A Framework for Assessing the Business Value of Information Technology Infrastructures

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ABSTRACT: Information technology (IT) infrastructure investments are an extremely important part of e-business and constitute a major portion of IT investments in many organizations. IT infrastructure investments include investments in connectivity, systems integration, and data storage that may be used by multiple applications. Prior research has recognized the importance of a flexible IT infrastructure as a source of competitive advantage. Evidence regarding the value of IT infrastructures is anecdotal, and there is a realization that large investments in IT infrastructures are often difficult to justify. This paper expands on the idea that the value of an IT infrastructure depends on its use in an organizational context, and presents a relatively simple approach to understanding and assessing the value of IT infrastructure investments. This approach is based on the asset valuation literature in finance. An example is provided to illustrate the proposed approach, and managerial implications are discussed.

KEY WORDS AND PHRASES: asset valuation, business value, economic analysis, IT infrastructure.
storage area networks), system integration (e.g., middleware), connectivity (e.g., networking components), and security technologies (e.g., firewalls). The people component includes infrastructure architects and other employees charged with infrastructure design and support. The process component includes processes for architecture standardization and infrastructure change reviews.

Organizations are increasingly recognizing the critical importance of an effective IT infrastructure [9, 10, 17, 46]. Developing and operating a flexible IT infrastructure has been identified as a major managerial concern [19]. The effectiveness of an IT infrastructure can be evaluated using criteria such as reliability, the ability to operate with low downtime; flexibility, the ability to quickly and economically adapt to changing business requirements; and upgradability, the ability to quickly and economically adapt to or deploy multiple, complex technologies as required.

More than in the 1990s, organizations today are carefully scrutinizing IT investments and questioning their value [11]. It is becoming increasingly important for CIOs and other IT managers to articulate the value of IT using concepts that CFOs and other finance executives can relate to [40, 46]. Although many organizations recognize that IT infrastructure investments are valuable, they also realize that they can be difficult to justify [46]. It has been recognized that traditional financial evaluation techniques, such as net present value (NPV), undervalue IT infrastructure investments [36, 43] since they do not carefully consider relatively intangible benefits such as flexibility.

Information systems (IS) researchers have attempted to value particular aspects of an IT infrastructure, such as upgradability [4, 13, 36, 43], using the theory of real options. However, infrastructure flexibility is a complex construct [18], and a framework for assessing the value of an IT infrastructure is lacking in the literature. Researchers as well as practitioners are also increasingly realizing that the manner and context in which IT is used is the major determinant of IT value [14, 20, 40]. Researchers have expressed opinions such as “Measuring the business value and analyzing variations in organizational performance from the interaction of IS and organizational context will make significant contributions to IS theory as well as to practitioners” [20, p. 30].

I develop a framework for understanding and assessing IT infrastructure value. This framework is based on an analysis of the dynamic relationship between the IT infrastructure and its usage in an organizational context, which includes business and technology changes, and applications using the infrastructure. It can be used to assess the value of existing infrastructures as well as to compare IT infrastructure investment alternatives. The proposed framework is based on the theory of financial asset valuation, and recognizes that the value of an IT infrastructure is dynamic, and in some respects similar to the value of financial assets. This research is indirectly related to the IS literature on real options. It uses the underlying theory of financial asset valuation to value IT infrastructure investments, but does not calculate option values. Also, the framework models uncertainty in a new manner. Unlike prior IS research on real options, which considers a single source of uncertainty, I examine multiple sources of uncertainty concurrently. Hence, I contribute to research on the evaluation of IT in-
vestments using financial modeling techniques [5, 6, 7, 16, 42] with a general model for evaluating IT infrastructure investments. I also extend the IS literature on flexibility and IT infrastructure value [18].

Literature Review

THE IS LITERATURE INCLUDES SEVERAL STUDIES on measuring the business value of IT. IT value research related to this paper can be classified into three streams. One stream consists of studies that use econometric techniques, ex post, to study how financial measures of organizational performance depend on measures of IT investments. Kohli and Devaraj [27] provide a synthesis and meta-analysis of this stream of research. Although some studies find evidence of firm-level financial benefits due to IT investments, the evidence is mixed. Hitt and Brynjolfsson [22] argue that IT investments may produce productivity benefits, but these productivity benefits need not translate into improved firm profitability. IT investments may increase consumer surplus while not improving firm profitability. Devaraj and Kohli [14] present empirical evidence of improved financial performance of organizations in the healthcare industry as a result of IT investments. Their econometric models use variables representing IT usage. It is important to consider IT usage in measuring IT value instead of using the dollar value of investments, since value depends on usage of IT and not on investment alone.

Another stream of research highlights the limitations of traditional financial evaluation methods such as NPV and proposes methods based on real options theory [6, 16] and other qualitative approaches [39]. Applications of real options theory to the evaluation of IT investments include automated teller machine networks [7], decision support systems [28], enterprise resource planning software [43], IT infrastructures in banks [36], software upgrades [42], and object-oriented middleware [13]. The last four studies attempt to model components of an IT infrastructure and consider only one type of uncertainty in determining option value. These studies typically use option valuation models from the finance literature, such as the Black-Scholes model [8], the Margrabe model [32], or the binomial model [23].

The IS literature also contains a stream of related research focusing on the organizational value of a flexible IT infrastructure. IS researchers have also recognized that IT infrastructure flexibility includes technical IT infrastructure flexibility as well as human IT infrastructure flexibility [9, 10, 18, 21]. Effective human infrastructures require technology management knowledge and skills, business functional knowledge and skills, interpersonal and management knowledge and skills, and technical knowledge and skills [30]. IT infrastructure flexibility is multidimensional and includes the ability to easily upgrade the infrastructure to network different parts of the infrastructure, to integrate disparate data sources through the use of middleware, to resist system failure due to redundant components or systems, and to easily add new applications due to use of components or application frameworks [10, 20, 25, 45]. In summary, the IS literature recognizes that IT infrastructure flexibility is a complex, multidimensional concept and represents the ability of the technical and managerial
parts of the infrastructure to effectively respond to multiple types of uncertainties including user requirements changes, technology changes, and system usage changes.

