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VALUING INFORMATION TECHNOLOGY INFRASTRUCTURES: A GROWTH OPTIONS APPROACH

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ABSTRACT

Decisions to invest in information technology (IT) infrastructure are often made based on an assessment of its immediate value to the organization. However, an important source of value comes from the fact that such technologies have the potential to be leveraged in the development of future applications. From a real options perspective, IT infrastructure investments create growth options that can be exercised if and when an organization decides to develop systems to provide new or enhanced IT capabilities. We present an analytical model based on real options that shows the process by which this potential is converted into business value. In this context, we discuss middleware as an example technology because it delivers shared and reliable IT services that enable the development of future IT applications. We derive managerial implications for the evaluation of IT infrastructure investments and how business value is determined by demand uncertainty and market competition, as well as by the IT infrastructure-driven cost advantage of the firm relative to its competitors. The findings of this research are: (1) the flexibility provided by IT infrastructure investment is more valuable when uncertainty is higher; (2) the cost advantage that IT infrastructure investment brings about is amplified by demand volatility for IT-supported products and services; (3) in duopoly competition, the value of IT infrastructure flexibility increases with the level of product or service substitutability; and (4) when demand volatility is high, inter-firm competition has a lower impact on the value of IT infrastructure.

KEYWORDS: Business value, capital budgeting, financial analysis, flexibility, IT investments, IT infrastructure, middleware technologies, option pricing, real options, systems integration.

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INTRODUCTION

Industry observers recognize that information technologies (**IT**) can deliver substantial value to firms that invest wisely. However, senior managers in many organizations complain about how difficult it is to evaluate IT investments and to gauge the value that they create. As a result, many leading IS researchers have been searching for a definitive means to scientifically assess the business value of IT investments and to standardize the methodologies that support managerial analysis. In a survey of over 500 leading companies, *InformationWeek* reported that senior managers were looking for better ways to understand and measure the benefits of IT investments, and nearly 95% were required to measure returns on IT investments (D'Antoni, 2003). We address this issue by providing a disciplined analysis of the value-generating capabilities of IT infrastructure investments (Panayi and Trigeorgis, 1998). We adopt a real options approach to gain an understanding of how infrastructure creates value and apply economic modeling techniques to reveal the business value of IT infrastructure investments.

The results of IT value research have been mixed (Chan, 2000). Roach (1991) reports a lack of productivity improvement with increasing organizational investments in IT. But Hitt and Brynjolfsson (1996) find that IT investment increases both productivity and consumer value, although firm profitability does not increase. Thatcher and Oliver (2001) demonstrate that IT investments made to reduce fixed costs increase productivity, but IT investments made to reduce variable costs increase firm profitability. Other studies emphasize a process-oriented view that reveals the path from IT investment to its locus of business value within the firm. Among them, Barua, et al. (1995) find only partial support for the hypothesized positive impacts of various inputs, including IT, on intermediate variables related to the production of goods and services. Related studies (e.g., Devaraj and Kohli, 2003; Kekre and Mukhopadhyay, 2002;

Mukhopadhyay, et al., 1997) are similarly equivocal in their assessments of IT value.

A reason for these inconclusive findings is the difficulty of measuring the value of IT investments (Brynjolfsson, 1993). The benefits of IT infrastructure investments are indirect and long-term (Renkema, 2000). So they are often assessed by conjecture, with reference to other analogous IT investments (Duncan, 1995). IT infrastructure is listed in *CIO Magazine* (www.cio.com) and *Computerworld* (www.computerworld.com) as a top management concern due to its impact on firms' efforts to achieve competitive advantage. A majority of IT expenditures in most organizations actually relate to infrastructure (Weill and Broadbent, 1998). So how IT infrastructure creates business value is important.

We apply a real options perspective to analyze the value of IT infrastructures, especially the strategic value that a company can obtain by investing ahead of its competition. We first describe IT infrastructure as resources that offer a foundation for future applications. Recognizing that IT infrastructure investment generates value through enabling future applications for IT-supported products or services, we conceptualize the investment as creating growth options and develop a framework for the valuation process (Kester, 1984). Using elements from prior literature (e.g., Barua, et al., 1991; Zhu and Weyant, 2003), we develop a formal model with real options thinking for the evaluation of IT infrastructure. We emphasize the sequential nature of IT infrastructure investment, demand uncertainty, the possibility of skewed demand, and the effects of market competition. We conclude with our contributions and a discussion of the managerial implications of this research.

IT INFRASTRUCTURE AS A SOURCE OF VALUE

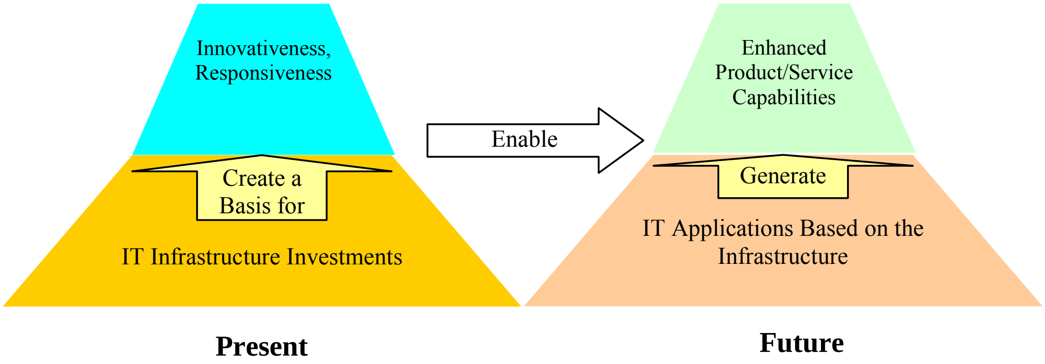
IT infrastructure provides the shared and long-term organizational IT resources that constitute a foundation for present and future business applications (Duncan, 1995; Weill and

Broadbent, 1998, p. 26). IT infrastructure comprises IT physical assets, IT intellectual assets, and IT-related procedural assets (Bharadwaj, 2000; Kayworth, et al., 2001). *IT physical assets* are the basic technical components shared across units of a firm. These include firm-wide technical platforms, common architectures, networks and databases. *IT intellectual assets* are IT-related knowledge, expertise and management of technology skills that exist in the firm. *IT-related procedural assets* are rules that specify how other IT assets are evaluated, acquired, constructed, implemented, utilized, enhanced and replaced. IT standards, for example, are *procedural assets*; they set up rules for system design and development.

A key capability of IT infrastructure is *flexibility* (Kulatilaka and Marks, 1998), the ability to support hardware, software, and networking technologies across a portfolio of systems capabilities, and to extend functionalities and capacities. Flexibility makes it feasible for a firm to create IT-based business innovations at a lower cost than its competition because the firm can adapt its systems and business processes to accommodate changing conditions cost-effectively (Duncan, 1995). A flexible IT infrastructure creates the basis for organizational innovativeness to rapidly develop or enhance products or services in a competitive market (Kayworth, et al., 2001). This potential value can be converted to real business value when management exploits the flexibility of the infrastructure to develop new resources. The associations between IT infrastructure, IT applications, and organizational capabilities are shown in Figure 1.

With an appropriate IT infrastructure, a firm can quickly add functionality to its core systems to meet market demands, refine the handling of data across systems to comply with new regulations, or link its systems with those of other firms. Delta Airlines' experience offers an example (Ross and Beath, 2002). Delta committed to a three-year project to build a shared data environment that integrated data on flights, customers, crews, equipment and baggage, so they were made available simultaneously to the appropriate parties. Later, Delta developed a new application to support its customer boarding business process. It leveraged the centralized flight and customer databases built up in the infrastructure project. The new boarding system streamlined the existing business process, leading to more efficient customer services (Ross and Beath, 2002). In other cases, infrastructure investment is explicitly targeted at building capabilities to support future demand. For example, the adoption of Web services at Danske Bank of Denmark was partly motivated by the ability that Web services provide to deliver new and complex product packages when they are needed for the marketplace (Sliwa 2003). In such cases, the "true value" of a firm's IT infrastructure can only be determined by resolving uncertainties that the firm has about the range of future needs that its infrastructure must address.

