1-2013

Technology Investment Decision-Making under Uncertainty: The Case of Mobile Payment Systems

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2013 46th Hawaii International Conference on System Sciences
https://doi.ieeecomputersociety.org/10.1109/HICSS.2013.624

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Abstract

The recent launch of Google Wallet has brought the issue of technology solutions in mobile payments (m-payments) to the forefront. In deciding whether and when to adopt m-payments, senior managers in banks are concerned about uncertainties regarding future market conditions, technology standards, and consumer and merchant responses, especially their willingness to adopt. This study applies economic theory and modeling for decision-making under uncertainty to bank investments in m-payment systems technology. We assess the projected benefits and costs of investment as a continuous-time stochastic process to determine optimal investment timing. We find that the value of waiting to adopt jumps when the related business environment experiences relevant shocks. Also, when the rate of benefit flows, the time horizon for decision-making, and the time value of money change, the recommended investment timing and optimal investment value will change too. We also consider how network effects influence decision-making for this IT investment context.

Keywords: Decision-making, economics, investment, mobile payments, network effects, stochastic processes.

1. Introduction

Mobile payments (m-payments) involve a mobile device used to initiate, authorize and confirm an exchange of financial value for goods and services. As the global smartphone market has rapidly grown, we have observed enormous interest in m-payments.

1.1. Background

Technologies. Google Wallet (www.google.com/wallet) is using near-field communication (NFC) technology (www.nfc-forum.org/aboutnfc) to provide a real "tap and go" m-payment solution. It was launched in 2011 in the United States. Its biggest competitor, Isis (www.paywithisis.com), arising from a joint venture involving Verizon, AT&T and T-Mobile, announced the launch of an NFC application in summer 2012. Meanwhile, PayPal (www.personal.paypal.com) announced that fifteen new retailers in the U.S. will bring innovation and flexibility for PayPal's offline payment and mobile shopping solutions. Apple, in March 2012, was also awarded a patent for iWallet by the U.S. Patent and Trademark Office.

The potential profits from implementing mobile payments in the marketplace are huge. Calamia [11] predicted that investments in mobile payment systems using NFC should reach US$670 billion by 2015. With the global adoption of smartphones, there are increasing numbers of mobile handsets with NFC connection capabilities that have been released by their manufacturers, such as the Nexus S by Samsung. There are also other innovative schemes which take advantage of third-party applications on various smartphone platforms to process payments. Square (www.squareup.com), 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. Ludwig [24] reported that more than one million merchants are now using Square's card reader to accept payments.

Stakeholders. Au and Kauffman [4] discussed key stakeholders in m-payment systems. They include consumers, merchants, mobile network operators, mobile device manufacturers, financial service firms, software and technology providers (and information security solution vendors) and government agencies. To achieve success with m-payments, all these stakeholders need to participate and cooperate in a cross-industry alliance to establish a set of common operational, process and technology standards. When they invest to adopt m-payment technology, the stakeholders face technological risks and various economic uncertainties, including unexpected market condition changes, consumer adoption, merchant responses, standards and regulation risks, and so on.

For example, fraud typically constitutes most of the transaction-related financial losses associated with e-payment technologies (e.g., credit cards, debit cards, Internet banking, etc.). It affects stakeholder beliefs about the likely benefits and costs associated with m-payments. It also gives rise to understandable concerns about whether any specific underlying technological solution is better in defending against undesirable financial losses. A recent example in the press is that Google Wallet is vulnerable to malicious hackers, who can gain access to the secure PIN numbers of its users [13]. This makes consumer credit card information vulnerable to attack and hijack. In addition, the lack of retail locations and relatively fewer NFC-capable mobile phones supporting m-payment processes are also hurdles to the wide adoption of m-payment on consumers' side. Some observers argue that the technology is a step backward when it comes to point-of-sale (POS) transaction support, because NFC-based m-payments require users to visit terminals for cash.

M-payment uncertainties. 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. Meanwhile, consumers are reluctant to share personal financial information due to security concerns; and they tend to ignore the vulnerability of their own information when there is a bandwagon for adoption that forms since they don't process all of the relevant information very well.

For merchants, they are expected to accept m-payments in return for goods sold and services renders. 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, changed transaction costs, and security problems. Banks may not be able to estimate the beneficial network effects that will accrue in the longer run, and so lack strong incentives to adopt the new technology.