My model for IT infrastructure value assessment integrates key ideas from these three research streams: *IT infrastructure value depends on usage* (first stream), *IT projects act like financial assets* (second stream), and *IT infrastructure flexibility has multiple dimensions* (third stream). These form the basis for my IT infrastructure valuation framework, which methodologically is closely related to the second stream.

### Understanding the Value of IT Infrastructures

**CONSIDER A SCENARIO WHERE AN ORGANIZATION** has some kind of IT infrastructure to start with, and an investment is made to augment this infrastructure, which could range from simple to sophisticated. *Simple infrastructure* includes low-bandwidth networks with a few basic applications, such as e-mail, connecting a limited number of users with limited security features, such as a firewall. *Sophisticated infrastructure* includes high-bandwidth networks connecting users within and outside the organization, supporting a large number of complex applications such as e-purchasing, customer relationship management (CRM), and XML-based electronic data interchange (EDI), with sophisticated middleware and security features such as intrusion detection, in addition to a firewall.

The term *value* denotes the NPV generated by IT applications that the IT infrastructure supports. NPV is likely to underestimate the value of the IT infrastructure. It does not consider the value of flexibility, as documented in prior research [16, 36]. The final measure of IT infrastructure value proposed is related to, but different from, NPV and considers flexibility.

The value of an IT infrastructure investment will be influenced by the extent to which it is used [14]. An IT infrastructure supporting sales transactions on the Web is clearly more valuable when there are a larger number of users. Similarly, an EDI infrastructure is more valuable when there are a larger number of EDI transactions of different types [33]. My model assumes that IT infrastructure value varies over time, due to variations in factors such as number of users and number of transactions. So I conceptualize IT infrastructure value as a function of the number of transactions, as well as the value of each transaction.

The reader should think of IT infrastructure value as a variable whose value changes over time with a certain pattern in a stochastic process. Let $s$ be the NPV of the infrastructure at any point in time. $s$ changes over time due to the increased usage of applications supported, environmental factors such as the economy and competition, addition of new applications, and events (such as a security threats) resulting in system downtime that may temporarily reduce the value of the infrastructure. They also include an opportunity to upgrade the infrastructure using more cost-effective technology, which may increase infrastructure value thereafter. Figure 1 illustrates the variation of IT infrastructure value over time and the different types of variations involved.
The change in IT infrastructure value is made up of three types of changes. Each of these changes can be positive or negative. The first type of change, the drift in value, is a relatively small change in value that, over time, accumulates to form a larger change in value. The second type of change is a noise term, or a very small instantaneous perturbation in value that does not exhibit a long-term pattern. The third type of change is a jump in value that is a sudden, relatively large change in value. These changes in IT infrastructure value can be influenced by factors that are both managerial controllable or uncontrollable.

These three terms can be understood by considering the example of an IT infrastructure that supports e-commerce, such as a storefront selling flowers and chocolates. The value of the IT infrastructure depends on the volume of transactions, which may increase over time as people become more comfortable with e-commerce, resulting in a positive drift. Increased competition or an economic decline may result in a decreasing trend in transaction volume for some period of time, resulting in a negative drift. There are likely to be day-to-day fluctuations in transaction volume or noise. Moreover, specific events (such as Valentine's Day) may result in a sudden positive jump in value. Other events, such as a denial-of-service hacker attack, could result in a sudden negative jump in transaction volume. These three types of changes in value represent a fairly general conceptualization of IT infrastructure value. However, the relative importance of each effect depends on what the IT infrastructure is used for, and on other factors. Figure 1 illustrates these effects and their combined effect on IT infrastructure value.

Let \( \alpha \) denote the drift rate of IT infrastructure value. This term represents the fact that, while day-to-day fluctuations are likely, the value of the infrastructure might exhibit a trend over the long term. The reader can think of IT infrastructure value as being driven by transactions, each having a certain value, then drift in value could be a result of drift in transaction volume, or drift in value of each transaction, or both. Factors that affect \( \alpha \) include exogenous factors such as economic factors; industry
and competition; proliferation of technology; trends in IT usability; and endogenous factors, such as managerial actions (including pricing, advertising, and training).

In the stock market, drift can be estimated using statistical analysis of past stock price data. In the case of an IT infrastructure, we do not have past data regarding IT infrastructure value in order to estimate drift. We can, however, collect usage data and analyze it for trends. IS research has applied usage variables in statistical analysis of IT value. Hence, we suggest that usage-based regression models can be used to estimate $\alpha$. Estimating trends in usage as a surrogate for trends in IT infrastructure value is approximate, since trends in IT infrastructure value also depend on trends in value per transaction. While it may be possible to estimate the latter in certain domains, a general approach may be more difficult. Also, from a practical standpoint, it may be easier to visualize usage trends when compared to trends in value per transaction.

We use $dz$ to represent the short-term perturbation in value or noise as a result of usage fluctuations and changes in value of transactions. A large number (due to many user transactions and exogenous factors) of small changes (in usage pattern of each user or information about exogenous factors) cause these variations in IT infrastructure value. We apply the Weiner stochastic process, which has been used to model other situations such as stock prices, to model these short-term perturbations in IT infrastructure value. A Weiner process is suitable for modeling situations where many small changes collectively lead to larger changes. One of its important properties is that the variance of the value of any variable following the Weiner process, during any time interval, increases with the length of the interval [15, 23]. This is consistent with the fact that the variance in value (due to factors such as variation in usage or variation in transaction value) of an IT infrastructure is likely to be larger if you consider a larger period of time (for example, a quarter instead of a month).