Figure 1. Present IT Infrastructure and Future Applications



One important component of IT infrastructure is middleware services, which are "generic services across applications and industries [which] run on multiple platforms, are distributed, and support standard interfaces and protocols" (Bernstein 1996, p. 89). We view middleware services as a component in the IT infrastructure structure suggested by Weill and Broadbent (1998) because middleware delivers shared services throughout a firm that become part of the foundation for other IT applications. Over the years, middleware technologies and products have been advancing quickly as an important part of distributed computing platforms. For example, DCOM and COM+ are deployed with Microsoft's products, Enterprise JavaBeans (**EJB**) provides a component architecture based on the J2EE platform, and CORBA is promoted by the Object Management Group (OMG). These technologies and products exhibit the basic capability of middleware: to provide interfaces and architecture for application developers to leverage common computing resources and to integrate application components that comply with certain interoperability requirements (Agha 2002).

For example, IBM's San Francisco Project yielded a proposal for a framework with three basic layers (Bobrer, et al., 1998). Its "foundation layer" is basically an object request broker, providing object modeling classes and application utilities. The top layer consists of business process components that incorporate specific business logic. The middle layer provides interfaces and mappings that enable developers of different top layer components to use the common foundation layer. Thus an organization can easily integrate functional applications purchased from any vendor whose software conforms to the specified framework.

Middleware technologies make organizational systems more scalable in capacity and functionality terms. Such scalability manifests itself in the flexibility of middleware technologies as IT infrastructure. For example, Wells Fargo Bank developed a customer relationship system by integrating disparate systems for different customer accounts which was supported by an object-oriented middleware technology (OMG, 2004). Later, the bank leveraged this architecture to provide additional applications that enhanced its services including access from the bank's "Interactive Voice Response Unit," automated teller machines, Internet banking and bill payment services.

In summary, IT infrastructures are shared enterprise IT resources, offering foundations for future development that are the source for organizational responsiveness and innovativeness.

The scalability and flexibility for future opportunities distinguish infrastructures from non-infrastructure assets such as local business applications (Weill and Broadbent, 1998). Also infrastructure investments bring in value that may be realized through implementing IT applications enabled by the infrastructure. Non-infrastructure investments create value mainly from applications. Implementing flexible IT infrastructures enables a firm to develop applications at lower costs (Ross and Beath, 2002).

In this sense, an IT infrastructure investment creates growth options which can be appropriately evaluated with options analysis, just as Delta Airlines gained capabilities to develop a new boarding system and Wells Fargo Bank built up an architecture that was to be leveraged for additional customer services. Once these companies invested in the new applications to offer new or enhanced services, they were able to attract more customers who would bring in more revenues. In addition to growth options, IT infrastructure may also create other opportunities for management. For example, the infrastructure embeds switching options if it enables management to change applications or move to systems from different vendors. Option analysis enables management to capture the business value of future opportunities. We offer a more detailed discussion of how real options thinking can help senior managers understand the value of IT infrastructure investments.

OPTIONS THINKING AND IT INFRASTRUCTURE CAPABILITIES

In this section, we review and apply real options thinking to IT infrastructure investments.

The Real Options Perspective

An option gives the *right* but not the *obligation* to its owner to take relevant actions in the future (Hull, 1996). Trigeorgis (1996) emphasizes managerial flexibility in uncertain investment environments, and develops the real options perspective for analyzing corporate budgeting and resource allocation decisions. This perspective offers a means to assess the potential value of an infrastructure or a technology platform investment, whose value comes mainly from future growth opportunities. Such value can be flexibly "unlocked" by future investments, enabling infrastructure capabilities to be turned into real assets (Amram and Kulatilaka, 1998; Sumit and Ankum, 1993; Trigeorgis, 1996). This bridges organizational competencies and market positioning strategies for effective managerial decision making and risk analysis (Kumar, 1996; Benaroch, 2002; Kogut and Kulatilaka, 2002; Kulatilaka and Marks, 1998; Schwartz and Sozaya-Gorstiza, 2003). It also creates an analytical basis for achieving appropriate timing of managerial actions that relate to technology adoption within the firm (Kauffman and Li, 2005).

Management holds a real option when an initial investment creates an opportunity for future value-bearing investment, but the firm is not required to make it. The value of the investment option comes from the expected benefits of the underlying asset obtained if the future investment is made. The value of the underlying asset is stochastic, and thus the market setting in which its value is realized will significantly affect the value of the option.

The real options perspective has been applied to assess the potential business value of IT investments (Dos Santos, 1991; Cheung and Bagranoff, 1991; Kambil, et al., 1993). Benaroch and Kauffman (1999) provide foundational arguments about the extent to which assets that are not traded in the market may still be conceptualized in real options terms. Taudes, et al. (2000) suggest that options pricing models may be used for justifying IT platform investments, such as SAP R/3. Kumar (1999) develops a framework that is intended to aid in understanding decision support system value. Clemons and Gu (2003) study the IT investment strategy of a credit card issuer when there is little historical information for variance estimates of future revenue and cost flows. Sambamurthy, et al. (2003) conceptualize IT-enabled capabilities as options which impact organizational agility in exploiting future business opportunities.

Analyzing IT Infrastructure Investments from the Real Options Perspective

Our present work embeds option-theoretic concepts in an optimization model. We emphasize three aspects: competitive adaptability for IT infrastructure decision making, path-dependent choices about future IT resources that will be value-bearing, and assessments about the influence of market uncertainty on the value of the decisions. First, by acquiring flexibility in its IT infrastructure, a firm is able to develop new IT resources to respond to market changes, which enhances the potential future business value of the firm (Kayworth, et al., 2001). IT infrastructure flexibility provides growth options for the firm that will allow it to adapt and extend some of its key systems to compete more effectively in future markets. IT infrastructure investment evaluation should account for the future benefits that the firm obtains from owning such options—in addition to the immediate benefits derived. We refer to the benefits that the firm obtains from holding the investment option as the *real option value* of the IT investment.

Second, the real option value is realized when new IT resources are implemented, for example, to capture customer demand or provide enhanced decision making capabilities. By *IT resources*, we refer to physical IT assets (including computer hardware, software, and networks), and IT intellectual assets (e.g., skills and knowledge). The future IT resources that become possible with earlier IT investments are the *underlying assets of IT infrastructure flexibility*. Assessing value must begin with the future IT resources that can be developed at a lower cost based on the planned IT infrastructure (Duncan, 1995).

Third, real options thinking emphasizes market uncertainty for valuing the underlying asset. An assessment of the business value of an IT infrastructure project should consider value drivers such as demand uncertainty or the intensity of competition, over some appropriate time horizon

(Zhu and Weyant, 2003). Real options thinking links IT infrastructure capabilities value with the dynamics of the market in which the firm competes, how customer demand materializes for its products or services, the ways in which the firm's strategy and tactics are implemented, and how its industry is regulated. Table 1 summarizes six basic concepts related to this perspective.

Table 1. Evaluating IT Infrastructure from a Real Options Perspective

OPTION CONCEPT	APPLICATION TO IT RESOURCES
Option	The ability to develop business applications enabled by an IT infrastructure that enables a firm to effectively respond to demand changes in its marketplace
Underlying asset	The possible IT resources (e.g., business applications) that can be built upon a specific IT infrastructure
Value of the underlying asset	The business value of possible IT applications to improve the service or product offerings of a firm, leading to higher profitability
Market volatility	Demand uncertainty for product or service offerings made possible by follow-on applications in the IT infrastructure; affects value of underlying asset
Exercise price	Expenditures associated with investment in follow-on IT applications
Option price	Expenditures associated with investing in a specific IT infrastructure
Time to expiration	Period of time from owning the IT infrastructure to when the follow-on IT investment opportunity runs out due to competition, regulation, technological advancement or demand changes, etc.

The ability to develop future applications is the *real option* that management obtains from owning the IT infrastructure. The *underlying asset* is the future IT resources made possible by that IT infrastructure. Accordingly, the *value of the underlying asset* comes from the value these applications will generate if they are implemented. Additional investment is required to implement these follow-on applications. This is analogous to the option *exercise price*. As an option's value varies with the volatility of its underlying asset, the value of a given IT infrastructure investment varies with the demand for the future business applications enabled by the IT infrastructure. Finally, the investment itself is analogous to the *option price* that a decision maker is willing to pay to hold the option. The price should balance the uncertainties for the stochastic benefits and costs. Our analysis shows how to evaluate IT infrastructure investments by using real option methods suited to gauging the value of future business applications enabled by the infrastructure and the relevant sources of uncertainty for value.

EVALUATING IT INFRASTRUCTURE INVESTMENT WITH REAL OPTIONS

Financial option pricing models are used to evaluate investments that involve environmental uncertainty and irreversible managerial decisions (e.g., Sick, 1989; Hull, 1996; Dixit and Pindyck, 1994). This approach can value the impacts of unobservable future changes on value streams associated with various types of investments. These include drilling oil wells (Smith and McCardle, 1999), buying capacity for airline operations, and determining optimal investment levels for plant and equipment for firms operating in cyclical markets (Dixit and Pindyck, 1994).

