Technology Investment Decision-Making under Uncertainty in Mobile Payment Systems

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Last revised: December 1, 2013

ABSTRACT

Innovations in the mobile payments industry provide potentially profitable investment opportunities for banks. Nonetheless, significant uncertainties are associated with decision-making for this IT investment context, regarding future market conditions, technology standards, and consumer and merchant responses, especially their willingness to adopt. As a result, traditional capital budgeting approach and experienced intuition have not been effective. We develop a model to support a bank's mobile payment systems adoption decision-making at the firm level when it faces endogenous technological risks and exogenous market conditions. This study applies theory and modeling from financial economics for decision-making under uncertainty to investments in m-payment systems technology. We assess the projected benefits and costs of investment as a continuous-time stochastic process to determine the optimal investment timing. We find that: (1) the value of waiting to adopt jumps when the related business environment experiences relevant shocks; (2) when the rate of benefits flows, the time horizon for decision-making and the time value of money change, the recommended investment timing and optimal investment will change too; and (3) when value jumps occur at different stages and in different directions, the optimal timing and maximal payoffs may exhibit unexpected changes. We illustrate how to use simulation-based financial option valuation approach to value the investment. We further discuss the application of our approach for systems that are subject to network effects, rational expectations and strategic interactions among different banks.

Keywords: Decision-making under uncertainty, electronic payments, financial economics, financial services, IT investments, jump diffusion, mobile payments, network effects.

The evolution of new technologies that enable consumers to conduct financial transactions using mobile devices has the potential to affect their financial lives in important – but as of yet, not fully known – ways…

Sandra F. Braunstein, Director, Division of Consumer and Community Affairs,
Board of Governors of Federal Reserve System.
In "Developing the Framework for Safe and Efficient Mobile Payments,"
In a hearing before the United States Senate [29],
March 29, 2012, Washington, DC

1. INTRODUCTION

As consumers have become increasingly connected via smartphones, tablets and other mobile devices in recent years, mobile payments have emerged across the world as a new and innovative means for payment. An *m-payment* is any payment where a mobile device is used to initiate, authorize and confirm an exchange of financial value in return for goods or services. Some industry participants view m-payments as the next revolution in payments at bricks-and-mortar merchants, while technology standards are migrating from *short message services* (SMS) to *near field communication* (NFC) or cloud computing technologies.

After 2011, a number of companies and industry partnerships announced new m-payment technology solutions built upon NFC contactless chips, cloud servers and attachable card readers that plug into mobile devices. The launch of Google Wallet in the United States provided a "tap and go" NFC m-payment solution in 2011. Its primary competitor, Isis, developed by Verizon, AT&T and T-Mobile, launched an NFC application in 2012. Also in 2012, Apple was awarded a U.S. patent for its iWallet, and so far, its m-payments strategy mostly has involved observing the market and waiting for things to develop further [31]. Other innovations take advantage of third-party applications on smartphone platforms, enabling merchants to process card payments. For example, Square, an application that supports merchant and consumer transactions, serves as a virtual wallet filled with virtual credit cards for authorized merchants in Square's ecosystem.

The potential profits from implementing m-payments are huge. Investments in m-payment

systems using NFC are expected to reach US$670 billion by 2015 [7], and more than one million merchants are using Square's card reader to accept payments [17].

Significant uncertainties are associated with investment decision-making for m-payments though. First, m-payment systems involve multiple stakeholders, including consumers, merchants, mobile network operators, mobile device manufacturers, banks, software vendors, and government agencies. These stakeholders need to participate and cooperate in cross-industry alliances to set common operational, process and technology standards. With m-payments, the stakeholders face technological risks and various economic uncertainties, including unexpected market condition changes, consumer adoption, merchant responses, and standards and regulation risks. For example, fraud typically constitutes most of the transaction-related financial losses associated with e-payment technologies. Stakeholders wonder about the likely benefits and costs, and there are understandable concerns about whether any specific underlying technological solution is better in defending against undesirable financial losses.

Such is the nature of uncertainties in m-payment: they go beyond purely technical issues to those involving consumers, banks, merchants, technology and infrastructure providers, and regulators, and the additional reservations they express about adoption. For consumers, their willingness to adopt m-payments is influenced by perceived usefulness and ease of use. For merchants, they are expected to accept m-payments in return for goods sold and services rendered. But merchants bear uncertainty risks as well. They may not know about the likely extent of consumer adoption and the nature and timing of bank adoption. For banks, they face infrastructure development issues, changing transaction costs, and security problems – and many "cost unknowns."

There also is no standard business model for m-payments. Nor has an effective revenue model been developed. Also, we have not yet seen any truly successful collaboration among the

stakeholders. Business networks that adopt business process standards will have a higher likelihood of firm participation, since the costs for participation and switching will be lower, thus enabling greater capacity for value creation in production that is undertaken with other network firms. In addition, because of lack of consumer demand, which is driven by the availability of many alternative payment choices, m-payments are not yet widely accepted [13]. Consumers either do not see any benefits or find it easier to pay with another safe and widely accepted method.

Finally, uncertainty about future regulation and the ownership of customer relationships are holding back mobile financial services adoption. The e-payments industry is heavily regulated, and participants in m-payment systems face high costs to comply with existing regulation. Regulations for mobile network operators and third-party participation in payment services are fragmented. There is confusion because multiple regulatory agencies have fragmented responsibilities for different aspects of payments and wireless transactions in most countries. Because the marketing value of customer data on m-payments is tremendous, uncertainties also arise when different parties share data and must negotiate the ownership of the customer relationship.

As major players in the financial services industry, banks play an indispensable role in the m-payments market's development and success. We study a new set of issues that involve the spectrum of affected stakeholders, with an emphasis on senior management decision-making at the banks. Bankers' m-payment systems adoption decisions involve technological risks, dynamic market conditions and the uncertain actions of other stakeholders. In such a complex environment, tradeoffs in decision-making, the variety of factors make it hard for management decision-makers to balance the trade-offs.

We will model the dynamic environment of the m-payments marketplace using a general stochastic process with value jump events. It enables us to offer insights on the appropriate time to

invest associated with the expected payoffs for the bank. It also supports estimation of the financial impacts that might arise in the presence of sudden shocks that affect the m-payments business and how this may influence the investment timing of the bank. We will leverage a simulation-based approach proposed by Longstaff and Schwartz [16] to value technology investment when the related business environment experiences relevant shocks.

In this research, we ask: (1) How can the value of m-payments technology investments be maximized under uncertainty? (2) How long can a bank postpone its commitment to a specific technological solution? (3) How does adoption by other stakeholders influence the timing of a bank's own adoption in the presence of changing expectations about the relevant business and technology standards for m-payments? And, (4) how should we model and analyze changing managerial sentiments in light of decision-relevant information that is revealed over time? To answer these questions, Section 2 presents our theoretical perspective, and Section 3 discusses the m-payments technologies market. Section 4 develops a stochastic model for bank decision-making for investments in m-payments technology. Sections 5 and 6 present our results, and Section 7 concludes.

2. THEORY

Different theoretical perspectives are relevant for m-payment technology investments: decision-making under uncertainty, real option methods, investment timing, and network effects.

2.1. Decision-Making under Uncertainty

The characteristics of m-payment systems investments make the financial economics of *decision-making under uncertainty* [5, 8] an appropriate theoretical perspective for evaluating a bank's flexibility to choose an optimal time to invest. We consider m-payment system investments as a process that involves managing the balance between value and risk. In our model, the

benefits and costs of m-payment investment follow a continuous-time stochastic process, and include a discontinuous value jump diffusion process. The stochastic process that is most commonly used is *geometric Brownian motion*. Models that include the geometric Brownian motion stochastic process assume no external competitive or regulatory impacts on the benefits flows and future payoffs from the IT investment, however. To address this shortcoming, we will incorporate a discontinuous jump diffusion process reflecting the external impacts on future payoffs.

A Poisson process can be used to capture rare events when the benefits flows change drastically, causing the investment payoffs to jump. Merton [21] has shown that the price of an American option is given by a complex mixed differential-difference equation that is difficult to solve. Longstaff and Schwartz [16] suggested a *least-squares Monte Carlo* method for option valuation when the underlying asset follows a jump diffusion process. It combines simulation and advanced regression methods to develop an approximation for a set of conditional expectation functions. Stentoft [26] showed that various approximations of option prices converge to the true price under certain conditions. These work offer a useful foundation for examining investment timing and key elements related to the decision-making process we wish to study.