Research question. We study a bank's m-payment adoption decision when facing endogenous technological risks and exogenous dynamic market conditions. Rather than proposing a standard business model or optimal revenue-sharing scheme for m-payment systems, one bank acts as a decision-maker who faces technological risks, volatile market conditions, and uncertain actions of other stakeholders in the m-payment system. The dynamic environment of the m-payment market faced by the bank is modeled using a general stochastic process with jump events.

With the uncertainties associated with investments in m-payments technologies in mind, effective strategic managerial decision-making requires a bank's managers to understand a number of key issues. (1) How can it maximize the business value of m-payments technology adoption under uncertainty? (2) How long can investment and commitment to a specific technological solution be postponed, up to the end of some maximal period of deferral? (3) How do adoptions 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? And, (4) how should we model and analyze changing managerial sentiments in light of decision-relevant information that is revealed over time?

1.2. Relevant Theoretical Perspectives

Decision-making under uncertainty. We view m-payment system investment as a process of managing the balance between value and risk. In our model, the benefits and costs of m-payment investment follow a continuous-time stochastic process. A bank has the flexibility of choosing an optimal time to invest based on the financial economics of decision-making under uncertainty [12]. We will examine optimal investment timing and identify key elements related to the decision-making process about it.

Real option methods. Information technology (IT) investment risk can be evaluated using a family of financial risk management methods. Benaroch [6] identified various IT investment options, including deferral, staging, exploration, scale alternation, outsourcing, abandonment, leasing, compound, and strategic growth options, that are relevant. Grenadier and Weiss [18] 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. Benaroch and Kauffman [8, 9] analyzed electronic banking network expansion, and suggested ways to overcome some of the methodological difficulties associated with realistic models for decision-making under uncertainty to enhance the prospects for senior management application. Banker et al. [5] examined Black-Scholes valuation in IT projects and showed that the restrictive assumptions may result in overvaluation. Fichman [16] argued that, when uncertainty and irreversibility are high, real option analysis should be used to structure the evaluation and management of project investment opportunities. Benaroch et al. [7, 10] proposed option-based risk management and pushed these ideas further. M-payments infrastructure investment enables a bank to make follow-on investment in other projects. The uncertainties make m-payment investment a risky project, and a bank may decide to abandon or defer the investment. Following these previous works, we use real option methods to model financial risks of m-payment system investment.

Investment timing. Investing in m-payment technology is an irreversible decision. Following McDonald and Siegel [25] and Farzin et al. [15], we study the optimal timing of m-payment investment when benefits and investment costs follow a continuous-time stochastic process. Uncertainties about future benefits and development costs cause them to fluctuate over time. Technologies become more valuable over time, while investment costs fall. IT investments often have high-upside potential, high uncertainty and indirect returns, which make them good candidates for being evaluated with decision-making under uncertainty methods [23].

Schwartz and Zozaya-Gorostiza [28] contributed a cost-benefit diffusion methodology for different kinds of IT investment decision-making, when the investment costs and benefits are subject to change over time. Kauffman and Li [21] modeled investment timing strategy for a firm that must decide whether to adopt one of two incompatible technologies, in the light of evolving expectations about future competition. Our modeling approach builds directly on these methods. We contribute new knowledge about how to support bank senior managers' decisions about m-payment technology investments.

Network effects. Our work also builds upon on the network externality literature. Katz and Shapiro [20] showed that consumers value a product more when it is compatible with other consumer choices. This is known as *network effects* [14]. Kauffman and Wang [22] showed that a consumer's utility from an e-payment system also depends on how many other consumers are using it. Milne [27] observed that some new payment mechanisms have been developed for the purpose of achieving high network effects. When more consumers use m-payment, more merchants will be willing to adopt this approach. As a result, the value of m-payment investment from a bank's view will be higher too. Such positive network effect affects multiple stakeholders simultaneously, constituting a positive driving force for m-payment adoption.

2. The M-Payment Market

A number of new technology solutions for m-payments emerged after 2011. 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 where the payment credentials are stored on a secure file server. Cloud-based solutions, such as PayPal, reduce customer security concerns, and also take advantage of the existing online payment platform to achieve network effects and interoperability.

Adoption constraints. Adoption of mobile payment systems is constrained by the extent of infrastructure availability [19]. Vision Mobile (www.visionmobile.com), a new 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 [31]. 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 under the right conditions. (See Table 1.)