In addition to trends and small perturbations, the value of an infrastructure may also be affected by major events that cause jumps in value, as shown in Figure 1. Examples of such events include deadlines, installation of new software on the IT infrastructure that increases revenue, mergers, software glitches, security breaches, and power outages. Each time there is a jump event, $j$, there will be a cost associated with responding to the event, $c_j$, and a benefit resulting from responding to the event, $b_j$. The net effect of these costs and benefits is a positive or negative jump in value of the infrastructure. We use two variables to describe jumps. The first is the frequency with which jump events that affect IT infrastructure value occur. The second denotes the expected value of a jump event. These variables and the associated modeling are discussed in greater detail in the fourth section.

Table 1 illustrates some events that may affect infrastructure value, as well as the associated costs and benefits. Common factors causing such events include changes in external business conditions (mergers, regulation, competition, globalization), business strategies and processes (mergers, process reengineering), technology changes (new products, obsolescence, major price changes, new standards), and legislation. For example, a recent survey of companies indicates that recent corporate accountability legislation has a significant effect on IT infrastructures [41].
Table 1. Types of Events Affecting IT Infrastructure Value

<table>
<thead>
<tr>
<th>Event</th>
<th>Jump event ((j))</th>
<th>Benefit ((b))</th>
<th>Cost ((c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Installation of new application due to business or IT changes.</td>
<td>Value generated by new application.</td>
<td>Cost of installing new application on the IT infrastructure.</td>
</tr>
<tr>
<td>2</td>
<td>Increase in number of transactions due to changes in business conditions.</td>
<td>Value generated by additional transactions.</td>
<td>Cost of scaling IT infrastructure.</td>
</tr>
<tr>
<td>3</td>
<td>Need to integrate applications due to mergers, globalization, and so on.</td>
<td>Value generated by integration.</td>
<td>Cost of required integration.</td>
</tr>
<tr>
<td>4</td>
<td>Need to combine formats from multiple documents as decision aids.</td>
<td>Value of the decision.</td>
<td>Cost of producing information in required format.</td>
</tr>
<tr>
<td>5</td>
<td>Security threat.</td>
<td>Potential value loss as a result of security threat.</td>
<td>Cost of procedures required to address threat.</td>
</tr>
</tbody>
</table>

Figure 1 illustrates that infrastructure value is a combination of long-term trends in usage-based value, short-term noise, or variations in usage-based value and jumps in value due to significant events. Researchers performing statistical analysis of actual network traffic have found that traffic patterns can be thought of as combinations of relatively few significant large components and a large number of small irregular variations [24]. It is important to realize that a significant portion of IT infrastructure value is based on flexibility, which determines how the infrastructure behaves over time in response to a variety of positive and negative events. IT infrastructure investments, such as investments in connectivity, systems integration, and data storage and retrieval (storage area networks, data warehousing, and data mining) often increase the value of the infrastructure by enhancing flexibility.

IT infrastructure investments can enhance the flexibility of the infrastructure in various ways: (1) by increasing jump sizes for positive events; (2) by decreasing jump sizes for negative events; (3) by increasing the arrival rate of positive events; and (4) by decreasing the arrival rate of negative events. These are illustrated in Figures 2 (items 1 and 2) and 3 (items 3 and 4).

We compare two hypothetical infrastructures, the not very flexible infrastructure (NVFI) and the very flexible infrastructure (VFI). The NVFI is efficient for a stable operating environment characterized by little or no change in factors that affect IT infrastructure value. However, the NVFI will be inefficient in a dynamic environment characterized by the need to quickly take advantage of positive events, or to minimize the impact of negative events. A VFI, on the other hand, may be more expensive to operate in a stable environment because of higher initial cost. But it may
be less expensive to operate in an environment characterized by a relatively high degree of change. Terms such as "agility" and "scalability" are sometimes used to describe infrastructure flexibility. Table 2 provides illustrative design decisions that make an IT infrastructure more flexible and highlight the differences between NVFI and VFI.

I assume that VFI contains investments that make the infrastructure more flexible (such as a server bank, which facilitates the addition of new servers). In Figure 2, VFI value (indicated by a dashed line) is initially lower than NVFI value (indicated by a solid line) due to its higher costs. Table 1 lists five events that result in value jumps. Since the VFI is more flexible than the original infrastructure, positive events (such as Event 2 in Table 1, a surge in Web sales transactions that increases the value of the infrastructure) result in a higher change in value (jump) for the VFI (due to a flexible architecture that enables addition of servers to the server bank at a low cost) than for the NVFI. This is shown in Figure 2 as higher increases in value for the VFI (dashed line) corresponding to positive events when compared to the NVFI (solid line).

In the case of negative events (such as a power surge causing system downtime), the VFI suffers a lesser reduction in value (jump) (perhaps due to the ability to trans-
### Table 2. IT Infrastructure Management Actions for Different Types of Events