There is a second stream of research that incorporates options thinking in cost-benefit analysis. It permits the analysis of real options in the context of corporate strategy (e.g., Amram and Kulatilaka, 1999; Kulatilaka and Perotti, 1998; Kogut and Kulatilaka, 2001; Luehrman, 1998a and 1998b). We leverage the second stream, but apply a formal modeling approach to create a normative understanding of how IT infrastructure investments should be evaluated. We do this by considering current and future costs and benefits as well as market factors influencing these costs and benefits. Although IT investment decisions may involve choices between different technologies (for example, COM+ and EJB) our analysis does not address such choices per se. Rather we emphasize the evaluation of IT infrastructure in general. Hence our approach can be applied to a broad range of investments including middleware technology, data warehousing technology, programming environments, or communications infrastructure.

Model Setup

We construct a model that considers relationships among the factors we have discussed to guide future improvements in decision making relative to option value-bearing IT infrastructure investments. In Stage 1, a firm invests in an IT project to implement an IT infrastructure technology with an initial cost of K. (See Table 2 for the modeling notation.) This cost includes the expenditures that the company has to bear in obtaining the hardware, software, telecomm and skills required for deploying and operating the infrastructure. It varies with existing IT assets that the firm owns, especially its IT platforms. For example, a company with Microsoft platforms in place should have a lower cost (a smaller K) in adopting COM+ than if it switches to EJB. In other words, existing IT platforms affect future IT infrastructure investments via different initial costs. The company may make the investment in a lump sum or by prototyping or some other means. Our model represents the total cost for owning the infrastructure as K. If the infrastructure project generates a direct benefit, this benefit is deducted from K. If the direct benefit from this project does not cover its investment costs in Stage 1, then we expect $K > 0$.

With the IT infrastructure implemented in Stage 1, the firm is able to provide a desired product or service in Stage 2 by developing additional IT resources, which creates a growth option. Developing these new IT resources typically requires follow-on investment (in the application, in the infrastructure, or in both). This is analogous to what investors must pay to exercise call options on stocks to balance risk and returns in portfolio management.

Now suppose that at Stage 2, the firm desires to provide a product or service with an attribute level s, for example, a criterion level of quality for the business. For instance, Delta Airlines decided to invest in new applications to improve its boarding process, and Wells Fargo Bank offered Internet banking services to its customers, leveraging the infrastructure they built in previous projects. The firm must bear fixed costs that are increasing in the attribute level, $f s^2$, and variable costs, cd, that are scaled by demand d. f and c are cost constants. To facilitate discussion, we hereafter use s to refer to product or service quality level.

The fixed cost term, fs^2, indicates that enhancing the quality level becomes increasingly difficult as the quality level increases. Such quadratic forms have often been used in managerial economics to model the costs in production and the optimization of production in the firm, as discussed by Simon (1978) in his Nobel Prize lecture. This assumption has been adopted by IS researchers to study the impacts of IT investments relative to product quality and competition through quality (Barua, et al., 1991; Thatcher and Oliver, 2001; Thatcher and Pingry, 2004).

Table 2. Notation Used in the Option Model

NOTATION	DEFINITION
$a_1,\ldots,a_7$	Parameters for deriving the second stage profit with skewed demand
c	Constant variable cost for offering the desired product or service at Stage 2
d	Demand for the product or service offered at Stage 2
f	Constant fixed cost for offering the desired product or service at Stage 2
$G(\theta)$	Expected value of the IT infrastructure, based on stochastic demand, θ
K	Investment cost for developing IT infrastructure at Stage 1
p	Price for the product or service offered at Stage 2
s	Attribute level (e.g., quality level) of the product or service offered at Stage 2
z	Cross-elasticity factor, representing interfirm competition in non-IT areas
$\pi^{INVESTMENT}$	Profit at Stage 2 when firm invests in the IT infrastructure at Stage 1
$\pi^{NOINVESTMENT}$	Profit at Stage 2 when firm does not invest in the IT infrastructure at Stage 1
$V^{INVESTMENT}(\theta)$	Expected value of IT investment when firm invests in IT infrastructure at Stage 1
$V^{NOINVESTMENT}(\theta)$	Expected value of overall IT investments when firm does not invest in IT infrastructure at Stage 1
θ	Stochastic portion of demand for product or service. Interpreted as the degree to which customer desires a one unit increase in the attribute level ($\theta > 0$)
θ_0	Expected value of demand, θ
σ^2	Demand variance of demand, θ
θ_1	In the base case, level of customer desire for the product attribute, above which the firm can gain a positive profit at Stage 2 by offering the product, given that it invested in IT infrastructure at Stage 1
θ_1'	In the base case, the level of customer desire for the product attribute, above which the firm can gain a positive profit at Stage 2 by offering the product, given that it did not invest in the IT infrastructure at Stage 1
θ_2	In the duopoly case, the level of customer desire for the product attribute, above which both firms can gain a positive profit at Stage 2 by offering the product, given that one firm invests in the IT infrastructure at Stage 1
θ_3	In the duopoly case, the level of customer desire for the product attribute, above which both firms can gain a positive profit at Stage 2 by offering the product, given that neither firm invests in the IT infrastructure at Stage 1
λ	Cost advantage of the IT infrastructure ($\lambda > 1$)

If the firm does not implement the IT infrastructure in Stage 1, then it will bear higher costs to reach quality level s. Also, if the firm waits until the second period to invest, then it will face a penalty cost for not having the infrastructure capabilities. Since time is costly, the penalty cost includes the extra time, costs and human resources required to offer the product or service at Stage 2. We represent the effect of delaying IT infrastructure investment by increasing the fixed cost by a factor of $\lambda > 1$ to $\lambda f s^2$. This cost advantage measures how the infrastructure can be leveraged to develop necessary new applications at Stage 2, which is captured as cost savings that the firm can enjoy with the infrastructure capabilities in place. The more the firm can exploit the infrastructure capabilities, the more it benefits from Stage 1 investment and the bigger the value of λ. This cost advantage may also be affected by the extent to which the infrastructure technology has advanced from Stage 1 to Stage 2. Technological advancement tends to lower the value of the infrastructure obtained in a previous period, which reduces the magnitude of λ.

We assume linear demand $d = \theta s - p$ for future IT-enabled products or services. θ is the stochastic portion of demand for the product or service with quality level s. This measures the degree to which the customer desires a one unit increase in the quality level of the product or service with price p. We also assume that demand increases with the quality level, so that $\theta > 0$.

The firm faces the following demand and cost functions if it implements the infrastructure:

Demand: $d = \theta s - p$ (1)

Investment costs: K (for IT infrastructure investment at Stage 1) (2)

$f s^2 + c\, d$ (cost of providing product or service with the attribute level s with IT
IT infrastructure at Stage 2 given an investment in IT infrastructure at Stage 1) (3)

We assume that firms are price takers, and decide on the quality level of the IT-enabled product or service in order to maximize profits. The cost coefficients f, c, and λ are constant ratios that can be estimated, and are not stochastic. We consider one IT-enabled product or service at Stage 2, and one product attribute. We focus on growth options from IT infrastructure, even though it may create other options for management, such as switching options.

With IT Infrastructure Investment in Stage 1

If the firm invests in the infrastructure at Stage 1, it can obtain a profit at Stage 2 as $\pi^{INVESTMENT} = -f s^2 + (p - c)\theta s + p c - p^2$. As a price taker, the firm decides on the quality level s of the product or service it offers. The first order condition for maximizing the above profit function leads to an optimal quality level to be selected by the firm $s^* = \frac{p-c}{2f}\theta$. Under this quality level, the optimal profit for making the Stage 2 IT infrastructure investment is $\pi^{INVESTMENT*} = \frac{(p-c)^2\theta^2 - 4fp(p-c)}{4f}$.