2.2. Real Option-Based Methods

Information technology (IT) investment risk can be evaluated using a family of financial risk management methods. Benaroch [4] identified various IT investment options, including deferral, staging, exploration, scale alternation, outsourcing, abandonment, leasing, compound, and strategic growth options. Grenadier and Weiss [12] used similar methods from financial economics to determine the optimal investment strategy for a firm that is faced with uncertainty from a sequence of technology innovations. Electronic banking network expansion has been a focus for the development of realistic models for decision-making under uncertainty to enhance the power

of senior management to effectively strategize.

Some researchers have questioned the validity of option-based approaches in financial evaluation. Banker et al. [3] examined the Black-Scholes model for valuation of IT projects and showed that the restrictive assumptions may result in over-valuation, in spite of the fact that the logic of the approach has been widely touted as being helpful in supporting the logic of strategic thinking related to IT investment decisions under uncertainty. Fichman [10] argued that, when uncertainty and irreversibility are high, real option analysis should be used to structure the evaluation and management of project investment opportunities. M-payments infrastructure investments enable a bank to make follow-on investments in other projects. The uncertainties make m-payment investments a risky project though, and a bank may decide to abandon or defer them.

2.3. The Timing of New Technology Adoption

Investment timing. Time plays an important role in investment decision-making. Prior studies have pointed out many factors that affect a firm's adoption of a new technology at a given time: when information acquisition [14, 19], information spillovers [18], and strategic interactions occur [24]. Investing in m-payment technologies is an irreversible decision. Uncertainties about the future benefits and development costs will cause them to be perceived by decision-makers as fluctuating over time – sometimes higher and sometimes lower, depending on their expectations of what it will take to implement m-payments, and what level of demand such services will garner in the market once they have been deployed. Technologies tend to become more valuable over time, while investment costs usually fall, which suggests the nature of the benefits and costs drifts that are involved. IT investments often have high-upside potential, but also high uncertainty and indirect returns, which make them good candidates for being evaluated with decision-making under uncertainty methods.

Information technology diffusion. Schwartz and Zozaya-Gorostiza [25] contributed a cost-benefit diffusion methodology for different kinds of IT investment decision-making, when the investment costs and benefits are subject to changes over time. An important thread in this literature has been modeling to support investment timing strategy for firms that must decide whether to adopt one of two incompatible technologies, in the light of evolving expectations about future competition. This is an important basis for a decision model related to m-payment technology investments, where uncertainties about the investment will be resolved over time.

2.4. Network Effects

The value of m-payment technology investments is tied to the extent of the network of organizations and people that adopt this payment approach. Consumers typically value a product or service more when it is compatible with other things. These are *network effects*, and a large literature has studied them. The related ideas have been applied in different contexts relevant to m-payments, including inter-organization systems, electronic data interchange, wireless phones, electronic banking and ATM networks, and electronic bill presentment and payment.

Milne [23] observed that some new payment mechanisms have been developed for the purpose of achieving high network effects. When more consumers use m-payments, more merchants will be willing to adopt this approach. As a result, the value of m-payment investments from a bank's view will be higher too. Such positive network effects touch multiple stakeholders simultaneously, constituting a positive force for m-payments adoption.

3. THE MOBILE PAYMENT MARKET ECOSYSTEM

Electronic payments innovations are continuously improving the effectiveness and efficiency of payment systems. Since the 1980s, payment card networks and the use of automated clearing house computing capabilities for the processing of paper checks have automated banking pro-

cesses. The country-level installed base of electronic payment capabilities is also an important factor influencing the diffusion and adoption level of m-payments. In the U.S., which was affected by the economic slump that began in 2008, e-payments increased 9.3% per year from 2006 to 2009, and represented almost 80% of all non-cash payment methods [9, 11].

M-payments evolution. The evolution of mobile financial services encompasses a combination of ongoing advances in hardware, software, and payment systems, including contactless payments, online banking, mobile phones (particularly smartphones), applications, and the convergence of electronic-commerce and mobile-commerce. In the late 1990s, the first initiatives in mobile commerce and banking were the launch of the two mobile phone-enabled vending machines in Finland, which accepted payments via SMS. Initiatives that allowed consumers to use their mobile phones to perform new functions surged in 2000, driven by the development of mobile Internet access, the popularity of the Internet and e-commerce, and the increased awareness of mobile phones as more than voice communication tools. After 2011, a number of new technology solutions for m-payments emerged. The infrastructure of safe and efficient m-payment systems is increasingly likely to be based on NFC contactless technology, now included in smartphones and merchant terminals, from the Google and Isis initiatives. Cloud-based m-payments represent another type of technology solution for which payment credentials are stored on a secure server. Cloud-based solutions like PayPal reduce customer security concerns, and take advantage of the existing online platform to achieve network effects and interoperability.

Smartphone adoption. Mobile phone manufacturers introduced smartphones that supported more effective web browsing and data capabilities. Smartphones offer a variety of enhanced capabilities, including ease of use, the developer and applications ecosystems, and security, which drive advanced m-payments usage. Adoption of m-payment systems is constrained by the extent

of infrastructure availability. Vision Mobile (www.visionmobile.com), a market analysis and

strategy firm, reported that the smartphone penetration rate surpassed 29% globally in 2011, with

2011 global smartphone sales reaching 486 million units [30]. The high penetration rate of

smartphones, especially in Europe, the U.S. and some Asia Pacific countries, provides a natural

infrastructure for m-payments to flourish. Smartphone penetration in Singapore, Japan, the U.S.

and Western Europe matches penetration of various kinds of cards. (See Table 1.)

Table 1. Mobile subscribers and smartphone penetration rate ranked by country, 2011

RANK	COUNTRY	POPULATION	SUBSCRIBERS	SMARTPHONES	MIGRATION RATE	PER CAPITA
1	SIN	4.9	8.1	4.4	54%	90%
2	HK	8.0	14.0	4.9	35%	61%
3	SWE	9.3	13.6	4.8	35%	52%
4	AUS	21.6	29.8	10.2	34%	47%
5	ESP	45.5	58.9	20.8	35%	46%
8	FIN	5.4	9.6	2.3	24%	43%
11	UK	62.1	82.4	25.0	30%	40%
16	USA	319.1	319.4	111.8	35%	35%
20	KOR	48.6	54.0	16.4	30%	34%
24	GER	82.0	107.7	23.0	21%	28%
33	JPN	126.9	126.8	18.1	14%	14%
41	CHN	1,360.0	963.1	77.1	8%	6%

Notes: Data are from Tomi Ahonen Consulting Analysis [1], based on raw data from Google/Ipsos, the Netsize Guide/Informa, and TomiAhonen Almanac 2011. Countries are rank-ordered by smartphone penetration rate. Population, subscribers and smartphones are in millions. The smartphone penetration rate is per capita.

M-payments benefits. These facts suggest the large potential benefits of m-payment adop-

tion. First, an encrypted contactless mobile platform or secure cloud server will help to minimize

fraud. Second, merchants will be more cost efficient by processing m-payment transactions.

They are more secure than traditional card transactions due to the use of dynamic data versus

static magnetic card data. Also, m-payments help to reduce potential costs associated with pay-

ment card industry security standards compliance. Third, consumers enjoy the convenience and

additional benefits of using m-payments, because mobile devices can easily incorporate multiple

payment methods, loyalty cards, virtual coupons, and customized discounts. Finally, mobile

phones allow financial services to be offered to people who do not have bank accounts. Given

the increase in smartphone adoption, the large installed base for e-payments, and the perceived benefits of m-payment, banks recognize the need for industry alliances to establish a set of common operational, process and technology standards. Otherwise, they may forgo future profits from m-payments and lose their central role in handling customer account relationships.

4. A MODEL FOR DECISION-MAKING UNDER UNCERTAINTY

We next present a model to evaluate a bank's m-payments technology adoption decision. We include a jump process for the possibility that an unexpected event may occur during the diffusion process, creating a shock on the value flows. Uncertainty in m-payments investment can be represented by multiple stochastic processes. They relate to investment costs, future benefits, and the possibility that a jump event may occur before the investment opportunity expires.

4.1. The Model

The bank is risk-neutral and value maximizing. It has the option to wait until an optimal time to invest. It can decide whether and when to invest *I* dollars to sign contracts with m-payments technology providers or set up m-payment systems infrastructure, such as an embedded-NFC point-of-sale (POS) service network. (See the Appendix A for our modeling notations.) The investment decision is irreversible; it will be hard for the bank to unwind payments to contractors or employees. We further assume that once the investment decision is made, the system will be installed and begin to function. The costs of operation and maintenance will be negligible.