<table>
<thead>
<tr>
<th>Events</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changes in system demand</td>
<td>• Use infrastructure with redundant processors, software for load balancing;</td>
</tr>
<tr>
<td>volume (number of transactions)</td>
<td>• Use architecture with integrated components, setup, and administrative tools;</td>
</tr>
<tr>
<td></td>
<td>• Use clustered servers in a scalable architecture;</td>
</tr>
<tr>
<td></td>
<td>• Use infrastructure with extra capacity;</td>
</tr>
<tr>
<td></td>
<td>• Use groups of low-end and medium-sized servers;</td>
</tr>
<tr>
<td></td>
<td>• Maintain mirror sites in multiple locations.</td>
</tr>
<tr>
<td>Price changes, poor vendor</td>
<td>• Use open architecture to accommodate multiple vendor products.</td>
</tr>
<tr>
<td>service/financials</td>
<td>• Use intelligent middleware for easy data/application segment reconfiguration;</td>
</tr>
<tr>
<td>Changes in usage patterns</td>
<td>• Use an architecture that supports multiple software standards;</td>
</tr>
<tr>
<td>resulting in need to modify</td>
<td>• Use an architecture that provides modular prebuilt components;</td>
</tr>
<tr>
<td>content or applications without</td>
<td>• Design the network to support gateways to other systems;</td>
</tr>
<tr>
<td>interruptions in performance</td>
<td>• Use multiple Web servers for different application tiers;</td>
</tr>
<tr>
<td></td>
<td>• Use a component-based architecture.</td>
</tr>
<tr>
<td>Availability of new technology</td>
<td>• Use off-the-shelf products integrated into the existing infrastructure;</td>
</tr>
<tr>
<td>or application that needs to be</td>
<td>• Use mix of generic/custom components for easy customization;</td>
</tr>
<tr>
<td>integrated into the infrastructure</td>
<td>• Use third-party solutions that can be easily and quickly integrated;</td>
</tr>
<tr>
<td></td>
<td>• Use existing infrastructure to reduce the cost of implementing a new application.</td>
</tr>
<tr>
<td>Events that result in system</td>
<td>• Use clusters of servers and redundant architectures;</td>
</tr>
<tr>
<td>downtime (bugs, viruses, power</td>
<td>• Use firewalls, virus detection software, and other security tools;</td>
</tr>
<tr>
<td>outages)</td>
<td>• Use multipath network design and fault-tolerant backbone components.</td>
</tr>
<tr>
<td>Mergers and acquisitions</td>
<td>• Use an open systems architecture;</td>
</tr>
<tr>
<td></td>
<td>• Use an architecture that is scalable.</td>
</tr>
</tbody>
</table>

*Note: The "Actions" discussed in the right-hand column are partly drawn from [1, 2, 18, 26, and 37].*
dashed line in Figure 2) is higher than NVFI average value (which is proportional to
the area under the solid line in Figure 2). (Calculation of VFI average value and NVFI
average value is discussed in the next section.)

The example in Figure 2 describes how the original and the enhanced infrastruc-
tures react to the same set of events that occur over time, \( t = 1, \ldots, 5 \). In general,
however, infrastructure investments can alter value by modifying the arrival rate of
value-adding events (e.g., additional applications) or value-subtracting events (e.g.,
system downtime due to software bugs), or result in the arrival of new events (e.g.,
due to new decision opportunities made possible by an online analytical processing
infrastructure).

Figure 3 illustrates the value of a VFI and NVFI in a manner similar to Figure 2.
However, in Figure 3, the events that affect the value of NVFI and VFI are not iden-
tical. For example, consider a scenario where the VFI is different compared to the
NVFI due to investment in a messaging bus that facilitates easy integration of appli-
cations. The availability of such a messaging bus could result in the organization
taking up and completing a larger number of systems integration projects in a given
time (having a higher arrival rate of positive events) than with the NVFI. This is
because the effort required to complete each system integration project without the
messaging bus would be significantly larger and lead to a lesser number of completed
projects in a given time with fixed development resources. Other infrastructure in-
vestments for redundant hardware or software may reduce the number of negative
events in a given time period, or reduce the arrival rate of negative events. Figure 3
illustrates a scenario in which VFI has a larger number of positive jumps in a period.
Similarly, VFI may have a smaller number of negative jumps due to features such as
enhanced security or redundant hardware.

Many IT infrastructure investments can add value in more than one way and are
best represented by a combination of the effects we have discussed. For example, use
of an open systems-based infrastructure reduces the cost of integrating systems (in-
creases the value of positive jump) in addition to reducing the time for integrating
systems (resulting in the earlier arrival of a positive jump) and may result in an in-
creased number of postmerger system integrations completed in a given period of
time. Also, a messaging bus may reduce the additional cost of integrating new appli-
cations, decrease the time required for implementation (resulting in early arrival of
positive jumps), and increase the number of systems integration projects completed
in a given time.

A Dynamic Model of IT Value

IT INFRASTRUCTURE VALUE IS DYNAMIC and varies over time. I now build a model
for calculating average IT infrastructure value over a period of time that will aid
managerial decision-making. I emphasize the dynamic nature of IT infrastructure
value and explain how average value for a specified period of time can be calculated.
Table 3 summarizes the mathematical notation used.
Table 3. Mathematical Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_0; s_t)</td>
<td>IT infrastructure value at time 0; (\ln(s_0)).</td>
</tr>
<tr>
<td>(s_t; s_{t+\Delta t})</td>
<td>IT infrastructure value at time (t); (\ln(s_t)).</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Drift rate of IT infrastructure value.</td>
</tr>
<tr>
<td>(z_t; dz_t)</td>
<td>Noise component of IT infrastructure value at time (t); noise component increment for time period (dt).</td>
</tr>
<tr>
<td>(\sigma^2)</td>
<td>Instantaneous variance of the &quot;noise&quot; component.</td>
</tr>
<tr>
<td>(y_t; y_t^0)</td>
<td>Value of jump event at (t) that changes IT infrastructure value from (s_t) at (t) to (s_{t+\Delta t}); (\ln(y_t)).</td>
</tr>
<tr>
<td>(\lambda; \lambda_t)</td>
<td>Arrival rate of jump events for single or multiple types of jump events, respectively.</td>
</tr>
<tr>
<td>(y_{\text{mean}}^0; y_{\text{var}}^0)</td>
<td>Mean and variance of (y_t^0) (assuming a single type of jump event in both cases).</td>
</tr>
<tr>
<td>(Y_n; Y_n)</td>
<td>Cumulative effect of (n) jumps during ([0, t]) (assuming a single type); cumulative effect of (n) jumps during ([0, t]) (assuming multiple jump types).</td>
</tr>
<tr>
<td>(y_{i,t}; y_t^i)</td>
<td>Value of occurrence (j) of jump event (assuming a single type of jump event); (\ln(y_t)).</td>
</tr>
<tr>
<td>(k)</td>
<td>Number of different jump event types.</td>
</tr>
<tr>
<td>(y_{\text{mean}}^0; y_{\text{var}}^0)</td>
<td>Mean and variance of (y_t^0) (assuming multiple jump types).</td>
</tr>
<tr>
<td>(b_j; c_j)</td>
<td>Benefit ((b)) or cost ((c)) associated with a response to jump event (j).</td>
</tr>
<tr>
<td>(r)</td>
<td>Discount rate.</td>
</tr>
</tbody>
</table>