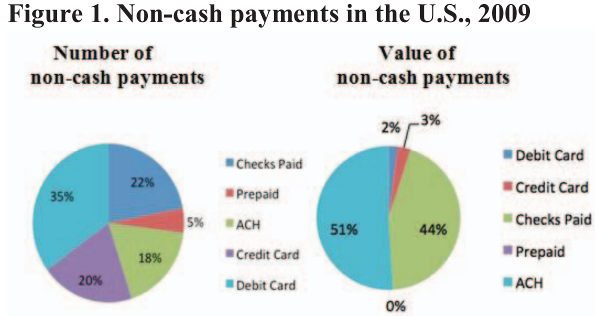
Table 1. Mobile subscribers and smartphone penetration rate ranked by country, 2011

Rank	Country	Pop.	Subscribers	Smartphones	Migration	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%
33	JPN	126.9	126.8	18.1	14%	14%
41	CHN	1360.0	963.1	77.1	8%	6%

Notes: Data are from TomiAhonen Consulting Analysis December 2011, based on raw data from Google/Ipsos, the Netsize Guide/Informa, and TomiAhonen Almanac 2011 Countries are rank-ordered by smartphone penetration rate. All figures are per capita. [1]

The country-level installed base of electronic payment capabilities is also an important factor influencing the diffusion and adoption level of m-payments. The penetration of various kinds of cards matches smartphone penetration in some countries, including Singapore, Japan, the U.S. and Western Europe. 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, according to a 2010 Federal Reserve study [17]. Figure 1 describes the number and value of non-cash payments in 2009 in the U.S.

Figure 1. Non-cash payments in the U.S., 2009



These facts suggest the large potential benefits of m-payment adoption. First, using an encrypted contactless mobile platform or secure cloud server will help to minimize fraud. Second, merchants become more cost efficient by processing mobile payment transactions. They are more secure than traditional card transactions due to the use of dynamic data versus static magnetic card data. Plus, the m-payment method also helps to reduce potential costs associated with payment card industry security standards compliance (www.pcisecuritystandards.org). Third, consumers have convenience and enjoy additional benefits by using m-payments, because mobile devices can easily incorporate multiple payment methods, loyalty cards, virtual coupons, and customized discounts. Finally, the ability to use a mobile phone allows financial services to be offered to people who don't have bank account, and others who may benefit from more financial services.

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 lose future profits from m-payments and their central role in handling customer account relationships.

3. Decision Model

We present a continuous time model to support a bank's m-payment system technology investment decision-making process. The bank is risk-neutral and faces uncertain investment cost and benefit flows. We include a jump process to capture the possibility that a sudden event may occur during the diffusion process that creates a shock with respect to the value flows.

3.1. The Model

The bank can decide whether and when to invest I dollars to set up m-payment system infrastructure, such as an embedded-NFC POS service network. (See Table A1 in the Appendix, which summarizes our modeling notation.) The investment decision is irreversible because it will be hard for the bank to unwind payments to contractors or employees. We further assume that that once the investment decision is made, the system will be installed and function immediately.

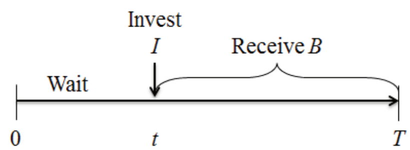
Technology innovations happen fast. Without loss of generality, we consider a finite time period [0, T] for investment. The benefit flows from investing in the m-payment system infrastructure occur only within this period; after that, the investment opportunity expires. The bank can invest at any point in time up to T, the maximum length of the deferral period. The current value of I is used as a forecast of related future investment benefits and costs. Considering uncertainty of investment costs, we assume that I exhibits geometric Brownian motion of the form:

$$dI = \alpha_I I dt + \sigma_I I dz \tag{1}$$

where dz is a standard Wiener process, α_I is a drift parameter describing the trend of cost change, and σ_I is the standard deviation affecting the volatility of I. We further assume that the drift parameter of the investment cost is negative, $\alpha_I < 0$, since the investment cost tends to decrease continuously over time, due to technological progress or the increased scale of the m-payment infrastructure.

After an investment is made, the bank will receive benefit flows until time T. (See Figure 2.)