IT innovation happens fast. We assume the investment opportunity lasts for the period of [0, *T*], when the benefits flows from investing in the m-payment system infrastructure occur. Thereafter, the investment opportunity related to the technology standard will expire. The bank can invest at any time up until *T*, the maximum length of the deferral period. The current cost of the investment is known, but future changes are uncertain. They follow geometric Brownian motion,

$dI = \alpha_I I dt + \sigma_I I dz$ (Changes in Investment Cost), where dz is a standard Wiener process, α_I is a

drift parameter for cost changes, and σ_I is the standard deviation affecting the volatility of the

investment cost, whose drift parameter is negative, $\alpha_I < 0$. Investment costs will tend to decrease

over time due to technological progress and the increased scale of the m-payment infrastructure.

After an investment is made, the bank will receive benefits flows until time T. (See Figure 1.)

Figure 1. Investment timeline
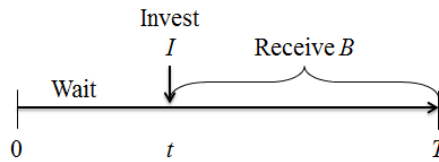
Let B denote the stochastic benefits flows arising from the m-payment investment, with $dB =$

$\alpha_B B dt + \sigma_B B dz$ (Stochastic Benefits Flows), where α_B is a drift parameter and σ_B is the standard

deviation of the cash flow described by a standard Wiener process. We assume σ_B is decreasing

over time: as more information is revealed, uncertainty over the benefits flows will be resolved.

For example, as time goes by, when an increasing number of NFC-enabled smartphones are in-

troduced or a standard business model for m-payments emerges, the uncertainty of the benefits

from investing will abate. Positive network effects are associated with a positive drift value for

cash flows during the lifetime of the investment, so $\alpha_B > 0$. As more consumers and merchants

use and support m-payments, the benefits flows will be higher. This also captures the trend in the

value of the network based on the growth of the user base. Another assumption is that no other

competitors offer a similar m-payment mechanism or enter the market in $[0, T]$, and there is no

correlation between the stochastic changes in the investment cost and benefits flows, and $\rho_{BI} = 0$.

The bank has an incentive to defer its m-payments investment decision due to: (1) declining

investment costs; (2) the resolution of uncertainty of the benefits flows; and (3) cash flows for a

later investment. Deferring m-payment investment is costly for the bank though. Investing later

shortens the length of time the bank will receive benefits flows. It may also miss the advantage of an earlier mover. When determining the optimal investment timing for m-payments infrastructure, the bank must consider all these factors, which may have countervailing effects.

The value of an investment in m-payment systems technology at time t is the expected present value of the stream of future benefits, adjusted for the relevant costs. Value can be assessed based on the discounted benefit flows from the time t when the bank makes the investment decision to the latest deferral time, T, with $V = E_t \left[\int_t^T B(\tau) e^{-r_f(\tau - t)} d\tau \right]$ (Investment Value). E_t is the expectation conditional on information available at time t and $B_t = B$, r_f is a risk-free discount rate, and τ is the period of time over which discounting occurs.

The process representing the benefits flow drift is given by $dB = (\alpha_B - \eta_B)Bdt + \sigma_B B dz^* = \alpha_B^* B dt + \sigma_B B dz^*$ (Benefits Flow Drift), where η_B is a risk premium due to benefits uncertainty, and dz^* is a risk-neutral measure for the Wiener increment. Integrating over the interval (t, T) gives $V = \frac{B}{r_f - \alpha_B^*} \left[1 - e^{-(r_f - \alpha_B^*)(T-t)} \right]$ (Discounted Investment Value). The expected value of investment I at time t is $E(I_t) = I_0 e^{(\alpha_I - \eta_I)t}$ (Expected Value of Investment Cost), where η_I is a risk premium for investment cost uncertainty and I_0 is the investment cost at time 0.

The decision to invest at time $0 \leq t \leq T$ is equivalent to exercising an option before its expiration date T. Let $F(B, I, t)$ denote the value of this investment opportunity at time t. Since B and I do not involve traded assets, but are the expected values of a pair of random variables, they will have risk premia associated with them. The net present value (NPV) of this investment opportunity with an embedded deferral option is $NPV = max\left[(V - I), 0\right] + ROV = F(B, I, t)$ (Investment NPV with Deferral). The related option value is $ROV = min\left[F(B, I, t) - (V - I), F(B, I, t)\right]$ (Real Option Value). Substituting the Discounted Investment Value and Expected Value of Investment Cost Equations under the risk-neutral measure into the Real Option Value

Equation gives: $ROV = \min\left[F(B,I,t) - \frac{B}{r_f-\alpha_B^*}\left[1 - e^{-(r_f-\alpha_B^*)(T-t)}\right] + I_0 e^{(\alpha_I-\eta_I)t}, \; F(B,I,t)\right].$

We then apply Ito's Lemma to obtain the *differential real option value* for the investment:

$$dROV = \frac{\partial ROV}{\partial t}dt + \frac{\partial ROV}{\partial B}dB + \frac{\partial ROV}{\partial I}dI + \frac{1}{2}\frac{\partial^2 ROV}{\partial B^2}dB^2 + \frac{1}{2}\frac{\partial^2 ROV}{\partial I^2}dI^2 + \frac{1}{2}\frac{\partial^2 ROV}{\partial B\partial I}dBdI \quad (8)$$

Substitution of the Changes in Investment Cost and the Stochastic Benefits Flows Equations, along with the expression for *dROV* into the Bellman Optimality Equation, $r_f ROV dt = E(dROV)$, yields the following complex expression for the second-order differential equation:

$$\frac{1}{2}\sigma_B{}^2 B^2 ROV_{BB} + \frac{1}{2}\sigma_I{}^2 I^2 ROV_{II} + (\alpha_B - \eta_B)B\, ROV_B + (\alpha_I - \eta_I)I\, ROV_I + ROV_t - r_f ROV = 0.$$

The Bellman Optimality Equation states that the value of a state under the optimal policy − in this case, the value of the investment opportunity − must equal the expected return for an action associated with that state. The relevant action is the exercise of the real option. The solution to the above second-order differential equation must satisfy two boundary conditions. [1]

This will yield the optimal decision rule. When $V - I > 0$ and *ROV* (B, I, t) > 0, the best decision for the bank is to wait, if waiting is possible. Only when *ROV* (B, I, t) = 0 and $V - I > 0$, will it be the optimal time to invest in m-payment technology at investment cost *I*. When $V - I < 0$, and *ROV* (B, I, t) $\geq I - V > 0$, the bank should wait for the cost flows to decrease or for the expected value to increase. If waiting is not possible, the project should be abandoned.

4.2. The Relevance of Jump Diffusion Process Modeling

So far, we have modeled a continuous diffusion process. It is more realistic to include a discontinuous jump into our continuous process to capture unexpected sudden changes in investment value. Such changes are *jumps* that might be caused by various developments. One is the

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[1] First, the value of the real option must be 0 at time *T*, *ROV* (B,I,T) = 0. This is because the decision to make the investment cannot be deferred anymore at time *T*. Second, at any other time, $0 \leq t < T$, the value of the investment opportunity will always be non-negative, with *ROV* (B,I,t) ≥ 0 for all $0 \leq t < T$.

entry of a strong competitor: for example, the entry of Isis and PayPal might cause the profits of Google Wallet or Square experience a sudden decline. Another possibility is that the promulgation of government regulation may lead to a jump up or down in the value of an m-payment system investment. For example, in some countries, financial services firms and mobile network operators have to obtain m-payment services licenses from the government for the authority to operate their businesses. Still another possibility is an unexpected economic situation that may occur like a financial crisis. In advanced economies, financial crises dramatically alter the future value of growth opportunities for financial services firms, as some may exit in tough economic times. Other events are possible too.

When the related business environment experiences sudden changes, the payoffs associated with investments in m-payments can be modeled as a mixed Poisson-Wiener process. Merton [20] referred to this as a *jump diffusion process*. If $B(t)$ is the benefits flow representing value derived from an m-payment investment at time t and Y is a random variable, then the value of the investment at time $t + dt$ will be the random variable $B(t + dt) = B(t)Y$, $Y \geq 0$, given that a jump occurs between t and $(t + dt)$. We view the influence of an event that occurs after the m-payment system investment is made as a Poisson process with independently distributed value jumps. They will have the value of 0 with probability $1 - \lambda dt$, and the value of 1 with probability λdt, where λ as the mean number of jumps per unit of time – that is, the *value jump rate*.