Single Type of Jump

We model the percent change in IT infrastructure value as a stochastic process [34, 38] with

\[
\frac{ds}{s} = \alpha dt + dz_t + (y_t - 1),
\]

if there is a jump in time period \(dt\), and if there is no jump with

\[
\frac{ds}{s} = \alpha dt + dz_t.
\]

\(\frac{ds}{s}\) is the percent change in IT infrastructure value during a small interval of time, \(dt\), from \(t\) to \(t + dt\).

The three terms in the right-hand side of Equation (1) represent different components of the change in value of the infrastructure. I assume one type of jump event. \(y_t\) is the value of a jump event that occurs at time \(t\) and changes IT infrastructure value from \(s\) at time \(t\) to \(s_{t+\Delta t}\) at time \(t + dt\). Hence, the jump size or change in IT infrastructure value due to the jump is \((y_t - 1)s_t\). Note that \(y_t\) can have a different value each time a jump occurs and hence is a random variable with an associated probability distribution. I also assume that \(y_t\) follows a Poisson distribution such that the probability of one jump be-
between \( t \) and \( t + dt \) is \( \lambda \, dt \), where \( \lambda \) is the arrival rate of jump events. In Equations (1) and (2), \( dz \) is the increment of a Weiner process [15], with mean 0 and instantaneous variance \( \sigma^2 \). To start with, I assume that there is only one type of jump event in order to derive our results. Subsequently, I generalize our results to the case of multiple jumps.

Consider a time interval \([0, T]\) over which IT infrastructure value is to be evaluated. The reader should think of \( T \) as the planning horizon for the investment. Let \( s_0 \) and \( s_t \) be the values of the infrastructure at times 0 and \( t \), respectively, where \( 0 < t \leq T \). Also, let \( n \) denote the number of jumps in IT infrastructure value during the time interval \([0, t]\), any length up to, and including, the planning horizon time. Then, based on Merton [34],

\[
s_t/s_0 = e^{(\alpha t + z_t)}Y_n, \tag{3}
\]

where \( Y_n = \prod_{j=1}^{n} y_j \) denotes the cumulative effect of \( n \) jumps in IT infrastructure value during the time interval \([0, t]\), with \( y_j \) defined as a random variable that denotes jump \( j \), with \( j = 1, \ldots, n \). If \( n = 0 \), it is also the case that \( Y_n = 0 \), so there are no jumps during \([0, t]\). But if \( n \geq 1 \), then we need to determine the cumulative effect of these \( n \) jumps in IT infrastructure value.

Note that Equation (3) can be rewritten as \( s_t = \ln s_0 + \alpha t + z_t + \sum_{j=1}^{n} y_j \). Next, we let \( s_t = \ln s_t, s_0 = \ln s_0, \) and \( y_j = \ln y_j \), which then results in

\[
s_t^* = s_0^* + \alpha t + z_t + \sum_{j=1}^{n} y_j^*. \tag{4}
\]

Press [38] shows that when \( y_j^* \) is normally distributed (or the magnitude of the jump, \( y_j \), is log normally distributed) with mean \( y_{\text{mean}}^* \) and variance \( y_{\text{var}}^* \), then the following are true:

\[
E\left[s_0^* + z_t + \sum_{j=1}^{n} y_j^*\right] = s_0^* + y_{\text{mean}}^* \lambda t \tag{5}
\]

\[
\text{var}\left[s_0^* + z_t + \sum_{j=1}^{n} y_j^*\right] = \left[\sigma_z^2 + \lambda \left(y_{\text{mean}}^* + y_{\text{var}}^*\right)\right] t \tag{6}
\]

\[
E[s_t^*] = E[s_0^* + \alpha t + z_t + \sum_{j=1}^{n} y_j^*] = s_0^* + \alpha t + y_{\text{mean}}^* \lambda t \tag{7}
\]

\[
\text{var}[s_t^*] = \left[\sigma_z^2 + \lambda \left(y_{\text{mean}}^* + y_{\text{var}}^*\right)\right] t. \tag{8}
\]

The last two equations are helpful in determining the mean and variance of IT infrastructure value over time.
Multiple Types of Jumps

Heretofore we considered only one jump event with an arrival rate of $\lambda$ based on [34, 38]. In general, we can have different types of jumps, including mergers, viruses, and the addition of new applications. Each of these jump event types is associated with different probability distributions. Hence, we need to extend the prior results for different jump event types.