Figure 2. Investment timeline



Let B denote the benefit flow arising from the m-payment investment. It follows a stochastic process:

$$dB = \alpha_B B dt + \sigma_B B dz, \tag{2}$$

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 benefit flows will be resolved. For example, as time goes by, when an increasing number of NFC-enabled smartphones are introduced or a standard business model for m-payment is formulated, the uncertainty of benefits from investing in m-payment will fall. Also, the initial cash flow $B_0(t)$ from investing will increase over time due to the larger installed base and increasing consumer demand.

The positive network effect should be associated with a positive value of the drift parameter for cash flow increases during the lifetime of the investment, so $\alpha_B > 0$. As more consumers and merchants use and support m-payments, the benefit flows will be higher. This positive drift parameter captures the trend in the value of the network based on the growth of user base. Another important assumption is that no other competitors that offer a similar m-payment mechanism will enter the market during the period of possible deferral. We further assume there is no correlation between the stochastic changes in the investment cost I and the benefit flows B, so $\rho_{BI} = 0$.

The bank has incentives to defer the m-payment investment decision because of: (1) declining investment costs over time; (2) the resolution of uncertainty of benefit flows over time; and (3) the larger initial cash flow from a later investment. On the other hand, deferring m-payment investment will be costly for the bank. Investing at a later time will shorten the length of time the bank will receive benefit flows from the investment. It also may miss the advantage of an earlier mover. Another related consideration is the time value of money. When determining the optimal investment timing for m-payment, the bank must consider all these factors, which may offset one another's effects.

The value of an investment in m-payment system technology at time t is the expected present value of the stream of future benefits B, adjusted for the relevant costs. Value can be assessed based on the discounted benefit flows from the time t the bank makes a decision to the maximal deferral time, T, and $V = E\left[\int_t^T B(\tau)e^{-r_f\tau}dt\ \right]$. Here, r_f is the risk-free discount rate or time value of money, and τ is the period of time over which discounting occurs.

The process representing the cash flow drift is given by $dB = (\alpha_B - \eta_B)Bdt + \sigma_B B dz^* = \alpha_B^* Bdt + \sigma_B B dz^*$, where η_B is the risk premium due to cash flow uncertainty, and dz^* is a risk-neutral measure for the Wiener increment.[1] The result of integrating over the interval (t, T) is:

$$V = \frac{B}{r_f - \alpha_B^*}\left[1 - e^{-(r_f - \alpha_B^*)(T-t)}\right]. \quad (3)$$

Also, the expected value of investment I at time t is:

$$E[I(t)] = Ie^{(\alpha_I - \eta_I)t}, \quad (4)$$

η_I is a risk premium due to investment cost uncertainty.

The decision to invest at any point of time $0 \le t \le T$ 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. Given that B and I do not involve traded assets, but instead represent the expected values of a pair of random variables, they have risk premium associated with them. The net present value (NPV) of this investment opportunity with an embedded deferral option can be written as:

$$NPV^A = max\ [(V - I), 0] + ROV = F(B, I, t). \quad (5)$$

The related real option value is:

$$ROV = min[F(B, I, t) - (V - I),\ F(B, I, t)]. \quad (6)$$

By substituting Equations 3 and 4 under the risk-neutral measure into Equation 6, we obtain:

$$ROV = \min\left[\begin{matrix} F(B, I, t) - \frac{B}{r_f - \alpha_B^*}\left[1 - e^{-(r_f - \alpha_B^*)(T-t)}\right] \\ + Ie^{(\alpha_I - \eta_I)t},\ F(B, I, t) \end{matrix}\right] \quad (7)$$

Applying Ito's lemma to obtain the *differential real option value* for the investment gives:

$$dROV = \frac{\partial ROV}{\partial t}dt + \frac{\partial ROV}{\partial B}dB + \frac{\partial ROV}{\partial I}dI$$

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

Then, we substitute Equations 1, 2 and 8 into the *Bellman optimality equation*, $r_f\ ROVdt$ = E($dROV$). This yields a second-order differential equation:

$$\frac{1}{2}{\sigma_B}^2 B^2 ROV_{BB} + \frac{1}{2}{\sigma_I}^2 I^2 ROV_{II} + (\alpha_B - \eta_B)BROV_B$$

$$+(\alpha_I - \eta_I)IROV_I + ROV_t - r_f ROV = 0. \quad (9)$$

The Bellman optimality equation says 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 the action from that state [30]. The action here is the exercise of the real option. The solution to Equation 9 must satisfy two boundary conditions. First, the value of the real option must be 0 at time T, because the decision to make the investment cannot be deferred anymore:

$$ROV(B, I, T) = 0. \quad (10)$$

Second, at any other time, $0 \le t < T$, the value of the investment opportunity is always non-negative:

$$ROV(B, I, t) \ge 0 \quad \forall\ 0 \le t < T. \quad (11)$$

An optimal decision rule that applies to m-payment technology investment is similar to the one proposed by Schwartz and Zozaya-Gorostiza [28]. If $V - I > 0$ and $ROV(B, I, t) > 0$, the best decision for the bank will be to wait, if that 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 cost I. But, if $V - I \le 0$ and $ROV(B, I, t) > 0$, then the bank should wait for the cost flows to decrease or for the expected benefit flows to increase. If waiting is not possible, the bank should abandon the project.

3.2. The Jump Diffusion Process

So far, we have considered a continuous diffusion process. It is more realistic to model a *discontinuous jump process* to capture large discrete movements or jumps of the value of the investment. A jump may be caused by the entry of a new competitor. For example, with the entry of Isis and PayPal, the profits of Google Wallet or Square might experience a sudden decline. Government regulation could also lead to a discrete jump up or down in the value of an m-payment system investment. For example, in some countries, financial services firms or mobile network operators have to obtain m-payment licenses from the government for the authority to operate their businesses. Another example is that other financial institutions or card associations may charge excessive fees for third-party payers.

The payoffs associated with investments in m-payment technology, when the related business envi-

[1] Sundaram [29, p. 8] provides useful motivation for this distinction. "A risk-neutral probability, or an equivalent martingale measure, is a probability distribution on future price paths satisfying two conditions: (1) the prices that occur with positive probability under the risk-neutral probability should be identical to the prices that occur with positive probability in the original model. (2) Under the risk-neutral probability, the expected return on all assets in the model should be the same."

ronment experiences shocks, can be modeled as a mixed Poisson-Wiener process. Merton [26] referred to this as a *jump diffusion process*. If $B(t)$ is the cash flow representing benefits derived from 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 only consider the influence of a Poisson event that occurs after the m-payment system investment is made. Let q denote a Poisson process with independently distributed jumps:

$$dq = \begin{cases} 0 \text{ with probability } 1 - \lambda dt \\ 1 \text{ with probability } \lambda dt. \end{cases} \quad (12)$$

with λ as the mean number of jumps per unit of time.

The benefit flows associated with an investment after the investment decision is made were shown in Equation 2. Therefore, the cash flows derived from investment at time t can be written, inclusive of the jump diffusion process, as:

$$dB = (\alpha_B - \lambda k)Bdt + \sigma_B Bdz + (Y - 1)Bdq \quad (13)$$

where $k \equiv E(Y - 1)$, dq and dz are assumed to be independent. $(Y - 1)$ is a random variable representing the percentage change in the value of the investment if the Poisson event occurs. The jump diffusion process will be continuous most of time, and only a small percentage of time will a discontinuous jump occur. The value of the investment is represented by the discounted cash flows, as shown in Equation 13, from the moment in which the bank made the decision to the end of investment time horizon.

4. Numerical Analysis

To illustrate our findings, we assess a bank's optimal investment timing and best payoffs using numerical analysis. We first discuss the meaning and value of the model parameters used in the analysis.

- 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 investment cost uncertainty is $\sigma_I = 0.2$.
- The investment decision must be made in the finite time horizon $[0, T]$. We assume $T = 5$ years, which is a reasonable length of lifetime for a specific m-payment technology.
- Once the investment decision is made at time t, the first benefit flow received is $B_0(t)$, where $B_0(t)$ is linearly increasing in t. We assume $B_0(t)$ is in a range of \$0.1 to \$1 million for $t \in [0, T]$. The change in benefit flow is $\alpha_B = 0.7$. The uncertainty of this benefit flow σ_B is linearly decreasing in the investment time t, and we assume $\sigma_B \in [0.1, 1]$ for $t \in [0, T]$.
- The bank knows the discount rate affecting its waiting cost. We assume the risk-free discount rate r_f = 6%. The bank knows the mean number of jump events per unit time $\lambda = 0.1$, the expectation of percent change in investment value if a jump event occurs, $k = 1$, and the random variable $(Y - 1)$ follows a normal distribution $N(1,1)$.