The benefits flows derived from investing at time t including value jump diffusion therefore are given by $dB = (\alpha_B + \lambda k)Bdt + \sigma_B Bdz + (Y - 1)\ Bdq$ (Benefits Jump Diffusion), where $k \equiv E(Y - 1)$, dq and dz are independent, and $E(dzdq) = 0$. $(Y - 1)$ is a random variable for the percentage change in investment value if the jump event occurs. The jump diffusion process will be continuous most of time, and only a small percentage of jumps will be discontinuous. The value of the

investment is represented by the discounted benefits flows from when the investment decision is made up to the end of investment time horizon T, adjusted for the relevant costs.

It is important to note two points about the meaning of the Benefits Jump Diffusion Equation. First, the expected percentage rate of change in benefits B is not α_B, but instead is $\alpha_B + \lambda k$. Why? Because over each small interval of time dt there is some probability λdt that the benefits flow will change by $100(Y-1)\%$. Increases in λ will change the expected benefits flow by increasing the likelihood of a sudden change in B. Second, if a benefits jump event occurs infrequently, then most of the time the variance in dB/B over a short interval of time dt will be given by $\sigma_B^2 dt$, based on Brownian motion. When the benefits jump event does occur, there will be a very large change in value. This will contribute to the variance, given that the information that becomes available at time t cannot be neglected. This enables us to work with the adjusted variance of the benefits flows, $Var[dB] = \sigma_B^2 B^2 dt + \lambda(Y-1)^2 B^2 dt$ (Benefits Jump Adjusted Variance).[2]

This variance has two components. The first, $\sigma_B^2 B^2 dt$, is the instantaneous variance of the change in benefits dB, which comes from the Brownian part of the process, and is conditional on no jump occurring. The second term, $\lambda(Y-1)^2 B^2 dt$, accounts for the scenario of a jump occurrence.

To gauge the influence of changing the rate of change in the benefits flow (λ), we must know the expected value of T_B, the amount of time that B changes continuously before a jump occurs. The probability the first event happens in the short interval $(T_B, T_B + dT_B)$ is $e^{-\lambda T_B} \lambda dT_B$. This gives the expected time until the benefits take a Poisson jump: $E(T_B) = \int_0^\infty \lambda T_B e^{-\lambda T_B} dT = 1/\lambda$.

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[2] Using an approximation for Brownian motion with $\alpha_B = 0$, $dB = \sigma\sqrt{(dt)}$ with probability $.5(1 - \lambda dt)$, $-\sigma B\sqrt{(dt)}$ with probability $.5(1 - \lambda dt)$, and $(Y-1)B$ with probability λdt.

5. SIMULATIONS, VALUATION AND SENSITIVITY ANALYSIS

We next conduct numerical simulations and sensitivity analysis of the model. We assess a

bank's optimal investment timing strategy and best payoffs in the presence and absence of value

jump. We also apply the Monte Carlo and least-squares Monte Carlo methods to the continuous

stochastic and discontinuous jump processes. We first develop a benchmark case and then per-

form sensitivity analysis with respect to some of the key parameters of the model.

5.1 Simulation Setup and Sensitivity Analysis

To initiate the simulation, the decision-maker who is contemplating adopting m-payments

technology at the bank must know the following information. (Table 2 summarizes this.)

Table 2. Simulation parameters

PARAMETER	DESCRIPTION	VALUE
I_0	Initial investment cost	$10 million
$B_0(t)$	Initial benefit flow	$0.1-1 million
α_I	Rate of cost change	-0.1
α_B	Rate of benefit change	0.7
σ_I	Cost uncertainty	0.2
σ_B	Benefit uncertainty	1.0-0.1
T	Maximal deferral time	60 months
λ	Mean number of jumps	0.05
k	% change of benefits, B	0.5
$E(Y)$	Expectation of Y	1.5
r_f	Risk-free discount rate	6%
N	Number of simulated paths	100,000
Δt	Duration of each time increment	1 month

Simulation assumptions. For the simulation, the bank knows the current investment cost I_0

and the rate of cost change α_I. We assume $I_0 = \$10$ million and $\alpha_I = -0.1$. In addition, the invest-

ment cost uncertainty is $\sigma_I = 0.2$. The investment decision must be made during prior to the end

of the investment time horizon T. We assume $T = 60$ months (5 years), a reasonable length of

lifetime for m-payment technologies to be available. Once the investment decision is made at

time t, the first benefit flow received is $B_0(t)$, which increases linearly. We further assume that

$B_0(t)$ has a range of $0.1 to $1 million over the investment time horizon. The drift or change in

the benefits flow is $\alpha_B = 0.7$, and the uncertainty σ_B of this benefit flow will decrease linearly over time. In addition, the bank knows the discount rate affecting its waiting cost. We assume a risky discount rate of 12% and the risk-free discount rate $r_f = 6\%$, which gives a risk premium $\eta_B = 6\%$. The bank also believes that the mean number of jump events per unit time will be $\lambda = 0.05$; and the expectation of the percentage change in investment value if a jump event occurs is $k = 0.5$. Finally, the random variable $(Y - 1)$ follows a normal distribution $N(0.5, 1)$.

We used Matlab to code the simulation and run the numerical analysis. Based on the parameters we selected, we first simulated 100,000 sample paths for the state variables I and B.[3] Future profit at time t can be calculated by adding the discounted cash flows from t to T, and the value of m-payment investment project will be the present value of future profits minus the current investment cost at time t. In the Monte Carlo simulation, the goal is to compare the discounted present value of the payoff at each time and then determine the optimal investment time based on the simulated values associated with all of the paths that occur.

The result of the numerical solution for the benchmark case is shown in Figure 2. The bank should invest at optimal time $t^* = 14$ months (1.17 years), and it expects \$4.10 million from the investment. To get to a deeper understanding of the insights from the model, we perturbed some of the key parameters and analyzed their impact on the investment valuation and decision timing. Figure 3 shows what happens when the investment time horizon is shortened to 48 months (4 years) or extended to 72 months (6 years). (In all of the following figures, the solid line represents the benchmark case.) Our simulation results suggest that the bank should invest slightly later compared to the benchmark case, at $t = 15$ months (1.25 years), and the maximum payoff

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[3] We used a large number of samples to make sure that the average payoffs were close enough to the expected m-payment investment benefit flows, and the parameter values were chosen to represent a typical electronic payments network development project.

will decrease to $2.42 million when the investment time horizon is shortened to 48 months (4 years). In contrast, if the investment opportunity expires in 72 months (6 years), the bank should make the decision earlier, at $t = 13$ months (1.08 years), and the maximum payoff will increase to $5.70 million. So when there is more flexibility in decision-making period, the bank should bring the m-payments investment project forward so as to achieve highest payoff, and vice versa.

The drift parameter for the benefits flow α_B captures the rate of change from the time of investment to the expiration date. We varied α_B from the benchmark value 0.7 to 0.6 and 0.8 in Figure 4. When $\alpha_B = 0.8$, we found that the highest payoff for m-payments technology investment also increased from $4.10 to $6.53 million, and the best investment time shifted to an earlier date, $t = 11$ months (0.92 years). When $\alpha_B = 0.6$, the bank should initiate the m-payments investment project at a later date, $t = 18$ months (1.5 years), and the maximal payoff will be $2.60 million. Thus, when future benefits are expected to grow more rapidly, the bank should make the investment earlier to receive a higher total payoff from the investment.

To complete our illustration of the continuous-time diffusion process, we further examined the impact of the time value of money on valuation and investment timing by adjusting the risk-free discount rate. Figure 5 shows that when $r_f = 0.5$, the optimal investment time occurs at $t = 13$ months (1.08 years) with a maximum expected payoff of $7.27 million. When $r_f = 0.7$, the corresponding optimal investment timing is located at $t = 16$ months (1.33 years) with a maximum expected payoff of $2.23 million. Comparing it with the benchmark case, we conclude that when the time value of money is less, the bank will benefit from an earlier investment.

## 5.2. Jump Diffusion Simulation

We next simulated a discontinuous jump diffusion process. To examine the impact of a jump event and sudden changes in value, we first considered one jump occurring at different stages

and in different directions during the investment horizon.