Assume that each type of jump event $i (i = 1, \ldots, k)$ has an arrival rate $\lambda_i$, jumps during a time period $t$, and a cumulative effect of $n_i$ jumps equal to $Y_{n_i}$. The Appendix illustrates that the mean and variance of IT infrastructure value at time $t$ are given by

\[
E[s^*_t] = s_0^* + \alpha t + \sum_{i=1}^{k} n_i \text{mean} \lambda_i t
\]  

\[
\text{var}[s^*_t] = \sigma^2 + \sum_{i=1}^{k} \lambda_i (y_{i,\text{mean}}^* + y_{i,\text{var}}^*)^2 t
\]

\[
E[s_t] = E[e^{s^*_t}] = e^{s_0^* + \alpha t + \sum_{i=1}^{k} n_i \text{mean} \lambda_i t}
\]

Equations (9) and (10) facilitate easy calculation of the mean and variance of IT infrastructure value at a particular point in time, if we assume that the magnitude of jumps follows a lognormal distribution. It is important to emphasize, once more, that the value of an IT infrastructure varies over time. Also, if we know the mean and variance of IT infrastructure value at a particular point in time, we can determine confidence intervals for value and also determine if the values of the original and enhanced infrastructures are different at some point in time. For IT infrastructure investment decisions, however, managers are likely to be interested in the average expected value of the infrastructure over some time period or planning horizon. The average expected value of the infrastructure for the planning horizon $[0, T]$ is given by the area under the curve for VFI and NVFI in Figures 2 or 3, divided by the planning horizon, $T$. This average expected value of the infrastructure for the planning horizon $[0, T]$, assuming a discount rate $r$, can be calculated as

\[
\frac{1}{T} \int_{0}^{T} e^{s_0^* + \alpha t + \sum_{i=1}^{k} n_i \text{mean} \lambda_i t} e^{-rt} dt \bigg| T = \frac{1}{T} \int_{0}^{T} e^{s_0^* + \alpha t + \sum_{i=1}^{k} n_i \text{mean} \lambda_i t - rt} dt \bigg| T
\]

\[
= \frac{1}{T} \int_{0}^{T} e^{s_0^* + \alpha t + \sum_{i=1}^{k} n_i \text{mean} \lambda_i t - r} dt \bigg| T.
\]

(12)
The result of this integration can be expressed in a way that makes it possible to do spreadsheet evaluation, as given by

\[
\left( e^{hT} - e^{0^*} \right) / hT, \quad \text{where } h = \alpha + \sum_{i=1}^{k} \lambda_i^{*} \text{mean} - r.
\] (13)

A lognormal distribution of \( y_t \) is assumed in deriving Equation (13). Since empirical data are not available to justify the choice of this distribution, I will explain why this assumption is reasonable. I do so by examining uses of the lognormal distribution described in other research studies. The lognormal distribution has been empirically determined to be appropriate for modeling the value of insurance claims [29]. This is particularly relevant, since negative events that cause a drop in infrastructure value can be considered similar to events that result in insurance claims. IT infrastructure investments aimed at reducing the impact of negative events (such as redundant infrastructure, security, etc.) are similar to buying insurance. The lognormal distribution is also commonly used in modeling demand for different types of products [29], including the use of telecommunications and computing services [3]. Demand modeling using lognormal distributions can also be considered relevant to this paper, since the value of a jump in infrastructure value (which is assumed to be lognormally distributed in this paper) due to a positive event (such as system integration) is influenced by the usage (demand).

The lognormal distribution has also been used to model IT value uncertainty in the IS literature on real options [5] and software failure rates [35]. Hence, the lognormal distribution seems to be a reasonable choice in the absence of any specific empirical data pointing to a particular distribution of uncertainties affecting IT infrastructure value. The concept of viewing IT infrastructure value as the difference in the average values of a VFI and an NVFI over a period of time is valid, irrespective of the probability distributions used. However, if distributions other than the lognormal are used, it may not always be possible to derive equations similar to Equation (13), and simulation will have to be used instead. The following section presents an example to illustrate the application of the model and its comparative statics.

An Illustrative Example

GLOBAL BANK IS A LARGE DIVERSIFIED FINANCIAL INSTITUTION based in a major southern city in the United States. IT is considered an extremely important and integral part of the bank's growth strategy, which is based on acquisitions. The bank has a sophisticated IT department with a fairly large IT infrastructure team. The infrastructure team consists of multiple enterprise architects who carefully design and evaluate the performance of the IT architecture. These architects realize that the IT infrastructure design should address a variety of requirements. These include the ability to quickly complete acquisitions, the ability to quickly integrate systems, the ability to quickly deploy new applications, scalability to handle spikes in transaction vol-
Table 4. Jump Events Affecting IT Infrastructure Value

<table>
<thead>
<tr>
<th>Number</th>
<th>Event</th>
<th>Arrival rate per year</th>
<th>IT infrastructure expected value change for VFI (million $)</th>
<th>IT infrastructure expected value change for NVFI (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acquisition</td>
<td>0.5</td>
<td>15 (0.1718)</td>
<td>7.5 (0.0896)</td>
</tr>
<tr>
<td>2</td>
<td>Spike in demand</td>
<td>100</td>
<td>0.05 (0.0006)</td>
<td>0.025 (0.0003)</td>
</tr>
<tr>
<td>3</td>
<td>System integration</td>
<td>10</td>
<td>1 (0.0124)</td>
<td>0.75 (0.0093)</td>
</tr>
<tr>
<td>4</td>
<td>Virus</td>
<td>50</td>
<td>-0.05 (-0.0006)</td>
<td>-0.06 (-0.0007)</td>
</tr>
<tr>
<td>5</td>
<td>New applications</td>
<td>4</td>
<td>3 (0.0368)</td>
<td>1.5 (0.0186)</td>
</tr>
</tbody>
</table>

Note: \( y_{i,mean}^{*} = \ln((\text{NPV of IT infrastructure} + \text{expected value of jump due to the event})/\text{NPV}) \).