Management can decide whether to exploit the infrastructure to provide a higher quality level, depending on profitability. The firm will make a follow-on investment at Stage 2 only when it can earn positive profit, i.e., $\pi^{INVESTMENT*} \geq 0$. Otherwise, it will defer. Thus the profit at Stage 2 with Stage 1 IT infrastructure investment becomes:

$$\pi^{INVESTMENT} = \begin{cases} 0; & \theta < \theta_1 \\ \frac{(p-c)^2\theta^2 - 4fp(p-c)}{4f}; & \theta \geq \theta_1 \end{cases} \qquad (4)$$

where $\theta_1 = \sqrt{\frac{4fp}{p-c}}$. This indicates that the firm gains a positive return on the follow-on IT investment at Stage 2 if demand for quality exceeds a certain level, θ_1. Only when the customers' desire for the quality exceeds the level represented by θ_1 does the firm find the Stage 2 investment to be profitable and, thus, will it be willing to make a follow-on investment.

Consequently, the expected value of the overall IT investment, $V^{INVESTMENT}(\theta)$, is given by:

$$V^{INVESTMENT}(\theta) = E(\pi^{INVESTMENT} \mid \theta \geq \theta_1) \cdot prob(\theta \geq \theta_1) - K \qquad (5)$$

So when the demand for enhanced quality of product or service reaches a “certain” level (which must be discovered by the decision maker), it becomes profitable for the firm to invest at Stage 2 to leverage the Stage 1 infrastructure and develop more applications to meet the demand.

No IT Infrastructure Investment in Stage 1

If the firm does not implement at Stage 1, it faces a different cost function. The demand function is the same ($d = \theta s - p$), the cost of IT infrastructure implementation at Stage 1 goes to 0, and the Stage 2 quality level s costs are increased by λ without the Stage 1 IT infrastructure:

$\lambda f s^2 + c\, d$ (cost of providing quality level s with IT infrastructure only at Stage 2) (6)

The firm, as a price taker, will choose a quality level to gain optimal profit at Stage 2. As above, its Stage 2 investment decision will be conditioned on whether customer demand for the product or service quality, θ, goes beyond a base level. The base level demand is different from when the firm invests at Stage 1: $\theta_1^{'} = \sqrt{\dfrac{4\lambda fp}{p-c}}$. The firm’s profit at Stage 2 becomes:

$$\pi^{NOINVESTMENT} = \begin{cases} 0; & \theta < \theta_1^{'} \\ \dfrac{(p-c)^2\theta^2 - 4\lambda fp(p-c)}{4\lambda f}; & \theta \geq \theta_1^{'} \end{cases} \tag{7}$$

and the expected value of IT investment without the Stage 1 infrastructure, $V^{NOINVESTMENT}(\theta)$, is:

$$V^{NOINVESTMENT}(\theta) = E(\pi^{NOINVESTMENT} \mid \theta \geq \theta_1^{'}) \cdot prob(\theta \geq \theta_1^{'}) \tag{8}$$

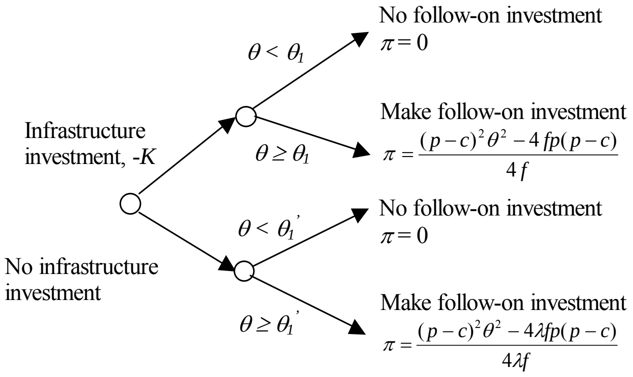
We show the investment decision in Figure 2. (The derivation details are in the Appendix.)

The expected value of IT infrastructure, $G(\theta)$, is the difference between the expected value with the IT infrastructure and without it (similar to how information value is computed):

$$G(\theta) = V^{INVESTMENT}(\theta) - V^{NOINVESTMENT}(\theta) \tag{9}$$

When $G(\theta) = 0$, the firm will be indifferent to investing in Stage 1. $G(\theta) > 0$ indicates that the IT infrastructure investment will create positive value, while $G(\theta) < 0$ indicates it will not.

Figure 2. Firm IT Infrastructure Investment Decision



ANALYSIS AND RESULTS

We next analyze the factors that affect the value of the growth option in our model.

Distribution of Demand

We assume the demand for new IT-enabled products or services represented by θ is log-normally distributed with expected value $E(\theta) = \theta_0$, and with demand variance σ^2:

$$\ln(\theta) \sim N\left(\ln(\theta_0) - \frac{1}{2}\sigma^2, \sigma^2\right), \tag{10}$$

With a log-normal distribution, we expect to observe more lower values of θ. The log-normal distribution is widely used (e.g., Kulatilaka and Perotti, 1998; Panayi and Trigeorgis, 1998). A log-normal θ has two implications for demand: (1) a customer's estimate of value of the product or service is always positive, indicating its desirability and (2) a small portion of the customers will value the product or service more highly than the majority of the customers.

The Monopoly Case

Consider the case when the company does not face competition for the IT-enabled product or service in Stage 2. The profit functions are represented by Equations 4 and 7. The value functions are derived below.

Value Functions. Plugging Equation 4 and the above log-normal distribution of θ into Equation 5, we derive the value function for Firm 1 when it makes infrastructure investment at Stage 1, $V^{INVESTMENT}(\theta_0,\sigma)$. This is shown in Equation 11. (See the Appendix for a derivation.)

$$V^{INVESTMENT}(\theta_0,\sigma) = \frac{(p-c)^2}{4f}\theta_0^2 e^{\sigma^2} \cdot \Phi(a_1) - p(p-c)\cdot\Phi(a_2) - K, \tag{11}$$

where $a_1 = \dfrac{\ln(\theta_0/\theta_1)^2 + 3\sigma^2}{2\sigma}$, $a_2 = a_1 - 2\sigma$, and $\Phi(\bullet)$ is the cumulative density function (**CDF**) of the standard normal distribution. Similarly, we derive the value function for Firm 1 when it does not make infrastructure investment, $V^{NOINVESTMENT}(\theta_0,\sigma)$. (See Appendix also.)

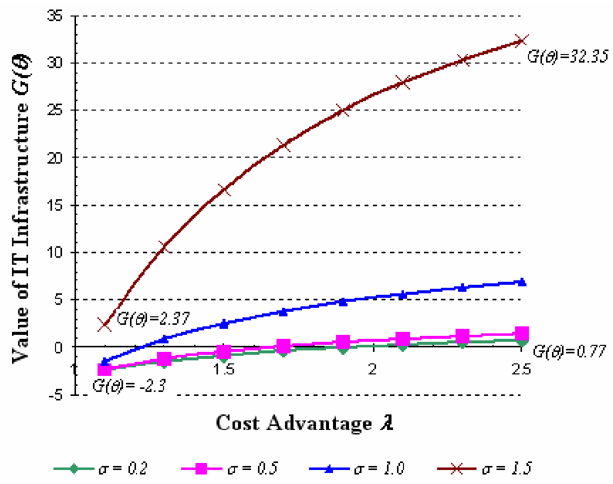
$$V^{NOINVESTMENT}(\theta_0,\sigma) = \frac{(p-c)^2}{4\lambda f}\theta_0^2 e^{\sigma^2} \cdot \Phi(a_3) - p(p-c)\cdot\Phi(a_4) \tag{12}$$

where $a_3 = \dfrac{\ln(\theta_0/\theta_1^{'})^2 + 3\sigma^2}{2\sigma}$, $a_4 = a_3 - 2\sigma$, and $\Phi(\bullet)$ is the standard normal CDF.

How does the expected value of the IT infrastructure, represented by $G(\theta)$, change with cost advantage λ and market volatility σ? Consider a numeric example. We normalize the costs by setting $f = c = 1$, and set $K = 3$, $p = 2$, and $\theta_0 = 5$. The value of $G(\theta)$ is shown in Figure 3.

Demand Volatility and Infrastructure Value. The value of $G(\theta)$ is larger with more market volatility. So the greater the variance of customer preferences for the newly-enabled product or service, the more valuable the investment in the IT infrastructure will be. This is consistent with Hull (1996): the option value increases with the volatility of the underlying asset. The rationale is that when demand variance for the product or service is large, the firm can expect a great value when uncertainty is resolved. So it is beneficial to invest in the infrastructure that enables the product or service to be offered later. The value comes from the flexibility to pursue follow-on projects. As a result, the firm can take advantage of the investment opportunity when it is profitable, and avoid it when the payoff is unacceptable.

Figure 3. Interaction Effect of Cost Advantage, Market Volatility on Infrastructure Value



Note: The sensitivity analysis is based on the parameters: $K = 3$, $f = 1$, $p = 2$, $c = 1$, and $\theta_0 = 5$.