Given a mean number of jumps per unit of time, λ, and the expectation and distribution of the random variable $(Y - 1)$, we randomly generated one jump event. In Figure 6, the solid line refers to the benchmark case: the continuous-time process without a jump. Recall that in this benchmark case, the optimal investment is at $t^* = 14$ months (1.17 years). The upper dashed line refers to a discontinuous process with an upward value jump occurring at time $t = 20$ months (1.67 years), and the random variable $(Y - 1) = 0.74$. The total payoff increases a lot, from \$4.10 to \$10.16 million. This is an example in which an upward jump happens after the optimal investment time t^* in the continuous-time process. The bank should invest at $t = 12$ months (1.00 year). This is like the benchmark case: extra benefits from the jump can be obtained afterwards. Because the expected percentage rate of change in benefits B increases in the Benefits Jump Diffusion Equation, the optimal timing is slightly earlier than for continuous-time process.

The lower dashed line refers to an example in which an unexpectedly very large jump happens before the optimal investment time in the continuous-time process. The jump occurs at time $t = 10$ months (0.83 years), and the random variable $(Y - 1) = -1.39$. Now the bank should invest at $t = 14$ months (1.17 years), exactly same as the benchmark case result, with a maximum expected payoff of \$4.63 million. Since we only consider the influence of a jump event that occurs after the m-payment system investment is made, the very large value jump will not affect investment timing. In sum, when an upward jump happens after t^* or an unexpected very large jump happens before t^*, the bank should time its investment similar to the continuous-time case.

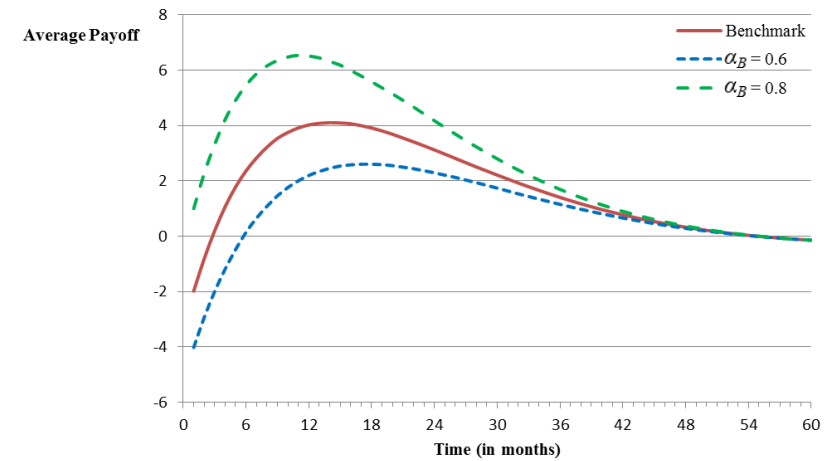**Figure 2. Investment timing benchmark simulation**
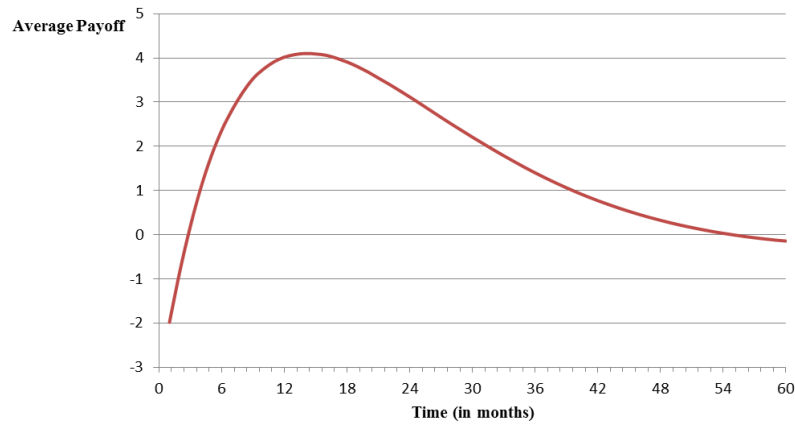
Optimal timing $t^* = 14$ months, then maximum payoff is $4.1 million.

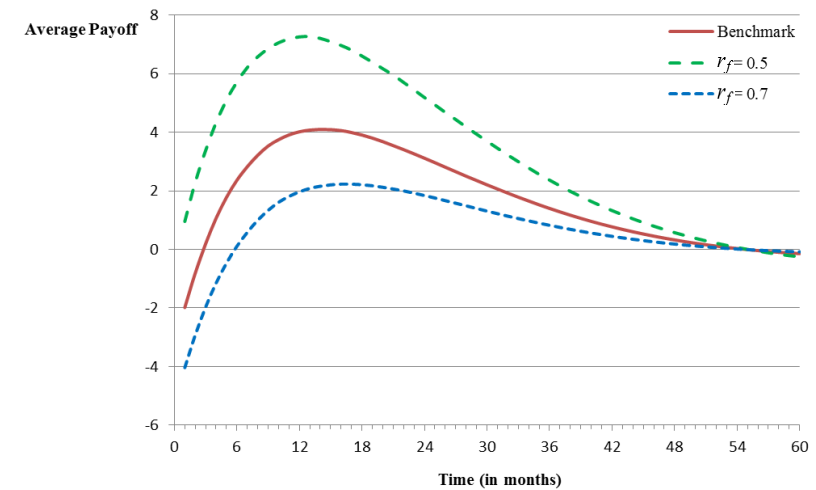**Figure 3. Optimal investment timing, $T = 4$ and $T = 6$ years**
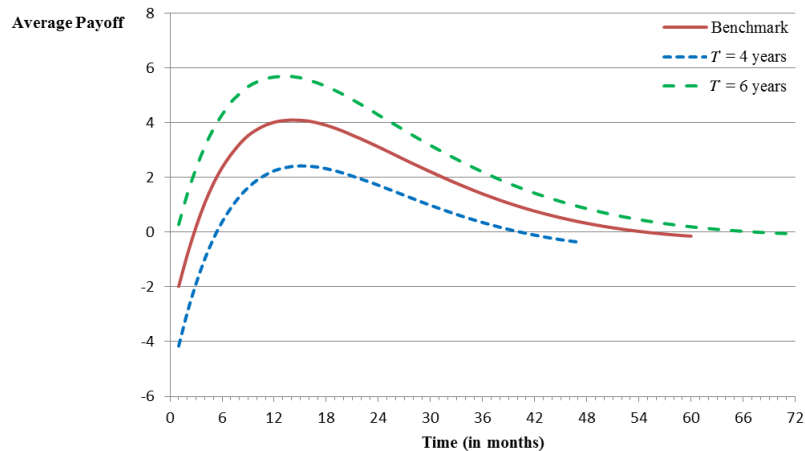
When $T = 4$ years, $t^* = 15$ months, maximum payoff is $2.42 million.
When $T = 6$ years, $t^* = 13$ months, maximum payoff is $5.70 million.

Figure 4. Optimal investment timing, $\alpha_B = 0.6$ and $\alpha_B = 0.8$

When $\alpha_B = 0.6$, $t^* = 18$ month, then maximum payoff is $2.60 million.
When $\alpha_B = 0.8$, $t^* = 11$ month, then maximum payoff is $6.53 million.

Figure 5. Optimal investment timing, $r_f = 0.5$ and $r_f = 0.7$

When $r_f = 0.5$, $t^* = 13$ months, then maximum payoff is $7.27 million.
When $r_f = 0.7$, $t^* = 16$ months, then maximum payoff is $2.23 million.

We further examined the cases in which upward jumps happen before or unexpected very large jumps occur after the optimal timing t^* in the continuous-time process. In Figure 7, the upper dashed line refers to an upward value jump event that occurred at $t = 10$ months (0.83 years), with the random jump in investment value of $(Y - 1) = 0.80$. The lower dashed line refers to an upward value jump that occurred at $t = 4$ months (0.33 years), with a random jump in investment value of $(Y - 1) = 0.34$. We observe that, when the value jump happens at $t = 10$ months, the bank should invest slightly earlier at $t = 9$ months to reap the extra benefits before the jump occurs. But the jump occurring at $t = 4$ months did not affect the continuous-time optimal timing, so the bank still should invest at $t = 14$ months. The total payoffs are \$11.42 million and \$4.65 million respectively, and both of them are higher than the benchmark case.

Similarly, in Figure 8, the upper dashed line refers to a very large value jump that occurred at $t = 20$ months (1.67 years), with the random jump in investment value of $(Y - 1) = -1.21$, while the lower dashed line refers to a very large unexpected jump that occurred at $t = 40$ months (3.33 years), with a random jump magnitude of $(Y - 1) = -0.68$. The event that occurred at $t = 20$ months (1.67 years) should make the bank shift its investment timing to a later time $t = 21$ months (1.75 years) to avoid possible loss. In contrast, the jump at 40 months does not change the optimal timing for investment largely and the bank should invest at $t = 15$ months (1.25 years). The related total payoffs are \$4.01 million and \$1.79 million, and both of them are lower than the benchmark case. In these two scenarios, the conclusion is that that the value jump time and magnitude will jointly influence on the best timing and maximum payoff for investment. (See Table 3.)