The infrastructure team uses a planning horizon of three years and updates the plan yearly. The current IT infrastructure supports applications whose NPV over the next three years is $30 million. It is expected that increased usage and business growth results in an increase in value of the infrastructure of 5 percent each year for the planning horizon. The infrastructure team has decided that the infrastructure needs to be upgraded in order to convert the current infrastructure, NVFI, to a VFI capable of handling the events described above. Table 2 provides illustrative examples of design decisions, or actions, that could help address different types of events. Management can use the framework described in this paper to evaluate this infrastructure upgrade decision as an IT investment. We can also think of VFI and NVFI as two infrastructure investment alternatives that management has and of the IT infrastructure value assessment model as helping management choose between these alternatives.

Table 4 provides a list of events that could impact IT infrastructure value for Global Bank during the next three years. For each event, the infrastructure team, together with the users, has identified an expected value of addition (or decrease) to the infrastructure value for the NVFI as well as the VFI. The new value of the infrastructure is NPV plus the expected value of the addition after each event. \( y_{i,mean}^{*} \) is the natural logarithm of \( [(\text{NPV} + \text{expected value of addition})/\text{NPV}] \). For example, it is expected that the average change in infrastructure value due to acquisitions is $15 million. If we assume that the initial value of the VFI is $80 million, the value of \( y_{i,mean}^{*} \) for the VFI is \( \ln[(80 + 15)/80] \), or 0.1718. VFI is more expensive than NVFI but is expected to result in cost savings or revenue increases when handling jump events. For example,
the VFI design uses application frameworks and a messaging bus that make it easy to quickly deploy new applications at very little additional cost. However, an initial cost and a maintenance cost are involved for the application frameworks and messaging bus.

Initial \((t = 0)\) infrastructure (NVFI) value (NPV of existing applications) is assumed to be $100 million. We also assume that additions to the IT infrastructure to make it more flexible result in additional costs. Hence, the additional value of a VFI has to be evaluated relative to the additional cost of setting up and maintaining a VFI. This cost may include hardware and software costs, as well as the cost of additional personnel, training, and managing change in business processes, and adding new personnel and business processes.

The benefits resulting from these costs (many of which improve flexibility and do not directly translate into revenues) are assumed to be significantly less than the additional costs. Hence, the value of the enhanced IT infrastructure (VFI) at time \(t = 0\) is assumed to be lower than that of the NVFI at $80 million. The drift rate of infrastructure value is assumed to be 5 percent, the annual discount rate is assumed to be 7 percent, and the time horizon for planning is assumed to be three years. Using Equation (13), the average value of the VFI is approximately $146 million, while the average value of the NVFI is approximately $67 million. It is interesting to note that the average value of the NVFI is lower than its initial value at \(t = 0\). This is attributed to the expected decrease in value resulting from negative events. Hence, the expected change in IT infrastructure value resulting from the investment to change an NVFI to a VFI is $79 million.

Clearly, the relative magnitudes of NVFI and VFI depend on the values of the different parameters used in Equation (13). Figure 4 shows the variation of the percent difference in infrastructure values (DIV) of the VFI and NVFIs as a function of drift rate and discount rate. Analysis of Figure 4 illustrates that a 200 percent increase in drift rate (from 0.3 to 0.9) decreases DIV by 23 percent and a 200 percent increase in discount rate increases DIV by 30 percent. Hence DIV is not very sensitive to changes in drift rate or discount rate. This is a useful result, since estimation of these parameters may be difficult, in practice, and it is good to know that errors in estimation will not have a significant effect on infrastructure value. However, estimating these parameters conservatively and using them in value calculations will...
help to more accurately value and articulate the value of IT infrastructure than would otherwise be the case.

Figure 5 illustrates the variation of DIV as a function of the change in infrastructure value caused by multiple jump types, $CIVMJ = \Sigma_{t=1}^{n} \lambda_{i} y_{i,mean}$. A critical magnitude of $CIVMJ$ (approximately 0.25) uncertainty is required before the additional investment in VFI becomes justified. Also, DIV is very sensitive to changes in $CIVMJ$. A 200 percent change in $CIVMJ$ (from 0.1 to 0.3) results in a change in DIV of approximately 157 percent (from -71 to +41). Hence, it is extremely important to consider the ability of the infrastructure to react to jump events in investment decisions.

Managerial Implications

ALTHOUGH MANY IT MANAGERS RECOGNIZE that the flexibility of an IT infrastructure has value, they are often unable to articulate that value [46]. As the Global Bank example illustrates, the value of flexibility is a significant component of IT infrastructure value. Failure to consider this component significantly understates IT infrastructure value. Our approach can help managers think through the different events that affect infrastructure value and to estimate and articulate the value of infrastructure flexibility. This approach can also be used by managers to compare and evaluate different IT infrastructure investment alternatives. The calculations can be implemented using a spreadsheet.

Parameter estimation is not always easy, though. Estimation of cash flows from applications in the infrastructure is the same as for NPV calculations that are commonly used. Identification of events and associated probabilities and additional cash flows requires additional effort. Similar estimation (identification of events, probabilities, and cash flows) has been reported by practitioners in evaluating R&D investments and other investments [12, 31]. Even though the estimation is approximate, it is better than traditional capital budgeting methods, which do not capture the value of flexibility [44].

Other approaches to estimating the value of flexibility also exist. The approach presented in this paper should be viewed as complementary to existing real options
methods, which represent one means of valuing flexibility. One benefit of using the real options approach is that it uses a risk-free interest rate. However, the approach also involves assumptions that are not always valid, as well as approximate parameter estimations. Also, considering multiple types of uncertainties—very important for IT infrastructure investments—is extremely complicated in the case of real options. I have shown that sensitivity analysis can be used to examine the effect of errors in parameter estimation. But the results are not very sensitive to the discount rate or drift rate used.

