful works clearly indicate one promising direction in which our model can be extended. Specifically, future studies should consider not only the technology competition as modeled here, but also the business competition among technology adopters whose investment strategies dynamically interact with each other.

This paper only models the dynamics of competition between two technologies, but we believe that there are at least two approaches that can help extend our model to the more general scenario, where a manager tries to adopt one of N competing technologies. The first approach requires the use of a multidimensional Brownian motion. The increment of such a Brownian motion has an N -dimensional normal distribution. A band can be defined on each axis, and a winning technology will emerge the first time when the coordinates of the Brownian motion go beyond the band associated with the technology. Mathematically, the N bands defined on the N axes can establish a compact set. Each point in this set can represent a vector of probabilities (p_1, p_2, \dots, p_N) , where p_k is the probability for technology k to win the competition. So the Brownian motion can stochastically characterize the uncertainties surrounding the competition among the N technologies. The advantage of this approach is that the standard properties of multidimensional Brownian motion can be applied. For example, the martingale property of multidimensional Brownian motion can still be used to link it to decisionmakers' expectations.⁸

The second approach only needs a standard Brownian motion defined in a two-dimensional Euclidean space, but it requires some geometric manipulation. For example, the trajectory of a standard Brownian motion in a triangle, as in Fig. 4, can be used to depict the competition process of three technologies.

Mathematically, each point in such a triangle can characterize the expected probability and time for each technology to win the competition. For both approaches, we doubt that closed-form optimal threshold solutions are derivable in most situations. However, recent advances in computation power and optimization algorithms should make it relatively straightforward to find numerical solutions.

Because it is impossible to give closed-form solutions for many complicated real options models, computer simulations and other computationally intensive approaches are suitable research tools [19], [29]. Although we derived a closed-form solution in this study of competing technologies, the reader should recognize that closed-form solutions are very difficult to derive in many other situations where real options analysis is appropriate. Fortunately, the newly available capabilities of com-

⁸See Durrett [25] for a proof. The downside of this approach is that rigorously applying multidimensional martingales requires mathematical knowledge beyond a first graduate course in real analysis (e.g., [69]).

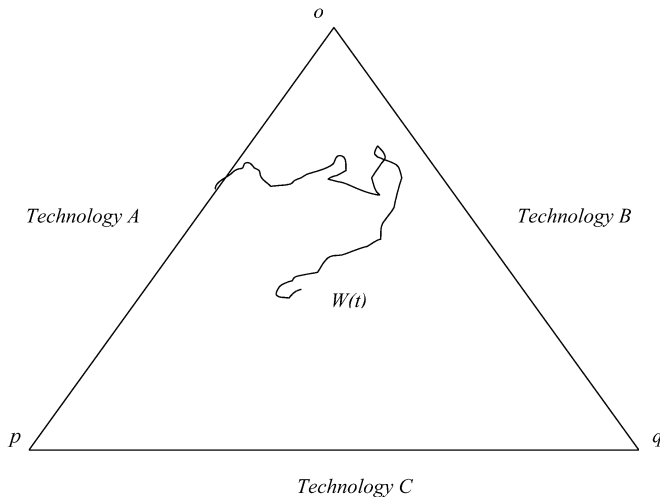


Fig. 4. Brownian motion characterization of the standards battle among three competing technologies.

puting resources make it possible, consistent with widespread advances in methodologies for computational finance, statistics and econometrics, to do numerical experiments and simulations that would not have been cost-effective only a few years ago. These new computationally intensive methods permit us to ask new and more refined research questions involving real options valuation in important applied settings. The answers that we are now able to obtain will help to guide senior management decisionmaking related to technology adoption and advance the frontiers of management science for decisionmaking under uncertainty.

APPENDIX A

UNDERSTANDING REAL OPTIONS: A BRIEF INTRODUCTION

The seminal works of Black and Scholes [15] and Merton [58] offer us a standard pricing model for financial options. Together with another colleague at MIT, Stewart Myers, they recognized that option pricing theory could be applied to real assets and nonfinancial investments. To differentiate options on real assets from financial options traded in the market, Myers coined the term “real options.” Today, that term has been widely accepted in the academic and business world. Many observers believe that the real options approach can play an important role in financial evaluation related to projects that are undertaken in the highly uncertain and technology-driven digital economy. We will present a simple example to give readers some useful intuition and an illustration of the value associated with real options and their significance in capital budgeting.