We used Matlab to code the simulation and run the numerical analysis. (See Table 2.) Based on the parameters we selected, we drew a sample of 100,000 simulated average m-payment investment payoffs. 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. Our goal is to compare the discounted present value of the payoff at each time and then determine the optimal investment time.

Table 2. Simulation parameters

Parameter	Description	Value
I_0	Initial investment	\$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	5 years
λ	Mean number of jumps	0.1
K	% change of benefits, B	1
$E(Y)$	Expectation of Y	2
r_f	Risk-free discount rate	6%

Figure 3. Investment timing benchmark simulation

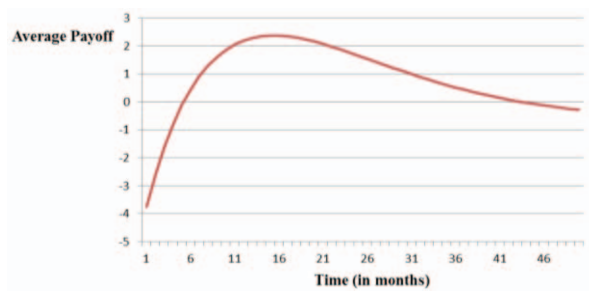


Figure 3 gives the benchmark case solution. The bank should invest at t = 1.6 years (19.2 months) and it is expected to obtain \$2.36 million from the investment.

Figure 4 shows what happens when the investment time horizon is extended to 6 years. In all of the following figures, the red line represents our benchmark case. Our simulation results suggest that the bank should invest earlier compared to the benchmark case, at t = 1.4 years (16.8 months), and the maximal payoff will increase to \$3.47 million.

When the drift parameter for the cash flow α_B increases from the benchmark value 0.7 to 0.9, we find that the highest payoff for m-payment technology investment also increases, from \$2.36 to \$5.46 million, and the best investment time t decreases to t = 1.0

years (12 months). The result is shown in Figure 5. This finding suggests that, when the changing rate of benefit flows increases, the bank should make the investment earlier, and it is expected to receive a higher total payoff from the investment.

Figure 4. Optimal investment timing, $T = 6$

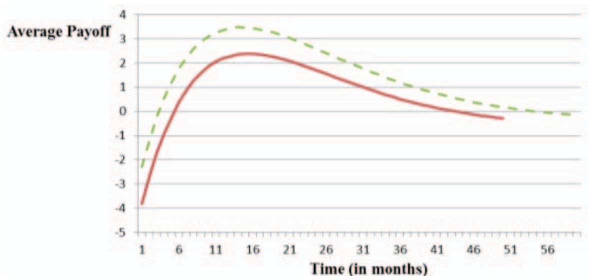
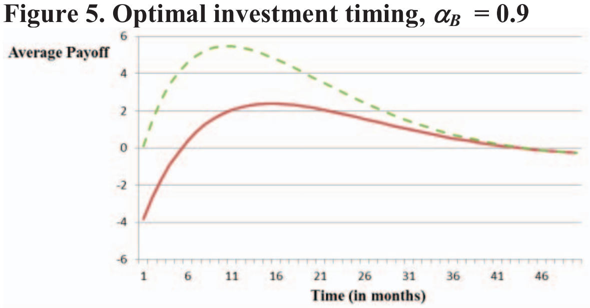
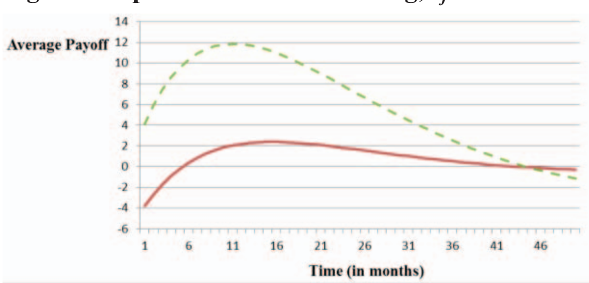


Figure 5. Optimal investment timing, $\alpha_B = 0.9$



To complete our illustration of the continuous-time diffusion process, we further adjusted the risk-free discount rate from $r_f = 0.06$ to 0.03. Figure 6 shows that the optimal investment time occurs at $t = 1.2$ years (or 14.4 months) with a maximum expected payoff of \$11.83 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, which will achieve higher value.