To explore the bivariate influence of value jump time and magnitude on the optimal investment timing, we made the random jump magnitude discrete. At each time step before $t^* = 14$, we

continuously increased the value jump magnitude by 1%. Similarly, at each time step after $t^* = 14$, we decreased the value jump magnitude by 1%. Figure 9 indicates three value jump regions based on the relationship between the value jump time (t) and the value jump magnitude ($Y - 1$), given the benchmark case optimal time t^*. When the value jump falls in the *Unchanged Region* (an unexpected downward value jump before t^* or an upward value jump after t^*), it cannot influence the continuous-time result, as we demonstrated. At a higher value jump magnitude, when the jump happens in the *Jump Diffusion Region* (an upward value jump happens before t^* or an unexpected downward value jump happens after t^*), it shifts the continuous-time optimal time to before or after the value jump time. When this is the case, the bank should invest sooner to reap extra benefits or defer the decision-making to avoid possible losses.

Table 3. Simulation results

SIMULATION	TIME (t)	Y	OPTIMAL TIME (t)	MAX PAYOFF
Benchmarking			14	$4.10 million
$T = 48$ months			15	$2.42 million
$T = 72$ months			13	$5.70 million
$\alpha_B = 0.6$			18	$2.60 million
$\alpha_B = 0.8$			11	$6.53 million
$r_f = 0.5$			13	$7.27 million
$r_f = 0.7$			16	$2.23 million
Value jump ↑	4	1.34	14	$4.65 million
Value jump ↑	10	1.80	9	$11.42 million
Value jump ↑	20	1.74	12	$10.16 million
Value jump ↓	10	-0.39	14	$4.63 million
Value jump ↓	20	-0.21	21	$4.01 million
Value jump ↓	40	0.32	15	$1.79 million

Note: The unit for time and optimal time is months. This table summarizes our numerical results for the benchmark case, sensitivity analysis for some key parameters, and one value jump that occurs at different times t and in different directions, ↑ or ↓.

**Figure 6. Upward jump at *t* = 20, unexpected large jump at *t* = 10**
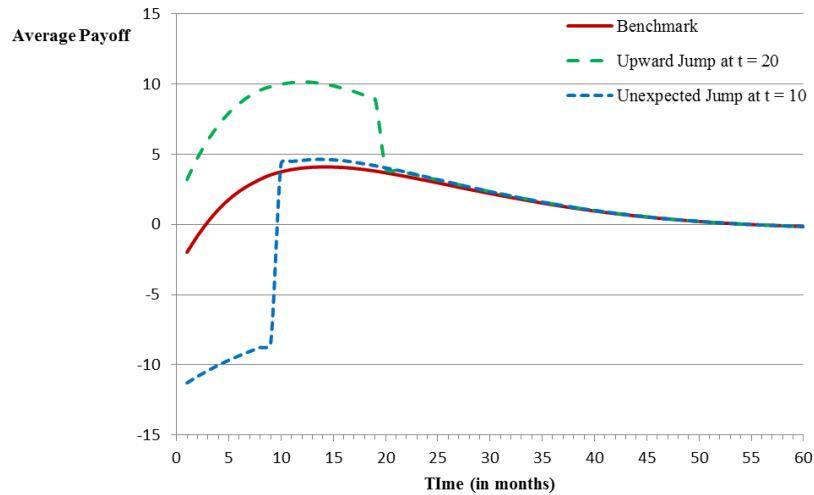
When an upward jump occurs at *t* = 20 months and *Y* =1.74, optimal timing t^* = 12; when an unexpected jump occurs at *t* = 10 months and *Y* = -0.39, then t^* = 14.
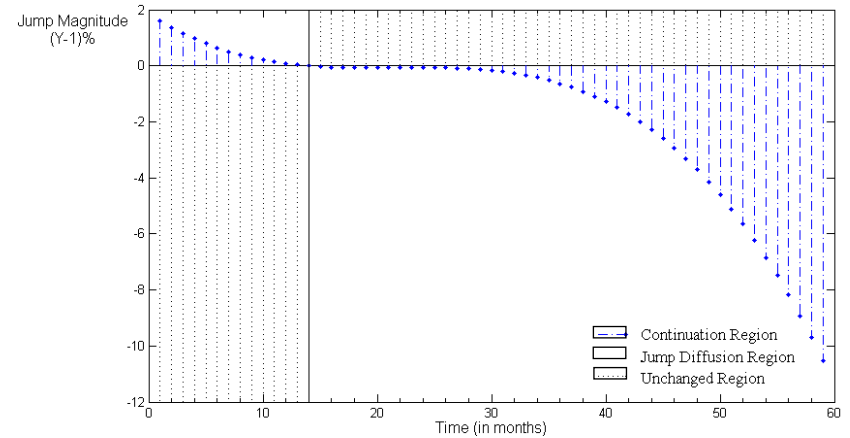
Figure 7. Upward jump at *t* = 4 and *t* = 10
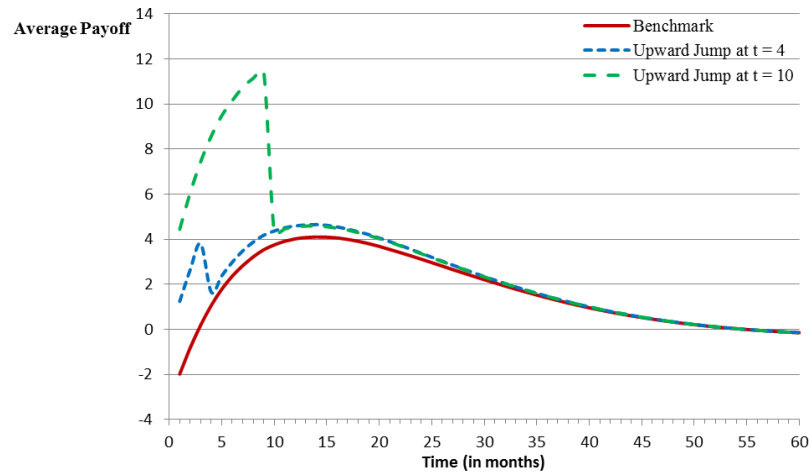
For an upward jump at *t* =10 month and *Y* =1.80, the optimal timing is t^* = 9; for an upward jump at *t* = 4 months and *Y* = 1.34, t^* = 14.

Figure 8. Unexpected large jumps at *t* = 20 and *t* = 40
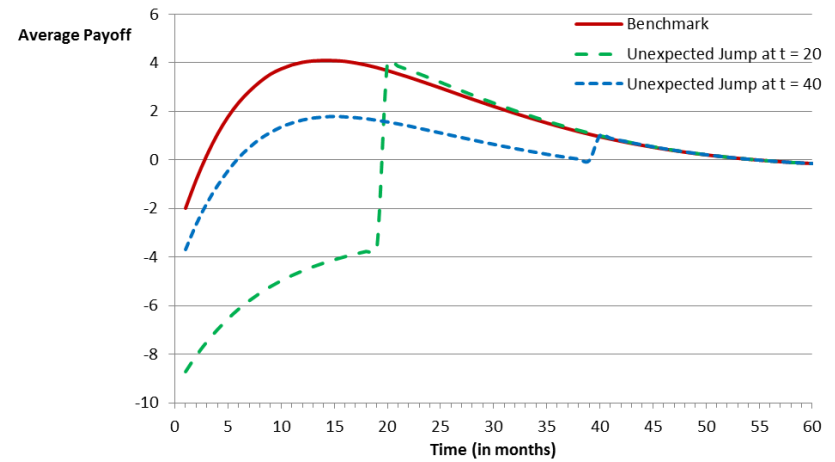
For an unexpected jump at *t* =20 months and *Y* = -0.21, t^*=21; for an unexpected jump at *t* = 40 months and *Y* =0.32, optimal timing t^* = 15.

Figure 9. Continuation, jump diffusion and unchanged regions

Continuation region: at a lower jump magnitude, an upward jump before t^* or an unexpected jump after t^*; jump diffusion region: at a higher jump magnitude, an upward value jump before t^* or an unexpected jump after t^*; unchanged region: an unexpected jump before t^* or an upward jump after t^*.