A. Real Options Example: This Year or Next Year?

Imagine that a software company is facing a new investment opportunity. It plans to spend \$100 000 to make its best-selling database system compatible with an emerging operating system (OS) in the market, but new OS is still in its infancy, so the company is not sure whether it will be widely accepted in the future. Suppose that uncertainty about the new OS can be totally resolved next year, and that the company is trying to maximize

its expected return from the \$100 000 investment project. According to the company’s estimation, the new OS has a 50% chance to be widely accepted next year. In this case, the expected increased cash inflow from this investment is estimated to be \$15 000 a year. In the case that the OS is not popular next year, the expected annual net cash inflow from this project will be \$7000. Further suppose that the discount rate for this investment project is 10%, the net present value (NPV) of this project can be calculated as

$$\text{NPV} = -100\,000 + \sum_{t=1}^{\infty} \frac{(15\,000 + 7\,000)}{2 \cdot (1.1)^t} = 10\,000.$$

Since the NPV of this project is positive, it seems that the firm should go ahead with this project. However, the conclusion is incorrect. Why? It does not account for the value of the option to defer the investment to the next year. Next, suppose that the company waits one year to watch the market’s reaction to the new OS. If a favorable situation occurs, then it will proceed to invest; otherwise, it will no longer pursue the project. Then, the NPV of this project will be

$$\text{NPV}' = \frac{0.5}{1.1} \left[\sum_{t=1}^{\infty} \frac{15\,000}{(1.1)^t} - 100\,000 \right] = 22\,727.$$

Evidently, it is better to take the option of deferring the investment to the next year. The value of this option is \$22 727 – \$10 000 = \$12 727. Let us further suppose that someone in the company argues that the investment costs will increase in the next year. But still, further calculation shows that the option will be valuable even if the costs rise as high as \$127 000 in the next year. Basically, this simple example shows the value of an option of deferring investment.

We now review the basic tools and concepts of option pricing theory, beginning with a definition. An *option* is the right, but not the obligation, to buy (a call) or sell (a put) an asset at a prespecified price on or before a specified date. For financial option contracts, the underlying assets are usually stocks. Until the late 1960s, researchers in Finance were unable to find a rigorous method to price options on stock. However, Black and Scholes [15] and Merton [58], using methods from infinitesimal calculus and the concept of dynamic portfolio hedging, successfully specified the fundamental partial differential equation that must be satisfied by the value of the call option, which permitted them to give the analytical solution known as the *Black–Scholes formula* for the value of an option.

Following the revolution in option pricing theory that the Black–Scholes model caused, many researchers recognized the new potential of this theory in capital budgeting. Traditional DCF methods were recognized for their inherent limitations: they did not yield effective estimates of value related to project investments with strategic options and many uncertainties. Myers [61] showed that a firm’s discretionary investment options are components of its market value. Mason and Merton [55] discussed the role of option pricing theory in corporate finance. Kulatilaka and Marks [44] also discuss the strategic value of managerial flexibility and its option like properties. Table II lists the similarities between an American call option on a stock and a real option on an investment project. Despite

TABLE II
COMPARISON BETWEEN AN AMERICAN CALL OPTION AND A REAL OPTION ON A PROJECT

AMERICAN CALL OPTION ON A STOCK	REAL OPTION ON A PROJECT
Current stock price	Present value of expected cash flows
Exercise price	Investment cost
Right to exercise the option earlier	Right to invest in the project at any time before the opportunity disappears
Stock price uncertainty	Project value uncertainty
Option price	Value of managerial flexibility associated with the project
Expiration time	Time window of the investment opportunity

the close analogy, some still question the applicability of option pricing theory to real options that usually are not traded in a market. However, Cox, *et al.* [21] and McDonald and Siegel [56] suggest that a contingent claim on nontraded assets can be priced with the adjustment of its growth rate by subtracting a dividend-like risk premium.