This implies that management should estimate market demand trends for IT-enabled products and services and incorporate their business value into the assessment of IT infrastructure investment. When there is a potential of a high demand for future IT-enabled products or services, firms have a great incentive to invest in a supporting IT infrastructure that enables them to develop new software functionality, products and services in the future, even if there is uncertainty in the market. This explains the rationale that banks used in the mid-1990s, as they started to make decisions about adopting ORB middleware technologies. The major drivers are to offer, expand and upgrade online banking services as demand evolves. For example, in 1996 when online banking was still in its infancy, Bank of America chose CORBA (common object request broker architecture) to support the development of its Creditcard Online system to offer credit card account information via the Internet because the company felt this architecture delivered the scalability necessary for handling a large volume of users and data that would be needed once the demand for online banking grew beyond the current levels (Patrizio, 1996).

Managers noticed the growth potential of online banking services even though there was uncertainty in the demand at that time. This growth potential made the distributed object computing architecture valuable.

The result has important implications for risk management. Variance in demand is recognized as a source of risk, and a project with a payoff of a high variance is typically viewed to be a high risk investment. We offer an alternative perspective. Since such a project will offer a large return if the demand is high, the firm should prepare for the possible opportunity by building the necessary infrastructure capabilities to obtain the *option* to develop the applications required for the project in future, should favorable conditions arise. Figure 3 indicates that an investment in IT infrastructure that enables this risky project is highly valuable. Management should make the investment to retain the option of developing the related applications. This way it can be exercised or not when uncertainty about demand is resolved.

Interaction between Demand Volatility and Cost Advantage. The results in Figure 3 also show an important insight that is not investigated in standard analysis: the volatility of demand that affects the payoff stream tends to amplify the cost advantage associated with Stage 1 investment through the interaction of these two factors. Although the cost advantage at Stage 2 increases the value of the IT infrastructure investment, it makes little difference when the demand volatility is low. In Figure 3, we observe that as demand volatility σ goes up, the value of the IT infrastructure investment, $G(\theta)$, increases across a range of cost advantages, λ. For example, when $\sigma = 0.2$, the value of $G(\theta)$ increases by just 3.07 (from –2.3 to 0.77) when the cost advantage λ increases from 1.1 to 2.5. But when $\sigma = 1.5$, the value of $G(\theta)$ changes from 2.37 to 32.35 when λ increases from 1.1 to 2.5. So the cost benefit that the infrastructure brings to the future project is larger when market demand is more uncertain. Thus, when there are alternative infrastructure technologies, the cost advantages that different infrastructures can bring should be carefully assessed and compared when highly volatile demand is expected.

Figure 3 also shows that when the firm operates in markets with high demand volatility, IT infrastructure investments will still be highly valued even if the cost advantage is small. For example, when the cost advantage is low at $\lambda = 1.1$, the firm can save about 10% of the follow-on investment at Stage 2 if it invests in the IT infrastructure at Stage 1. In this case, the value of $G(\theta)$ is negative when the demand volatility is low at $\sigma = 0.2$ or $\sigma = 0.5$, but it becomes positive when $\sigma = 1.5$. Therefore, firms that operate in changing markets should be more willing to invest to implement IT infrastructure in Stage 1 even if the potential cost savings are small.

Strategic Value under Imperfect Competition

To understand how competition affects infrastructure value, we extend our basic model to consider a duopoly: one firm being an IT leader and the other an IT follower. The IT leader, Firm 1, has an opportunity to invest in an IT infrastructure technology. In a window of opportunity, only the leader can make this investment. We label this period as Stage 1. At Stage 1, Firm 1 chooses whether to implement the IT infrastructure. Firm 2, the follower, chooses not to invest, due to the lack of resources. At Stage 2, both firms observe the demand for the product or service that can be offered as a result.

Demand Function. Whether the firms decide to develop the applications depends on demand. If Firm i ($i = 1, 2$) builds the applications to support a new product or service offering, it maximizes profit by setting an appropriate quality level, s_i ($i = 1, 2$). If Firm i (1, 2) does not invest, it will be unable to offer the product or service, so $s_i = 0$. If both offer the service, then each faces competition from the other. To model duopoly competition with strategic IS, Barua, et al. (1991) introduced a *cross-elasticity of substitution factor* to capture inter-firm competition.

They interpreted this as the extent to which the services are differentiated due to non-IT factors (e.g., brand recognition and advertisements). We follow this logic in representing inter-firm competition. Incorporating cross-elasticity, the demand function for Firm *i* becomes:

$$d_i = \theta(s_i - z \cdot s_j) - p, \quad \text{where } i = 1, 2 \text{ and } j = 2, 1 \tag{13}$$

The cross-elasticity of substitution factor z ($0 < z < 1$) determines the negative effect that an increase in the competitor's quality level has on each firm's demand. When the z is large, the two firms offer highly substitutable services. A competitor's quality will have a negative effect on the other's demand. A high z implies competition based on non-IT factors.

Cost Functions. The cost functions for Firm 1, the market leader, are as in Equations 2 and 3 with IT infrastructure implementation in Stage 1, and Equation 9 without IT infrastructure:

- If Firm 1 implements at Stage 1, its investment cost is K, and the cost of providing quality attribute s with the IT infrastructure investment at Stage 2 is given by $fs_1^2 + cd_1$.
- If Firm 1 does not implement at Stage 1, it incurs no investment cost and the modified cost of providing quality attribute s in the absence of the IT infrastructure, $\lambda fs_1^2 + cd_1$.
- Meanwhile, Firm 2's cost will be $\lambda fs_2^2 + cd_2$.

Profit Functions. If the IT leader Firm 1 develops the infrastructure at Stage 1, then at Stage 2, three different scenarios can occur regarding the two firms' investment decisions. In the first, only a small group of customers desire the IT-enabled product or service. This makes the effort to develop additional IT capabilities unprofitable for either firm. As a result, neither will invest in Stage 2. In the second, the market shows a moderate level of desire for the IT-enabled product or service quality. Demand surpasses a certain threshold θ_1 so that Firm 1 finds it attractive to offer the IT-enabled product or service; but Firm 2 would still lose money on it because its costs are higher. Hence only Firm 1 enters the market and gains a positive return on its follow-on IT investment based on IT infrastructure from Stage 1. In the third case, customers appreciate the

IT-enabled product quality so much that the demand for the product exceeds an even higher level, represented as θ_2. High demand makes it profitable for both firms to serve the market with additional investments in IT resources in Stage 2, although Firm 1's profit will be reduced by the competition from Firm 2. Firm 1's profit is presented in Equation 14.

$$\pi_1^{INVESTMENT} = \begin{cases} 0; & \theta < \theta_1 \\ \dfrac{(p-c)^2\theta^2 - 4fp(p-c)}{4f}; & \theta_1 \le \theta < \theta_2 \\ \dfrac{(\lambda-2z)(p-c)^2\theta^2 - 4\lambda fp(p-c)}{4\lambda f}; & \theta \ge \theta_2 \end{cases} \text{; where}$$

$$\theta_2 = \sqrt{\frac{4\lambda fp}{(1-2\lambda z)(p-c)}} \tag{14}$$

If Firm 1 does not take advantage of its leading position and decides not to invest in the IT infrastructure at Stage 1, it will compete with Firm 2 on the same level in Stage 2. When the demand for IT-enabled service or product quality goes beyond a certain level, both firms will make a profit by making the follow-on investment. Otherwise, neither will invest. Firm 1's profit in this situation is summarized in Equation 15.

$$\pi_1^{NOINVESTMENT} = \begin{cases} 0; & \theta < \theta_3 \\ \dfrac{(1-2z)(p-c)^2\theta^2 - 4\lambda fp(p-c)}{4\lambda f}; & \theta \ge \theta_3 \end{cases};$$

$$\text{where } \theta_3 = \sqrt{\frac{4\lambda fp}{(1-2z)(p-c)}} \tag{15}$$

Value Functions. Again assuming the demand for the product/service quality level has a log-normal distribution (Equation 10), the solution for Firm 1's value function when it makes an IT infrastructure investment at Stage 1 is:

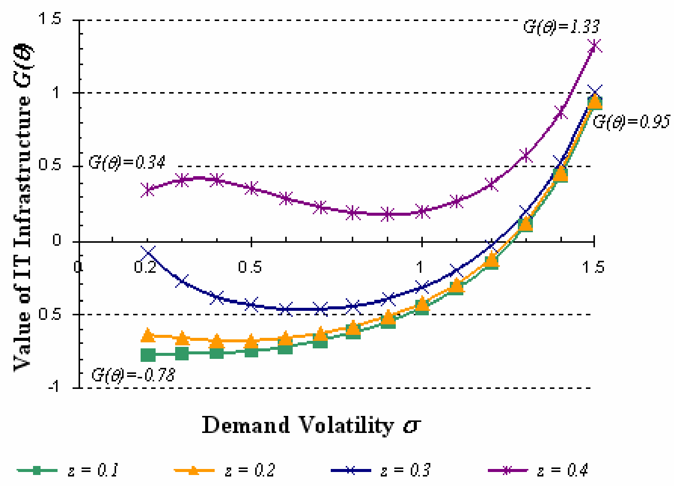
$$V_1^{INVESTMENT}(\theta_0,\sigma) = \frac{(p-c)^2}{4f}\theta_0^2 e^{\sigma^2}\cdot N(a_1) - p(p-c)\cdot N(a_2) - \frac{2z(p-c)^2}{4\lambda f}\theta_0^2 e^{\sigma^2}\cdot N(a_5) - K, \tag{16}$$

where $a_1 = \frac{\ln(\theta_0/\theta_1)^2 + 3\sigma^2}{2\sigma}$, $a_2 = a_1 - 2\sigma$, $a_5 = \frac{\ln(\theta_0/\theta_2)^2 + 3\sigma^2}{2\sigma}$, and $\Phi(\bullet)$ is as before. We can derive Firm 1's value function when it does not make infrastructure investment at Stage 1:

$$V_1^{NOINVESTMENT}(\theta_0, \sigma) = \frac{(1-2z)(p-c)^2}{4\lambda f}\theta_0^2 e^{\sigma^2} \cdot N(a_6) - p(p-c) \cdot N(a_7) \qquad (17)$$

where $a_6 = \frac{\ln(\theta_0/\theta_3)^2 + 3\sigma^2}{2\sigma}$, $a_7 = a_6 - 2\sigma$, with $\Phi(\bullet)$ again is as before. Plugging Eq. 16 and 17 into Eq. 9, we obtain *G(θ)*, the IT infrastructure value. We depict the effects of competition and market volatility on *G(θ)* with $K = 3, f = c = 1, p = 2, \theta_0 = 5$, and $\lambda = 1.1$. (See Figure 4.)

Figure 4. Effect of Competition on IT Infrastructure Value



Note: The parameter values for the model are set as: $K = 3, f = 1, p = 2, c = 1, \theta_0 = 5$, and $\lambda = 1.1$.

Competition and Infrastructure Value. In Figure 4, the value of IT infrastructure, *G(θ)*, increases with the extent of competition, based on the cross-elasticity of substitution, z. That is, IT infrastructure becomes highly valuable when the competitor's newly-supported product or service has a big negative effect on the firm's demand or is viewed as a close substitute in the marketplace. Also, Figure 4 shows that the value of *G(θ)* is always positive when the competition level is high, $z = 0.4$, no matter what the demand volatility is. Instead, when the level of direct competition is low, $z = 0.2$, $G(\theta)$ also is negative when demand volatility is low. But IT infrastructure value is monotonically increasing with demand volatility, so investments will be justified in uncertain markets. In a competitive environment, investing in flexible IT infrastructure is likely to be profitable in the long run.

Intense competition makes the capabilities of IT infrastructures more attractive, and as a result, firms are more willing to invest in them. For example, Orenstein (1998) reports that in 1998 telecomm firms were making the largest expenditures on ORB middleware projects, taking the leading role in adopting this IT infrastructure technology. With deregulation in the telecomm and the telephone industries in the United States, however, competition among telecomm firms increased to the point that some would characterize it as "hypercompetition" (D'Aveni, 1995). Thereafter, the growth of the Internet led to the opening up of new markets. But it also induced entry of competitors from other industries, such as cable TV, Internet services, and computer and IT companies. Facing this hypercompetition, telecomm firms tended to appreciate the business value that could be derived from the scalability and heavily invested in ORB middleware.

Interaction between Competition and Demand Volatility. A second observation is that the impact of the level of product and service substitutability and interfirm competition on the value of IT infrastructure falls when demand volatility increases. When it is low (i.e., a small σ), firms facing a high competition from substitute products (a large value of z) will find that having a flexible IT infrastructure is more valuable than in a mildly competitive environment. With low demand volatility of $\sigma = 0.2$, the value of $G(\theta)$ increases from -0.78 to 0.34 when the cross-elasticity of substitution level z changes from 0.1 to 0.4. But when volatility is high, the gap in IT infrastructure value that will be observed between different levels of competition is greatly reduced. Again, Figure 4 shows this. With a higher demand volatility of $\sigma = 1.5$, $G(\theta)$

increases from about 0.95 to 1.33 when z changes from 0.1 to 0.4.

Figure 4 also shows that the impact of demand volatility on infrastructure value falls when the competition level increases. When the competition between firms is mild (low z), the value of the IT infrastructure is greatly influenced by the demand volatility. In Figure 4, with $z = 0.1$, $G(\theta)$ jumps from -0.78 to 0.95 when demand volatility σ increases from 0.2 to 1.5. In contrast, when competition is severe, the change in the IT infrastructure value caused by the change in the demand volatility is relatively small. The trend in Figure 4 shows that with $z = 0.4$, $G(\theta)$ changes from 0.34 to 1.33 when the demand volatility σ increases from 0.2 to 1.5.

In Figure 4, we also observe that within a certain range, the demand volatility has a negative effect on infrastructure value when the competition level is high. With $z = 0.3$, $G(\theta)$ decreases as the demand volatility goes from 0.2 to 0.6, and then goes up again if the demand volatility increases further. This is because in a market where demand is relatively stable but competition is intense, the return on IT infrastructure decreases as the demand volatility increases.

The complex interaction effect in Figure 4 implies that intense competition increases the value of infrastructure investment at an early stage as a strategy for gaining a first-mover advantage. When the market is projected to have a low uncertainty in demand, it is important to closely monitor market competition since it makes a big difference in infrastructure value. But with high uncertainty of demand, the investment decision can be made mainly based on the estimation of demand volatility since the competition level has little effect on the value of the infrastructure. Our duopoly analysis shows that a flexible IT infrastructure brings value to the firm when it faces high competition or high demand volatility. However, the extent of competition reduces the effect of demand volatility, and vice versa.

CONCLUSION

We proposed an application of real options thinking for assessing IT infrastructure investments based on the characteristics of IT infrastructure, especially flexibility in creating new products and services that take advantage of infrastructure capabilities.

Primary Contributions

Investment in IT infrastructure makes organizational IS scalable in capacity and extensible in functionality, endowing management with flexibility and adaptability to respond to market changes by developing follow-on applications using the foundation of the IT infrastructure. We conceptualized these capabilities as real options and argued that managers should consider the value of the follow-on applications. Following the logic of previous option methods, we modeled flexible IT infrastructure value with a two-stage investment decision process.

Our model considers both the cost-benefit relationship of the IT infrastructure and the market volatility of customer demand for follow-on investment-supported products and services in evaluating the IT infrastructure investment. We use our model in two ways: (1) to study the effects of a skewed distribution of customer preferences (demand) on the value of the IT infrastructure, and (2) to show how market competition in a duopoly market is affected by different levels of cross-elasticity of substitution for products and services. The cross-elasticity of substitution factor that we employ is a relatively direct proxy for the level of competition among firms. Our analysis shows that interactions among demand volatility, the extent of the competition, and the cost-benefit of the technology constitute the contingencies that shape the business value curve of IT infrastructure. These observations are relevant to middleware infrastructure technologies, which have features that give rise to growth options.

Managerial Implications

The results of our analysis emphasize the need for management to identify the option-bearing technological features associated with IT infrastructure that can be exploited to take advantage of future market changes. These IT infrastructure capabilities enable management to exert active management methods to adjust to market changes. For instance, an essential feature of infrastructure technologies (especially middleware) is the standardized interfaces that they offer to make business applications and their underlying platforms interoperable. This provides flexibility for adding new IS functionality and increasing system capacity at lower costs. The potential value from this flexibility will be realized when a firm leverages an IT infrastructure's scalability to meet market demands more effectively than its competitors.