Infrastructure valuation needs to be an ongoing effort that involves organizational learning; it is not a one-time effort. It is possible to collect data on events and their associated probabilities and cash flows after investments have been made, or as and when significant events occur, and use this information to evaluate future IT infrastructure investments. In some cases, an investment can improve the infrastructure’s ability to handle multiple events. For example, a messaging bus may make it easier to integrate existing applications, add new applications, and facilitate application integration during acquisitions. In some other cases, infrastructure enhancements can improve the infrastructure’s ability to handle some types of events, while decreasing the infrastructure’s ability to handle other kinds of events. For example, while use of a proprietary (single-vendor) application framework can facilitate system integration and deployment of some new applications, it may also make it more difficult to integrate disparate systems from different vendors during a merger or acquisition. Hence, managers need to evaluate synergies as well as tradeoffs resulting from infrastructure design decisions and compare multiple infrastructure designs. The approach I have presented is useful in comparing the average expected value of alternative infrastructure designs under uncertain conditions.

The qualitative insight that can be gained by parameter estimation and the use of Equation (13) is also extremely important. This insight helps managers better understand and articulate how the dynamics of an organization affect IT infrastructure value. Use of the IT infrastructure value assessment framework increases managerial visibility into the value of a flexible IT infrastructure and is also useful in evaluating IT infrastructure investment alternatives. It will provide a basis for organizational learning and improved management of IT infrastructures.

Conclusions and Future Research

TRADITIONALLY, IT VALUE HAS BEEN VIEWED as a static concept, though there has been recent recognition that IT value depends on its use in an organizational context. This is particularly true of IT infrastructures that support multiple applications. I presented a new approach to understanding and evaluating the value of IT infrastructures. My approach builds on the idea that IT flexibility is a significant source of value. I propose a method of understanding and estimating the value resulting from flexible interaction between an IT infrastructure and its organizational context. I further emphasize the need to conceptualize IT value as a dynamic (time-varying) con-
cept and present a straightforward method for estimating the value of IT infrastructure assets. Basing the proposed framework on the theory of financial asset valuation addresses the need to develop and articulate measures of IT value for use by CFOs and other financial executives [40].

I recommend selective use of the IT infrastructure value assessment framework. It is appropriate for large investments in environments characterized by significant uncertainty or jump-causing events. First, it can be used to sensitize senior management to the fact that IT infrastructures are not merely costs but can add significant value. Second, it can be used to assess IT infrastructure value for related investment decisions. Moreover, visual representations of flexibility and IT infrastructure value (as in Figures 2 and 3) can help IT managers better communicate the value of flexible IT infrastructures, sensitizing senior managers to their value. My experience with presenting early versions of this research to executives indicates that managers can relate easily to the idea of events that cause jumps in value. Flexible infrastructures magnify the effects of positive events and lessen those of negative ones.

Despite the simplicity of the model, parameter estimation—particularly of drift, noise, and the mean value of jumps—may be difficult and merits additional research. Estimation requires careful study and understanding of how an IT infrastructure functions in an organizational context. Although I emphasize the desirability of flexible IT infrastructures, it is important to realize that flexibility is not always cost effective. Investing in a flexible IT infrastructure in an environment with only a few jumps of small magnitude may not be justified.

Viewing an IT infrastructure as a dynamic asset whose value follows a stochastic process and examining different types of options on this asset may help to produce other models of IT asset valuation that provide interesting insights. Case studies of IT infrastructure valuation will be fruitful research efforts, as will comparisons of different models of uncertainties that affect IT infrastructure value and approaches to improve parameter estimation.

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NOTE

1. Although real options analysis presents a promising conceptual framework for IT project evaluation, it has limitations: assumptions regarding uncertainty modeling, tradability, and risk neutrality; estimating the expiry time of an option [6, 7]; the absence of contracts to enforce exercise of options [43]; and difficulties in modeling multiple types of uncertainties in options (multidimensional options) [44]. Recent IS research on real option-based evaluation of IT investments has recognized the need for additional research that uses a more realistic modeling of uncertainty [5].
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Appendix. IT Infrastructure Expected Value and Variance with Multiple Types of Jump Events

Equation (6) generalizes to \( k \) different jump event types with 
\[
E[s_i^*] = E[s_0^* + \alpha t + z(t) + \sum_{j=1}^{k} \sum_{i=1}^{n_j} y_{ij}^*],
\]
where \( y_{ij}^* \) refers to the magnitude of occurrence \( j \) of jump type \( i \), with \( n_j \) occurrences of jump type \( i \) during \([0, t]\). I assume \( y_{ij}^* \) are independent random variables.

\[
E[s_i^*] = E[s_0^* + \alpha t + \sum_{j=1}^{k} \sum_{i=1}^{n_j} y_{ij}^*] = s_0^* + \alpha t + \sum_{j=1}^{k} \sum_{i=1}^{n_j} y_{ij}^*.
\]

In Equation (A1), \( y_{i,\text{mean}} \) is the mean of \( y_i^* \). The variance of \( s_i^* \) is given by

\[
\text{var}[s_i^*] = \text{var}[s_0^* + \alpha t + \sum_{j=1}^{k} \sum_{i=1}^{n_j} y_{ij}^*] = \text{var}[s_0^* + \alpha t] + \text{var}[z_i]
+ \sum_{j=1}^{k} \sum_{i=1}^{n_j} \text{var}[y_{ij}^*] = \sigma_z^2 + \sum_{j=1}^{k} \sum_{i=1}^{n_j} \left[ y_{i,\text{mean}}^2 + y_{i,\text{var}}^2 \right].
\]

In Equation (A2), \( y_{i,\text{var}} \) is the variance of \( y_i^* \) since, in the case of a single jump, 
\[
\text{var}[s_i^*] = [\sigma_z^2 + \lambda(y_{\text{mean}}^2 + y_{\text{var}}^2)] t.
\]