Based on this solid theoretical foundation, many researchers have investigated the valuation of various real options in the business world. One of the most basic real options models was developed by McDonald and Siegel [57]. In their model, they discuss the optimal time for a firm to invest in a proprietary project whose value evolves according to a stochastic process called *geometric Brownian motion*. Their results suggest that the option to defer an investment may be very valuable under some circumstances. Ingersoll and Ross [37] also discussed the option of waiting to invest and its relation with uncertainty. Brennan and Schwartz [17] examined the joint decisions to invest and abandon a project. Kulatilaka and Trigeorgis [46] adopted real option theory to value the managerial flexibility to switch inputs and outputs. Grenadier [30] discussed how to value lease contracts by real options theory. The interested reader should see Li [51] for additional details on the applications of real options theory to technology related business problems.

APPENDIX B MATHEMATICAL PROOFS OF KEY FINDINGS

A. Proof of Theorem 1—Optimal Investment Timing Strategy Theorem

Before a company invests in a new technology project, it will have an option to invest in the project. This value of this option is denoted by $G(w)$. It must satisfy a Bellman equilibrium differential equation, $(1/2)\sigma^2 G''(w) - rG(w) = 0$, in the continuation region, where there are values of w for which it is not optimal to invest.

Note that we need three conditions to solve the differential equation. The reason is that the optimal investment threshold w^* is a free boundary of the continuation region. The first condition is a *value-matching condition* $G(w^*) = V + F(w^*)$, which

says that upon investing, the expected payoff will be $V + F(w^*)$. The second condition is a *smooth-pasting condition*, $G'(w^*) = F'(w^*)$, that is necessary to guarantee that the threshold point w^* is the true optimal exercise point for the real option [22]. The third is a *symmetry condition* $G(+w) = G(-w)$, which comes directly from the symmetric structure of our model's specification.

We note that, in some cases, w^* will be outside $[-W, +W]$. This means that the continuation region goes beyond the decision region, and so the optimal strategy is to invest when w reaches either $+W$ or $-W$, the boundaries of the decision region. To satisfy the equilibrium differential equation and the third condition, it turns out that the solution must take the form $G(w) = D(e^{(w\sqrt{2r}/\sigma)} + e^{-(w\sqrt{2r}/\sigma)})$. In this expression, D is a constant to be computed and values of w occur within the continuation region. The other two conditions can be used to solve for the two remaining unknowns, the constant D and the optimal investment threshold w^* . The positive optimal investment threshold w^* and constant D must also satisfy the equations shown at the bottom of the page, where A and B are defined where we derive $F(w)$. The solution to the system of equations is given by

$$\begin{cases} w^* = \frac{\sigma}{\sqrt{2r}} \ln \left[\frac{A-B}{V} + \sqrt{1 + \left(\frac{A-B}{V}\right)^2} \right] > 0 \\ D = A + \frac{V}{2} \left[\frac{A-B}{V} + \sqrt{1 + \left(\frac{A-B}{V}\right)^2} \right]^{-1} \end{cases} .$$

The reader should note that we assume $w^* < W$, and $w^* = W$, otherwise. Similarly, the negative threshold w^{**} and D' can be solved as follows:

$$\begin{cases} w^{**} = \frac{\sigma}{\sqrt{2r}} \ln \left[\frac{B-A}{V} + \sqrt{1 + \left(\frac{B-A}{V}\right)^2} \right] = -w^* < 0 \\ D' = D \end{cases} .$$