Management should envision applications that can release the potential for high returns from an infrastructure investment. For example, banks considering implementing a middleware technology may try to assess its option value in the context of online banking services. This is because middleware has been proven in use as a platform for effective electronic banking application development. But, even though the technology is known to work, still there may be uncertainty with respect to demand for specific kinds of electronic banking services, for example the lack of a compelling business case for mobile technology-based e-banking applications. This market volatility will be the source of real option-based business value. So to develop an effective investment strategy, it is critical to understand where IT infrastructure capabilities will be more likely to impact the business in the future and to assess the potential value that can be generated by them.

Our analysis also offers managerial implications for adopting IT standards, by viewing technological standards as part of the firm's infrastructure (Weill and Broadbent, 1998).

Adopting standards may require additional investments in terms of higher development and training costs that are related to the infrastructure investment at Stage 1. But it also enhances the firm's ability to extend the functionality of the firm's systems and the productivity of the IS department, which enables the firm to capture future business opportunities or move ahead of its competitors by more quickly offering new applications at a later stage. In this sense, adopting IT standards creates real options for management, and the real options perspective provides an approach for evaluating investments in IT standards. Accordingly, our analysis implies that IT standards become more valuable when demand volatility or competition is higher. Decisions to adopt standards are also affected by the uncertainties that companies have to deal with when there are competing specifications for a common technology (Grenadier and Weiss, 1997). Competing specifications often modify standards value, and not always for the better.

Besides the features of IT infrastructure technologies, senior managers should take into account the complex impacts that external market factors have on the potential value of IT infrastructure capabilities. Specifically, the realized value of investments in IT infrastructure is typically a function of the cost advantage for building follow-on applications, the volatility of market demand for the associated product or service, and the level of competition between firms. The implication is clear: in assessing the potential value of IT infrastructure technologies, management should develop appropriate estimates of demand volatility, the effect of substitute products, and the interaction between these factors. This perspective also has important implications for risk management. When facing high demand uncertainty, the strategy that management should take is to develop the underlying infrastructure capabilities while building the applications later, when the critical uncertainties have been resolved.

Limitations and Extensions

In spite of the new perspective and the findings that we offer, it is important to consider the limitations associated with this approach to IT infrastructure valuation and its emphasis on growth options. First, the assumptions underlying our model allow us to consider the case of one attribute (e.g., quality) of one IT-enabled product or service. But an investment in an IT infrastructure technology may impact more than one product or service that the firm offers, and multiple attributes of those products or services. For such cases, the important issue is the interdependencies and interactions among these products and services, and among attributes that are affected. If the products or attributes are independent from each other, we can aggregate their effects on attribute level (s) and demand (d). In this case, our model and analysis remain valid. But when there is a high level of interdependence, our model must be changed to accommodate interaction effects. Such cases would require a portfolio management approach, as a recent empirical study by Bardhan, et al. (2004) suggests. Another assumption of our model is the deterministic nature of the costs at Stage 2, which downplays the uncertainty involved in the cost factors. This restriction needs to be relaxed if the uncertainty of costs over time is to be better studied.

Second, this study focuses on the valuation of one round of infrastructure investment while in reality technologies evolve over time. When technological advancement brings in a new generation of infrastructure technology, the value of existing infrastructure technologies is reduced. Our model addresses the effect of technological evolution by adjusting the cost advantage ratio λ. Specifically, technological advancement lowers λ. The drawback of our model regarding technological evolution is that it treats infrastructure investments independently when a firm decides to upgrade its infrastructure to the new generation. For example in moving from DCOM to COM+, the firm must engage in another round of infrastructure investment. A dynamic model is needed to account for the interaction effects between generations of technologies. In this respect, the theoretical perspective demonstrated in Au and Kauffman (2001) may be helpful to reveal the value of deferring investment in an uncertain market.

Third, our model assumes a simplified linear relationship between demand and the attribute level of the product or service offered, while more complicated scenarios of IT infrastructure investments may exhibit a nonlinear relationship when firms face dynamic market demand. We hope that the present research will motivate others to follow up on our work to incorporate these changes and some of the other aspects of IT infrastructure investments.

We also recognize several issues in applying this type of analysis in practice. First, our prior research and consulting experience involving real option analysis has shown that it is relatively difficult for senior managers to properly conceptualize the range of real options that is relevant. Management would either underestimate or over-estimate the number of future business options. The problem is the lack of an appropriate stopping rule. Second, another problem has been noted in recent research by Gustafson and Luft (2002), and Tallon, et al. (2002), but it continues to be present in the kinds of analysis that we have discussed. At issue is the ability of senior managers to accurately estimate the central moments of a statistical distribution of outcomes—variance, in particular. Our experience has shown that many managers do not really have a “gut feel” for the estimation of variance, despite their understanding of its technical definition as a statistic. These issues present as a concern that relates to the applicability of real option analysis methods in different management, technological and market environments. It will take a shrewd and perceptive senior manager, who knows the technological sources that create real options from IT infrastructure, and has some intuitive feel for the vagaries of the marketplace.

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MATHEMATICAL APPENDIX

Mathematical Representation of the Investment Value Function

Several derivations illustrate how we arrived at the main results. Substituting Equation 7 for

$\pi^{INVESTMENT}$ in Equation 8, we represent the value function as:

$$\begin{aligned} V^{INVESTMENT}(\theta_0,\sigma) &= E(\pi^{INVESTMENT} \mid \theta \geq \theta_1)\cdot prob(\theta \geq \theta_1) - K \\ &= \int_{\theta_1}^{\infty} \frac{(p-c)^2\theta^2 - 4fp(p-c)}{4f} d[F(\theta)] - K \\ &= \int_{\theta_1}^{\infty} \frac{(p-c)^2\theta^2 - 4fp(p-c)}{4f} \cdot f(\theta)\cdot d\theta - K \end{aligned}, \qquad \text{(A1)}$$

where θ_1 is the same as in Equation 6. *F(θ)* is the cumulative density function and *f(θ)* is the probability density function of θ. When θ follows the log-normal distribution $\ln(\theta) \sim N\left(\ln(\theta_0) - \frac{1}{2}\sigma^2, \sigma^2\right)$, we substitute $\theta = e^x$ in Equation A1 to arrive at:

$$\begin{aligned} V^{INVESTMENT}(\theta_0,\sigma) &= \int_{\ln\theta_1}^{\infty} \frac{(p-c)^2(e^x)^2 - 4fp(p-c)}{4f}\cdot d[N(x)] - K \\ &= \int_{\ln\theta_1}^{\infty} \frac{(p-c)^2(e^x)^2 - 4fp(p-c)}{4f}\cdot \varphi(x)\cdot dx - K \end{aligned} \qquad \text{(A2)}$$

where *x* is normally distributed as $x \sim N\left(\ln(\theta_0) - \frac{1}{2}\sigma^2, \sigma^2\right)$, *N(x)* is the cumulative density function and *φ(x)* is the probability density function of *x* , $\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}}\cdot e^{-\frac{1}{2\sigma^2}\left[x-(\ln\theta_0 - \sigma^2/2)\right]^2}$.

Derivation of the Value Function When Infrastructure Investment Is Made at Stage 1

Equation A2 can be extended as follows:

$$\begin{aligned} V^{INVESTMENT}(\theta_0,\sigma) &= \int_{\ln\theta_1}^{\infty} \frac{(p-c)^2(e^x)^2 - 4fp(p-c)}{4f}\cdot d[N(x)] - K \\ &= \int_{\ln\theta_1}^{\infty} \frac{(p-c)^2}{4f}\cdot e^{2x}\cdot d[N(x)] - \int_{\ln\theta_1}^{\infty} p(p-c)\cdot d[N(x)] - K \\ &= \frac{(p-c)^2}{4f}\int_{\ln\theta_1}^{\infty} e^{2x}\cdot d[N(x)] - p(p-c)\int_{\ln\theta_1}^{\infty} d[N(x)] - K \end{aligned}. \qquad \text{(A3)}$$

Substituting $y = \frac{x-(\ln\theta_0 - \frac{\sigma^2}{2})}{\sigma}$ in the integral in the first term in Equation A3, we get:

$$\begin{aligned} \int_{\ln\theta_1}^{\infty} e^{2x} d[N(x)] &= \int_{y_1}^{\infty} e^{2\sigma y + 2(\ln\theta_0 - \sigma^2/2)} d[\Phi(y)] = \int_{y_1}^{\infty} e^{2\sigma y + 2(\ln\theta_0 - \sigma^2/2)}\cdot \phi(y)\cdot dy \\ &= e^{2(\ln\theta_0 - \sigma^2/2)}\int_{y_1}^{\infty} e^{2\sigma y}\cdot \phi(y)\cdot dy \end{aligned}, \qquad \text{(A4)}$$