With a lower value jump magnitude, the upward jump occurring before t^* or an unexpected downward value jump occurring after t^* in the *Continuation Region* will not affect the continuous-time optimal timing. For lower values of $|Y - 1|$, the bank should process information about market shocks that affect firm and market-level perceptions associated with IT investments as endogenous stationary risks. This implies that a decision-maker may exercise the investment option at an earlier stage when a surge of benefits related to an upward value jump event is sufficiently high. At a later stage, only when the bank forecasts that a major event is in the offing will there be an incentive to keep the investment opportunity open for a longer period of time.

5.3. Least-Squares Monte Carlo Valuation

The real option framework applies traditional option pricing method with the Black-Scholes-Merton model to deal with IT investments under uncertainty [5]. The difficulty in applying this model is that there is no obvious and objective value for the underlying project: the option value based on the Black-Scholes-Merton model does not include a trend term in its solution. Moreover, there is an over-valuation problem associated with the application of the Black-Scholes-Merton model [3]. Over the years, another approach involving a *twin security* that mimics the discounted cash flow value of the underlying asset has been advocated to estimate the volatility of its value. The idea is that, in order to obtain a good substitute for the objective value of a project, it is appropriate to replicate the characteristics of a non-traded IT investment with something that is traded. An alternative way to do this is to construct a replicating portfolio of traded securities whose value and volatility also approximate those of the underlying asset.[4]

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[4] This perspective has been best articulated by Robert Merton [22, p. 326], in the 1998 *American Economic Review* article on the occasion of his December 1997 receipt of the Alfred Nobel Memorial Prize in Economic Sciences: "My principal contribution to the Black-Scholes option-pricing theory was to show that the dynamic trading strategy prescribed by Black and Scholes to offset the risk exposure of an option would provide a perfect hedge in the limit of continuous trading. That is, if one could trade continuously without cost, then following their dynamic trading

The simulation-based least-squares Monte Carlo method enables us to estimate the volatility of the project's value, as well as to approximate the option value of the investment opportunity. This also allows us to estimate the optimal stopping rule for the investment option. If the value of investing in m-payments for the next period (the next month in our case) is greater than the value of investing for the current period, then the bank should defer investing; otherwise, it should execute its m-payments technology investment project immediately. Similarly, the least-squares approach also can be applied using a more complex jump-diffusion process. For what follows, we continue to use most of the benchmark simulation parameter values from Table 2. (See Appendix B for our numerical solution procedure.)

The results of our numerical valuation are 0.52 for the case when there is no possibility of a value jump $\lambda = 0$, and 0.35 when a value jump can occur with the probability $\lambda = 0.05$, given $k = 0$. Thus the value of the m-payments opportunities is lower when there is a possibility of a value jump, holding fixed the expectation that the value jump magnitude will be 0 across the different cases. This means that if a jump does not occur, then the investment opportunity will be less likely to be deep in the money and thus, the investment option will be not worthwhile to exercise when $\lambda = 0.05$. In the presence of the occurrence of an upward jump in value, the m-payments investment will be much more valuable than it would have been otherwise. Our results further imply that a gain to the bank from upward movement in the value of the investment still may not offset the overall effects of value jumps over time [15]. So a bank will have less incentive to keep the investment opportunity open and may wish to adopt a more aggressive posture with an

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strategy using the underlying traded asset and the riskless asset would exactly replicate the payoffs on the option. Thus, in a continuous-trading financial environment, the option price must satisfy the Black-Scholes formula or else there would be an opportunity for arbitrage profits." This is a useful perspective since it means that whether one uses a twin security or an equivalent portfolio of market-traded securities, the result will be the same: the characteristics of a non-securitized asset can be represented well enough and in a manner that is similar to what happens with real markets for assets that are thinly traded or lack liquidity [2].

early investment strategy. Our simulation bears out this intuition. For $\lambda = 0.05$, the value of the investment opportunity is 0.72 for $k = 0.5$, which is higher than the cases in which $k = 0$ and $k = -0.5$, where the respective values are 0.35 and 0.16.

6. DISCUSION AND MANAGERIAL IMPLICATIONS

While the future configuration of the payments landscape cannot be predicted with certainty, the customer base and traditional payments systems revenue model are under stress and have been severely impacted due to ongoing and fundamental technological changes. Unless the banks focus on m-payments innovations, they may lose additional core customers and revenues, as new players exploit the opportunities through emerging technologies that are driving digital convergence and the participation of entirely new kinds of stakeholders. The success of m-payment systems technologies rely on joint participation from multiple stakeholders, including consumers, merchants, network operators, device manufacturers, financial services, and software and technology providers. Success also depends on some exogenous factors, such as the nature of government regulation, future technology innovation, and changes in the costs of technology. As a result, a bank's senior managers face various uncertainties and, as a result, still find it difficult to decide whether and when to adopt a specific m-payments technology. To help them make more effective investment timing decisions, we proposed a continuous-time stochastic model for decision-making under uncertainty. We now will offer a number of additional recommendations to the senior managers.

- **Recommendation #1 (Take Advantage of Payoff-Relevant Information Revelation for Emerging Technology Investments).** *A bank's senior managers should develop appropriate expectations about future trends regarding technology standards and market conditions, as well as the volatility of investment costs and benefits, as information is revealed over time.*

We used a stochastic process to simulate cost and benefit changes over time. It allows the

value of the investment opportunity to change continuously as new information arrives. This is not typical with multi-stage discrete-time models. This raises the issue of rational expectations. Senior managers may not be able to assemble the information they need for decision-making all at once. There are costs and frictions associated with sorting out what information is meaningful and action-relevant. In our multiple-stakeholder setting, information processing is difficult because bank managers will act based on interactions with other stakeholders in the m-payments ecosystem. Their information processing is complicated, which may lead to inappropriate expectations and cause their action to be different from the investment strategy of the model.

Another important managerial consideration is that a bank possibly should invest in m-payment systems technology at an early stage to gain first-mover advantage. Once a specific m-payment technology is successfully developed and adopted, it is likely to achieve strong network effects (as we have seen in the past couple years with Square's add-on device to make payment cards swipable via a mobile phone). The first-mover will be rewarded with high payoffs from developing the network. However, first-mover advantage will inevitably decrease, and may even eliminate the flexibility that a bank may benefit from in dealing with uncertainty. Moreover, strong network effects tend to drive decision-makers toward making investment decisions earlier. Thus, the combination of first-mover advantage and strong network effects may hasten senior managers' decision-making process and lead to pre-emptive investment strategies that run the risk of an unexpected large value jump occurring that may be disadvantageous.

- **Recommendation #2 (Support Standardization and Subsidy Strategies for New Technology Investments).** *A bank that acts as an early adopter should subsidize the customer-side and merchant-side adoption of m-payments to achieve network effects and more rapid growth, as well as adopt a de facto standard that has achieved critical mass to gain investment returns over a longer time horizon.*

Our model is applicable to m-payment systems technology investments subject to strong network effects. Bank decision-makers must process information related to interactions with oth-

er stakeholders in the marketplace also. For example, when there are more consumers who are willing to use this new technology, more merchants will accept and provide m-payment devices. As a result, the bank will also value this m-payment technology more, and hence is more likely to invest in developing network infrastructure for it. This, in turn, will make m-payments more valuable to consumers and merchants. In other words, positive cross-network effects will arise in this business platform, which are captured by the high volatility of profits and the positive drift parameter of the benefits flows in our model. A forward-looking technology sponsor can implement a subsidy strategy early on to enhance customer-side and merchant-side network size to achieve stronger network effects and more rapid growth. This also may help the technology standard that is being promoted to achieve critical mass, which will also enable the bank to gain substantial business value from m-payments in the long run.

- **Recommendation #3 (Create the Capabilities to Predict Jump Diffusion in Investment Value for Technological Innovations).** *A bank's senior managers should aim to identify unexpected jump events that may cause sudden changes in the investment value of m-payments systems, and understand the potential impact on the appropriate investment timing in light of changes in the potential payoffs.*

We used a discontinuous jump process to model large movements and radical changes that may occur in investment value. This approach allows a bank's managers to consider unexpected exogenous shocks in the environment, such as the entry of a new competitor into the existing market, unexpected economic developments, or sudden changes in government regulations. Our analysis of the value jump process provides bank decision-makers with guidance on how to respond to uncontrollable exogenous shocks. For example, when some kind of a "black swan" event happens that dramatically reduces the value of the investment, the bank may wish to defer the investment opportunity to avoid possible loss. We saw this happen in another area of financial IS and technology in December 2009, when the U.S. Senate held hearings to address how to adjust the regulatory process in the financial markets in light of then-recent developments in al-

gorithmic and high-frequency trading. An analogous development occurred in the m-payments arena in March and July 2012, when the Senate held a different set of hearings on how to develop a framework for safe and efficient m-payments. The payments industry in the U.S. is heavily regulated, so many banks have been cautious about their entry into the market for m-payments services, and have adopted a wait-and-see strategy.