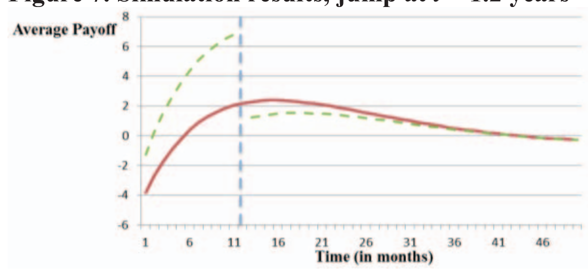
Figure 6. Optimal investment timing, $r_f = 0.03$



We simulated a discontinuous jump diffusion process too. For simplicity, we considered one jump event and a positive change in value during the investment horizon. (See Figures 7 and 8.) Given a mean number of jumps per unit of time, λ, the expectation and distribution of the random variable $(Y - 1)$, we randomly generated one jump event.

In Figure 7, the red line refers to the benchmark case, namely, the continuous-time process without a jump. Recall that in this benchmark case, the optimal investment is at $t = 1.6$ years. The green line refers to a discontinuous process with a jump event occurring at time $t = 1.2$ years (14.4 months), and the random variable $(Y - 1) = 1.15$. So this is an example in which a jump happens before the optimal investment time in the continuous-time process. We find that the bank should invest sooner to capture this potentially positive jump. It should choose an earlier investment time $t = 1.1$ years (13.2 months). This strategy helps the bank achieve a much higher maximal payoff, \$6.79 million.

Figure 7. Simulation results, jump at $t = 1.2$ years



In Figure 8, the jump event occurred at time $t = 3.1$ years (37.2 months), and the random variable $(Y - 1) = 1.34$. This is an example that jump happens after the optimal investment time in the continuous benchmark case. We find that now the bank should invest at $t = 1.7$ years (20.4 months), which is quite similar to the benchmark case result, but the total payoff increases a lot, from \$2.36 to \$5.04 million.

Figure 8. Simulation results, jump at $t = 3.1$ years

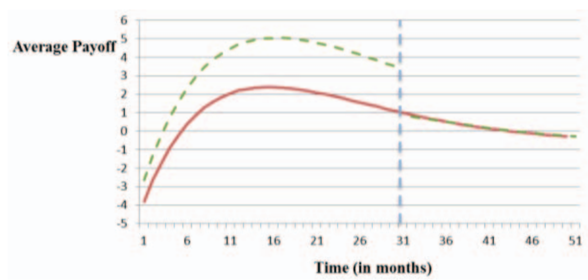


Table 3 provides a summary of our results.

Table 3. Simulation results

Simulation	Optimal Time (t)	Maximal Payoff
Benchmarking	1.6 years	\$2.36 million
$T = 6$ years	1.4 years	\$3.47 million
$\alpha_B = 0.9$	1.0 years	\$5.46 million
$r_f = 0.03$	1.2 years	\$11.83 million
Jump at $t = 1.2$	1.1 years	\$6.79 million
Jump at $t = 3.1$	1.7 years	\$5.04 million

5. Discussion

The success of m-payment system technologies rely on joint participation from multiple stakeholders, including consumers, merchants, network operators, device manufacturers, financial services, and software and technology providers. It also largely depends on some exogenous factors, such as government regulation, future technology innovation, and IT cost changes. As a result, a bank's senior managers face various uncertainties and typically find it difficult to decide whether and when to adopt a specific m-payment technology. To help them make good investment timing decisions, we proposed a continuous-time stochastic model for decision-making under uncertainty.

We use Brownian motion to simulate cost and benefit changes over time. It allows the value of the investment opportunity to change continuously as new information arrives, which is not featured in multistage discrete-time models. In addition, we apply a discontinuous jump process to capture large discrete movements or radical changes that might 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 to the existing m-payment market, any unexpected economic situation, or sudden changes in government regulations. Taking all these endogenous and exogenous uncertainties into consideration, we are able to develop an optimal investment timing strategy for the bank and estimate the profitability of its m-payment investment.

Our model is especially applicable to m-payment system technology investments subject to strong network effects. Bank decision-makers must process information related to interactions with other stakeholders in the marketplace also. For example, when there are more consumers who are willing to use this new technology, more merchants will provide the 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 an infrastructure network for it. This in turn will make m-payments more valuable to consumers and merchants. In other words, positive network effects will exist among these multiple stakeholders, which, in our model, are captured by the high volatility of profits and the positive drift parameter of the benefits flows. Our analysis of the jump process also provides bank decision-makers with guidance on how to respond to uncontrollable exogenous shocks. For example, when a catastrophic event happens that reduces the value of the investment to a large extent, the bank should abandon the investment opportunity permanently. Or if the value of the investment is expected to experience a significant upward jump, our analysis will recommend making the investment decision at an earlier time so that the bank can reap extra benefits brought on by the positive jump.