In Equation A4, $y_1 = \frac{\ln\theta_1 - (\ln\theta_0 - \sigma^2/2)}{\sigma}$, *Φ(y)* is the cumulative density function and *ϕ(y)* is the probability density function of the standard normal distribution. Using the formula for the normal integral (Patel and Read, 1996), we compute the integral in Equation A4 as:

$$\begin{aligned}&\int_{y_1}^{\infty} e^{2\sigma y}\cdot\phi(y)\cdot dy = e^{4\sigma^2/2}\cdot\Phi(y-2\sigma)\,|_{y_1}^{\infty} = e^{2\sigma^2}\cdot\Phi(2\sigma-y_1)\\ &= e^{2\sigma^2}\cdot\Phi\left(\frac{2\ln(\theta_0/\theta_1)+3\sigma^2}{2\sigma}\right)\end{aligned}\quad . \tag{A5}$$

Plugging Equation A5 into Equation A4 gives:

$$\begin{aligned}&\int_{\ln\theta_1}^{\infty} e^{2x}d[N(x)] = e^{2(\ln\theta_0-\sigma^2/2)}\int_{y_1}^{\infty} e^{2\sigma y}\cdot\phi(y)\cdot dy\\ &= e^{2(\ln\theta_0-\sigma^2/2)}\cdot e^{2\sigma^2}\cdot\Phi\left(\frac{2\ln(\theta_0/\theta_1)+3\sigma^2}{2\sigma}\right) = e^{\ln\theta_0^2}\cdot e^{\sigma^2}\cdot\Phi\left(\frac{\ln(\theta_0/\theta_1)^2+3\sigma^2}{2\sigma}\right).\\ &= \theta_0^2\cdot e^{\sigma^2}\cdot\Phi\left(\frac{\ln(\theta_0/\theta_1)^2+3\sigma^2}{2\sigma}\right)\end{aligned} \tag{A6}$$

Substituting $y = \dfrac{x-(\ln\theta_0-\frac{\sigma^2}{2})}{\sigma}$ in the integral's second term in Equation A3 gives:

$$\begin{aligned}&\int_{\ln\theta_1}^{\infty} d[N(x)] = \int_{y_1}^{\infty} d[\Phi(y)] = \Phi(-y_1) = \Phi\left(-\frac{\ln\theta_1-(\ln\theta_0-\frac{\sigma^2}{2})}{\sigma}\right)\\ &= \Phi\left(\frac{\ln(\theta_0/\theta_1)^2-\sigma^2}{2\sigma}\right)\end{aligned}\quad , \tag{A7}$$

where $y_1 = \dfrac{\ln\theta_1-(\ln\theta_0-\sigma^2/2)}{\sigma}$, and *Φ(y)* is the standard normal cumulative density function.

Plugging Equations A6 and A7 into Equation A3 yields Equation 11, as we saw earlier in this article:

$$\begin{aligned}&V^{INVESTMENT}(\theta_0,\sigma) = \frac{(p-c)^2}{4f}\int_{\ln\theta_1}^{\infty} e^{2x}d[N(x)] - p(p-c)\int_{\ln\theta_1}^{\infty} d[N(x)] - K\\ &= \frac{(p-c)^2\cdot\theta_0^2\cdot e^{\sigma^2}}{4f}\cdot\Phi\left(\frac{\ln(\theta_0/\theta_1)^2+3\sigma^2}{2\sigma}\right) - p\cdot(p-c)\cdot\Phi\left(\frac{\ln(\theta_0/\theta_1)^2-\sigma^2}{2\sigma}\right) - K\end{aligned}$$

Derivation of the Value Function When No Infrastructure Investment Made at Stage 1

Following the same procedures, we can derive the value function for the case when no infrastructure investment is made at Stage 1, based on Equations 1 to 6. We can obtain the optimal attribute level, $s^{NOINVESTMENT*}$, and optimal Stage 2 profits, $\pi^{NOINVESTMENT*}$, both modified with λ:

$$s^{NOINVESTMENT*} = \frac{p-c}{2\lambda f}\theta \tag{A8}$$

$$\pi^{NOINVESTMENT*}=\frac{(p-c)^2\theta^2-4\lambda fp(p-c)}{4\lambda f} \qquad \text{(A9)}$$

The Stage 2 profit when no IT infrastructure investment was made at Stage 1 is conditioned on whether customer demand for the product or service, θ, goes beyond a base level. The base level demand is different from the base demand when the firm makes an investment at Stage 1. We represent this base level as $\theta_1^{'}=\sqrt{\frac{4\lambda fp}{p-c}}$. The firm's optimal profit at Stage 2 becomes:

$$\pi^{NOINVESTMENT}=\begin{cases}0; & \theta<\theta_1^{'}\\ \dfrac{(p-c)^2\theta^2-4\lambda fp(p-c)}{4\lambda f}; & \theta\geq\theta_1^{'}\end{cases} \qquad \text{(A10)}$$

In this case, expected value of IT investment becomes Equation 12:

$$\begin{aligned}V^{NOINVESTMENT}(\theta_0,\sigma)&=\int_{\theta_1^{'}}^{\infty}\frac{(p-c)^2\theta^2-4\lambda fp(p-c)}{4\lambda f}d[F(\theta)]\\&=\frac{(p-c)^2}{4\lambda f}\int_{\ln\theta_1^{'}}^{\infty}e^{2x}\cdot d[N(x)]-p(p-c)\int_{\ln\theta_1^{'}}^{\infty}d[N(x)]\\&=\frac{(p-c)^2\cdot\theta_0^2\cdot e^{\sigma^2}}{4\lambda f}\cdot\Phi\left(\frac{\ln(\theta_0/\theta_1^{'})^2+3\sigma^2}{2\sigma}\right)-p\cdot(p-c)\cdot\Phi\left(\frac{\ln(\theta_0/\theta_1^{'})^2-\sigma^2}{2\sigma}\right)\end{aligned}$$

Derivation of the Value Function in the Case of Imperfect Competition

Similarly, we derive the value functions in the case of imperfect competition. Firm 1's value function for an infrastructure investment at Stage 1 is shown in an expansion of Equation 16:

$$\begin{aligned}V_1^{INVESTMENT}(\theta_0,\sigma)&=\int_{\theta_1}^{\theta_2}\frac{(p-c)^2\theta^2-4fp(p-c)}{4f}d[F(\theta)]+\int_{\theta_2}^{\infty}\frac{(\lambda-2z)(p-c)^2\theta^2-4\lambda fp(p-c)}{4\lambda f}d[F(\theta)]-K\\&=\frac{(p-c)^2}{4f}\int_{\ln\theta_1}^{\ln\theta_2}e^{2x}d[N(x)]+\frac{(\lambda-2z)(p-c)^2}{4\lambda f}\int_{\ln\theta_2}^{\infty}e^{2x}d[N(x)]-p(p-c)\int_{\ln\theta_1}^{\infty}d[N(x)]-K\\&=\frac{(p-c)^2\theta_0^2\cdot e^{\sigma^2}}{4f}\Phi\left(\frac{\ln(\theta_0/\theta_1)^2+3\sigma^2}{2\sigma}\right)-p(p-c)\Phi\left(\frac{\ln(\theta_0/\theta_1)^2-\sigma^2}{2\sigma}\right)\\&-\frac{2z(p-c)^2\theta_0^2\cdot e^{\sigma^2}}{4\lambda f}\Phi\left(\frac{\ln(\theta_0/\theta_2)^2+3\sigma^2}{2\sigma}\right)-K\end{aligned}$$

Firm 1's value function with no IT investment at Stage 1 is an expansion of Equation 17:

$$\begin{aligned}V_1^{NOINVESTMENT}(\theta_0,\sigma)&=\int_{\theta_3}^{\infty}\frac{(1-2z)(p-c)^2\theta^2-4\lambda fp(p-c)}{4\lambda f}d[F(\theta)]\\&=\frac{(1-2z)(p-c)^2}{4\lambda f}\int_{\ln\theta_3}^{\infty}e^{2x}d[N(x)]-p(p-c)\int_{\ln\theta_3}^{\infty}d[N(x)]\\&=\frac{(1-2z)(p-c)^2\theta_0^2\cdot e^{\sigma^2}}{4\lambda f}\Phi\left(\frac{\ln(\theta_0/\theta_3)^2+3\sigma^2}{2\sigma}\right)-p(p-c)\Phi\left(\frac{\ln(\theta_0/\theta_3)^2-\sigma^2}{2\sigma}\right)\end{aligned}$$