In contrast, if the value of the investment is expected to experience a significant upward value jump at an early stage, our analysis will recommend making the investment decision earlier so that the bank can reap extra benefits likely to be brought on by the positive jump. In the presence of strong positive network effects within an m-payments system, the participation decisions of key stakeholders, such as large card and merchant associations or other banks, will enhance the installed base of firms and lift the expected consumer transaction volume in a short period of time. The actions of these key stakeholders will create new network effects and reduce uncertainty market-wide about the outcome of competition among different technology standards. Since the bank will have less incentive to retain the option of making an investment because of the expected value jumps, when a technology has the possibility to become standard in the marketplace and strong network effects exist, senior executives will be more willing to accelerate their investments to harvest value amid the more rapid growth of m-payments market.

7. CONCLUSION

Our contributions are threefold. First, we propose a new modeling perspective at the firm level to enrich managerial knowledge on how financial economics theory can be used to support decision-making under uncertainty for m-payments and other IT investments. Second, we offer practical advice and recommendations to senior managers in banks by helping them assess investment timing and the business value of m-payment investments. Our numerical analysis pro-

vides useful observations for the applied context. We show that, when the benefits are expected to flow over a longer time horizon or at an accelerating rate, the bank will have more managerial flexibility and should invest earlier to receive higher total payoffs from the investment.

Third, our work also demonstrates the usefulness of a mixed Poisson-Wiener process in modeling the dynamically changing value of an underlying investment in m-payments systems infrastructure. Our numerical results show that, when the market experiences shocks that affect firm-level and market-level perceptions associated with technology investments at different stages of development, a bank should consider adopting different investment strategies to achieve high payoffs. We also show the applicability of option valuation, the Longstaff-Schwartz least-squares Monte Carlo valuation method, to value m-payments and other kinds of IT investments.

A number of limitations deserve comment. The advantages of being a first-mover are not considered in the current model. Also, we have assumed that the bank can immediately implement an m-payment solution once it makes the investment decision. This assumption makes it possible for benefits to flow without any uncertainty about a lag in the formation of business value. The reality is different, of course: a bank will need some period of time, which will be of uncertain length, to develop the necessary infrastructure. So the business value from investing will be obtained only some time later. In the investment process, the time at which the benefits flows start to be received is also a random variable, and the benefits flows that will be obtained during the development process will be relatively small. By assuming an appropriate amount of time for the installation of the infrastructure and the start-up of the benefits flows, our model can be adapted for application in a variety of settings. Excluding these factors may result in a loss of contextual richness. By limiting the number of factors that we considered though, we traded off complexity to achieve tractability. Finally, it will be beneficial to further validate the results of

this research when m-payment systems are mature enough to offer successful cases of investment and implementation that can be empirically assessed.

Financial institutions have been cautious entrants into the m-payments market space, leaving the door open for a leader to emerge and gain significant first-mover advantage. An interesting direction for future research is to address the issue of investment timing in a competitive setting. This will only be valuable if we can discover aspects of the m-payments systems technology investment process that are truly unique in the industry setting, since so much research has already been done on investment timing with competition. For example, for new technologies, we often see firms that are able to leapfrog the competition and adopt previously unavailable systems, which probably would invalidate the assumptions of most standard game-theoretic approaches.

In addition, blended models involving wait-and-see game-theoretic interactions between competitors and information updates that occur over time to motivate options-based evaluation, contextualized in a well-defined multi-stakeholder technology services platform are worthwhile to explore for building additional theory. A key observation about bank-led innovations in electronic payments over the years is that *coopetition* [6], rather than direct firm-to-firm competition, offers the best description of how firms actually have interacted in the industry. Market leaders become most successful when they create value by supporting the participation of other potential competitors [28]. Such firms act as *value-makers* in the larger market – for themselves, customers and competitors; and they also may be able to become successful *value-takers* as a result [15]. This will require them to find ways to appropriate value from their innovations though [27].

With slowly evolving consumer needs and the available revenue pools from e-payment likely to remain unchanged among large financial services firms that are already heavily invested in such services, value creation will be at the heart of profitability, not first-mover advantage. Our

view is that value creation and value management in the m-payments systems and technology

solution space will play out with a blend of competition, cooperation, innovation and surprise.

One great hope in this area is that m-payments will unlock hitherto unforeseen demand for elec-

tronic payment services, by decontextualizing the settings in which payments are made to sup-

port the exchange of economic value. For this to happen, consumers will need to become much

less dependent on the use of cash in all of the places they pay for things on a daily basis.

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APPENDIX A. Table A1. Modeling Notation and Definitions

MATH	DEFINITION	COMMENTS
V, B	Investment, benefits at time t	PV of future benefits flows B, that fluctuate over time
I, ROV	Bank's investment I, real option value	For m-payment technology, for the deferral option
α_B, α_I	Benefit (+), investment (-) drift	Subject to Brownian motion
σ_B, σ_I	Standard deviation of B, I	Affects volatility of benefits, investment costs
η_B, η_I	Risk premia on B, I	Due to benefits and investment uncertainties
ρ_{BI}	Correlation of B and I	$\rho_{BI} = 0$, equates with uncorrelated cost-benefit
r_f	Risk-free discount rate	Discounts future benefits and costs
dz	Wiener increment	Defines standard Brownian motion
t, T	Time; maximum deferral time, or # periods in which cash flows occur	dt is a small increment in time; bounds option's exercise time; cash flows can be benefits or costs for bank
λ	Mean # of jumps per unit of time	In dt, probability that a jump will occur is λdt
k	Change % for benefit flows, B	Due to a jump, with $k \equiv E(Y - 1)$
Y	Δ value, random variable	Measures after-shock change in value
$q(t)$	Shock-led value jump process	Changes in value q are given by dq

APPENDIX B. NUMERIAL SOLUTION PROCEDURE

One important problem in option pricing theory is the valuation and optimal exercise of derivatives with American-style exercise features. In the management of IT investment risk, these types of real options also can be found. When more than one factor affects the value of the option, valuation and optimal exercise of American option is an especially challenging problem. The Longstaff-Schwartz method [16] provides a simple, yet powerful simulation approach to approximating the value of American options. The method is readily applied when the option value depends on multiple factors. Simulation also allows state variables to follow general stochastic processes, such as a jump diffusion process [20].

At the final exercise date, the optimal exercise strategy for an American-style option is to exercise the option if it is in the money. Prior to the final date, however, the optimal strategy is to compare the immediate exercise value with the expected cash flows from continuing, and then exercise if immediate exercise is more valuable. Thus, the key to optimally exercise an American option is identifying the *conditional expected value of continuation*. A central part of the Longstaff-Schwartz method is the approximation of a set of conditional expectation functions, so it is appropriate to use the cross-sectional information in the simulated paths to identify the conditional expectation functions.

We solve the model by applying a variation of the Longstaff-Schwartz method to approximate the value of all future benefits flows at each date, given the current value of the two governing state variables, I and B. This involved first simulating 100,000 sample paths for the two state variables. We regressed the subsequent projected benefits flows from continuation on a set of functions of the values of the relevant state variables. The fitted values of this regression are efficient unbiased estimates of the conditional expectation function. The regression coefficients are used to approximate the expected value of continuation. We also used another procedure to compare the execution value and continuation value at each date to determine the optimal stopping rule. The optimal stopping rule estimated by the conditional expectation regressions from one set of paths should lead to out-of-sample values that closely approximate the in-sample values for the investment option [26].

Then we compared the value of the m-payment investment project for the case where there is no possibility of a jump, $\lambda = 0$, and when a jump may occur with the probability of $\lambda = 0.05$. In the Benefits Jump Variance Equation, when λ increases, the conditional variance of the future benefits flow increases. We adjusted the parameter values of the means and variances for the two cases to give a more meaningful comparison. Because of the martingale restriction implied by the risk-neutral framework, the means for the two cases will be the same. We assumed that σ_B is linearly decreasing in the interval [0.1, 1]. So when $\lambda = 0$, σ_B^2 also will be decreasing in [0.01, 1] for $t \in [0, T]$. Similarly, when $\lambda = 0.05$, σ_B^2 is decreasing in the interval [0.0225, 1.0125] for $t \in [0, T]$.