Admittedly, the applicability of our model relies on the bank's senior managers' to have appropriate expectations about future trends regarding the technology, the market, as well as the volatility of investment costs and benefits. Au and Kauffman [2, 3] pointed out the issue of *rational expectations.* They noted that senior managers may not be able to assemble the information needed for decision-making 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 becomes more difficult because bank managers will act based on interactions with other stakeholders in the m-payment ecosystem. The information processing is rather complicated, which could lead to inappropriate expectations and eventually cause the recommendation to deviate from the optimal investment strategy suggested by the related theoretical model.

6. 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 kinds of technology investments. Second, we offer practical advice and recommendations to senior managers in banks by helping them assess investment timing and estimate business payoffs from m-payment investments. Our numerical analysis provides useful observations for the applied context. For example, we show that, when benefits are expected to flow in a longer time window or at a faster increasing rate (i.e., a large drift parameter for benefit flows), the bank should invest earlier and it can 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 the underlying m-payment investment. Our numerical results show that, when the jump event occurs at different times, a decision-maker should employ different investment strategies.

We note some limitations with our approach. For example, first-mover advantage is not included in our current model. An important theoretical perspective is that a bank should invest in m-payment systems technology at the early stage to gain first-mover advantage. Once a specific m-payment technology is successfully developed and adopted, it will achieve strong network effects. The first-mover will be rewarded with very high payoffs from developing the network. This, however, is not in the model either yet. Another limitation of our model is that we assume the bank can immediately implement an m-payment solution once it makes the investment decision. This assumption makes it possible for benefits to flow into the bank without any additional uncertainty of a value lag. The reality is different, of course: a bank will need some period of time, which is of uncertain length, to develop the necessary infrastructure. So the business value from investment will be obtained only some time later. Finally, our results are theoretical: they cannot be validated because m-payment systems are not mature enough to provide successful cases of investment and implementation.

We are currently extending this research in two ways. We are continuing our modeling work, with the idea of including first-mover advantage. The bank, when making the investment decision, must consider the tradeoff between the advantage achieved in its role as an early network developer and the uncertainty risks brought on by the early adoption of a new technology. This will support our efforts to generalize our analysis approach to real-world settings.

We also are extending our work with numerical analysis. For example, we are using simulations to test our findings for a larger set of parameter values. We expect to discover systematic relationships between the model outcomes, and the parameter values of interest, such as the volatility of costs and benefits, and the probability that a jump of a given magnitude will occur. We are also interested in identifying exogenous risk factors that affect investment decision quality.

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Appendix, Table A1. Modeling notation

	Definition	**Comments**
V	Investment value at time t	PV of future benefits flows B
B	Benefits flows at time t	Fluctuates over time
I	Bank's investment I	For m-payment technology
ROV	Real option value	For the deferral option
α_B	Benefit drift (+)	Subject to Brownian motion
α_I	Investment drift (-)	Subject to Brownian motion also
σ_B	Standard deviation of B	Affects volatility of benefits
σ_I	Standard deviation of I	Affects volatility of costs
η_B	Risk premium on B	Due to benefits uncertainty
η_I	Risk premium on I	Due to investment uncertainty
ρ_{BI}	Correlation of B and I	$\rho_{BI} = 0$: uncorrelated cost-benefit
r_f	Risk-free discount rate	Discounts future benefits and costs
dz	Wiener increment	Defines standard Brownian motion
t	Point in time	dt is a small increment in time
T	Maximum deferral time; number of periods over which cash flows occur	Bounds the option's exercise time; cash flows can be benefits or costs for the bank from $0 \leqslant \tau \leqslant T - t$
λ	Mean number of jumps per unit of time	In the time interval dt, probability that a jump will occur is λdt
k	Change % for benefit flows, B	Due to a jump, and $k \equiv \mathrm{E}(Y - 1)$
Y	Δ value, random variable	Measures after shock change
$q(t)$	Shock-led jump process	Changes in value q is given by dq