The negative optimal investment threshold will be $-W$ if w^{**} is beyond $[-W, 0]$. We also know the values of the two thresholds w^* and $-w^*$, where $w^* \in [0, W]$. So for a given $w \in [-W, +W]$, the firm should invest immediately if w is outside of $[-w^*, w^*]$. If $w \in [-w^*, w^*]$, the firm should adopt a technology once $w(t)$ reaches either w^* or $-w^*$. If w reaches

$$\begin{cases} D(e^{(w^*\sqrt{2r}/\sigma)} + e^{-(w^*\sqrt{2r}/\sigma)}) = V + Ae^{(w^*\sqrt{2r}/\sigma)} + Be^{-(w^*\sqrt{2r}/\sigma)} \\ D(e^{(w^*\sqrt{2r}/\sigma)} - e^{-(w^*\sqrt{2r}/\sigma)}) = Ae^{w^*\sqrt{2r}/\sigma} - Be^{-w^*\sqrt{2r}/\sigma} \end{cases}$$

w^* first, then the firm will adopt Technology S_1 since $F_1(w^*) > F_2(w^*)$, but if it reaches $-w^*$ first, then Technology S_2 will be adopted because $F_1(-w^*) < F_2(-w^*)$.

B. Proof of Proposition 1—Investment Deferral Tradeoff Threshold Ratio Proposition

From Theorem 1, we know that the optimal investment threshold is W or $-W$ if the following inequality, $w^* = (\sigma/\sqrt{2r}) \ln \left[(A-B)/V + \sqrt{1 + (A-B)^2/V^2} \right] \geq W$, holds. Since $\ln(\cdot)$ is monotonically increasing, the inequality is equivalent to $(A-B)/V + \sqrt{1 + (A-B)^2/V^2} \geq e^{(W\sqrt{2r}/\sigma)}$. The term $A-B$, can be simplified as $A-B = Ze^{(W\sqrt{2r}/\sigma)} / (e^{(2W\sqrt{2r}/\sigma)} - 1)$. This inequality will hold if $(Z/V) \geq e^{(2W\sqrt{2r}/\sigma)} - 1$. Otherwise, the inequality will be equivalent to $(Z/V) \geq (1/2)(e^{(2W\sqrt{2r}/\sigma)} + e^{(-2W\sqrt{2r}/\sigma)}) - 1$. As $(1/2)(e^{(2W\sqrt{2r}/\sigma)} + e^{(-2W\sqrt{2r}/\sigma)}) - 1 \leq e^{(2W\sqrt{2r}/\sigma)} - 1$. We prove that the optimal investment threshold will become W and $-W$ when Z/V is greater than or equal to η , where $\eta = (1/2)(e^{(2W\sqrt{2r}/\sigma)} + e^{(-2W\sqrt{2r}/\sigma)}) - 1$. The remainder of the proposition directly follows from the fact that $w^* = (\sigma/\sqrt{2r}) \ln \left[(Z/V) \frac{e^{(W\sqrt{2r}/\sigma)}}{e^{(2W\sqrt{2r}/\sigma)} - 1} + \sqrt{1 + (Z/V)^2 \frac{e^{(W\sqrt{2r}/\sigma)}}{e^{(2W\sqrt{2r}/\sigma)} - 1}} \right]$. This completes the proof.

C. Proof of Proposition 2—Comparative Statics Proposition

We know that for any $w^* \in (0, +W)$, we have $w^* = (\sigma/\sqrt{2r}) \ln \left[(A-B)/V + \sqrt{1 + (A-B)^2/V^2} \right]$. In the proof for Proposition 1, we showed that the term, $A-B$, can be simplified as $A-B = Ze^{(W\sqrt{2r}/\sigma)} / e^{(2W\sqrt{2r}/\sigma)} - 1$. From this, we can prove that $\partial(A-B)/\partial Z > 0$, $\partial(A-B)/\partial W < 0$, $\partial(A-B)/\partial r < 0$ and $\partial(A-B)/\partial \sigma > 0$. Since $A-B > 0$, $V > 0$ and $\ln(\cdot)$ is monotonically increasing, we can further deduce that $\partial w^*/\partial V < 0$, $\partial w^*/\partial Z > 0$, and $\partial w^*/\partial W < 0$. In addition, we know that $(\partial \sigma/\sqrt{2r})/\partial \sigma = 1/\sqrt{2r} > 0$ and $(\partial \sigma/\sqrt{2r})/\partial r = -(\sigma/2\sqrt{2})r^{-3/2} < 0$. This permits us to conclude that $\partial w^*/\partial \sigma > 0$ and $\partial w^*/\partial r < 0$. This completes the proof.

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