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Effects of ambiguity on innovation strategies

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Abstract

Technological innovations significantly influence individual firms and other innovations, such as financial innovations. The future of a firm depends on its innovation investment strategy. According to the literature, innovation investments are affected by ambiguity. This study examines how ambiguity affects the innovation strategies of managers. We show that the innovation strategies of ambiguity-averse managers differ from those of ambiguity-neutral managers. Unlike ambiguity-neutral managers, ambiguity-averse managers consider a broader variety of innovation strategies for a wider range of future innovation arrival times. Regarding the profitability of a future innovation, ambiguity-averse managers delay the investment decision until the profitability of the innovation is less ambiguous. Moreover, we examine innovation strategies under various conditions, including the risk of innovation outdatedness, management disputes, and the varying volatility of innovations.

Keywords: Technological innovation, Ambiguity, Innovation strategy

JEL Classification: C41, D81, O32

Introduction

According to Boston Consulting Group (BCG, 2021) report, the portfolio of the 50 Most Innovative Companies outperforms the Morgan Stanley Capital International (MSCI) index by more than three percentage points per year. In terms of the performance of innovative firms, BCG notes that few firms are prepared to invest in innovation and emphasizes the importance of being prepared.[1]

Maintaining innovation initiatives is a significant concern for firms, as companies like Blackberry, Nokia, and Kodak have realized.[2] As Pisano (2015) points out, an innovation strategy is critical in maintaining innovation initiatives and improving innovation. Good innovation strategies improve alignment among various groups within a firm and clarify the goals and priorities of innovations. Bristol-Myers Squibb adopted an innovation

[1] Note that innovations differ from other general projects. Investments in general projects include investments in renovations and the expansions of current production lines. By contrast, innovative investments can be in new labs, resulting in a new technology or product (e.g., new drugs). In addition, they are distinguished by accounting treatment. The expenses of general investments correspond to capital expenditures (CAPEX) but those of innovative investments appear in Research and Development (R&D) expenses (Coiculescu, Izhakian, and Ravid 2022). This paper focuses on the strategies of technological innovations rather than general projects such as investments in renovations.

[2] BBC News, "Nokia, Apple and creative destruction." https://www.bbc.com/news/business-27238877, May 2014.

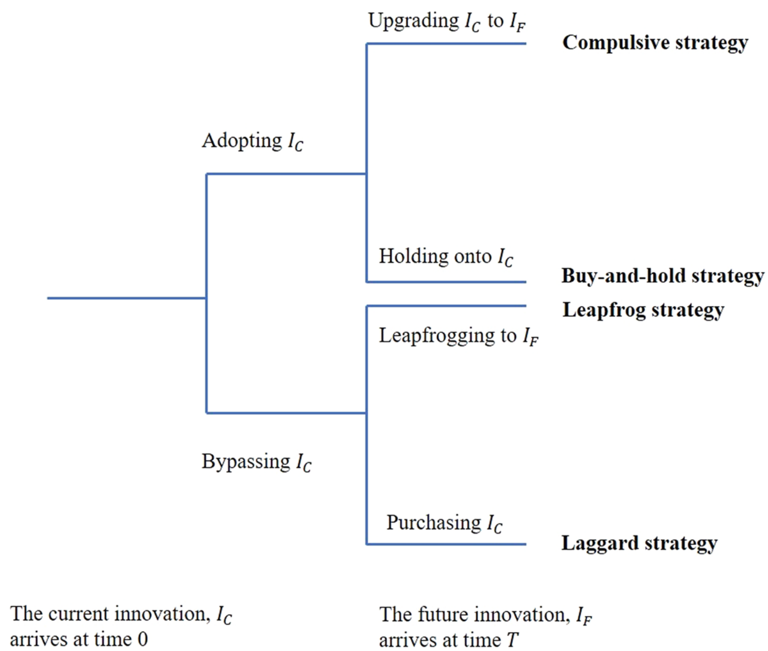

Fig. 1 Managers' strategies for adopting current and future innovations. When the current innovation, I_C arrives, managers can either adopt or bypass it. Managers' strategies for adopting future innovation, I_F depend on the strategy for I_C. After the early adoption of I_C, managers can either upgrade to I_F or hold on to it. If managers bypass I_C, they can either leapfrog to I_F or purchase I_C

strategy for biotechnology drugs against cancer, which resulted in significant growth.[3] Innovation strategies are particularly salient in the banking industry because technological progress is closely linked to financial innovation (Frame, Wall, and White 2018). Furthermore, using Corning Inc. as an example, Pisano (2015) demonstrates the importance of an innovation strategy for steady and long-term innovation.

Hence, firms must solve innovation strategy selection problems to maintain steady and long-term innovation. Following Grenadier and Weiss (1997), we simplify a firm's choice problem by adopting current innovation or bypassing it and waiting for future innovation. Because the firm's managers can consider two alternatives in each case, they have four different innovation strategies: compulsive, buy-and-hold, leapfrog, and laggard. Managers who adopt a current innovation can either upgrade it to a future innovation (the compulsive strategy) or hold on to it (the buy-and-hold strategy). Meanwhile, if managers bypass a current innovation, they can jump to future innovation (the leapfrog strategy) or purchase the current innovation in the future (the laggard strategy). We expect that each strategy will be adopted based on the specific characteristics of the innovations, such as the expected profitability of future innovation. Figure 1 summarizes the firms' four innovation strategies.

However, managers should consider ambiguity an important characteristic of innovation when adopting innovation strategies. Innovation activities and decisions are subject to the uncertainty of innovation outcomes, that is, risk. Furthermore, estimating the distribution of outcomes for innovative products is difficult; innovation is subject

[3] See a related article: Bristol Myers Squibb (BMY) Q1 earnings and revenues surpass estimates. https://finance.yahoo.com/news/bristol-myers-squibb-bmy-q1-121512740.html.

to the uncertainty of probabilities associated with future outcomes, that is, ambiguity. For example, consider innovations in the medical and pharmaceutical industries, where innovative products (i.e., new drugs) are necessary for firms to survive and grow. One of the most important tasks for managers when considering innovation strategies is estimating how successful a new medicine is as a result of innovations (e.g., Wong et al. 2019; Zhou et al. 2020). Because a series of clinical trials is mandatory, managers must assess the likelihood of success at each trial step, which impacts their innovation strategies. In reality, managers confront the ambiguity of innovation, which is the unknown probability of innovation success.

Given this context, this study examines how ambiguity influences managers' strategies for adopting technological innovation.[4] The literature shows that a firm's managers as decision-makers tend to be ambiguity-averse (e.g., Halevy 2007). We investigate how the innovation strategies of ambiguity-averse managers differ from those of ambiguity-neutral managers. We contribute to the growing body of literature on the effects of ambiguity on corporate decisions like capital structure (Izhakian et al. 2022; Lee 2017), investment (Nishimura and Ozaki 2007), risk management (Kim 2021), and innovation (Beauchêne 2019).

We contend that ambiguity-averse managers consider four innovation strategies: compulsive, buy-and-hold, leapfrog, and laggard. We extend the work of Grenadier and Weiss (1997) by including ambiguity and examining the probabilities of adopting the four strategies. Our model shows that ambiguity significantly affects managers' innovation adoption. First, ambiguity-averse managers are more cautious than ambiguity-neutral managers when adopting an innovation strategy because ambiguity is related to the speed with which a future innovation will arrive (i.e., its expected arrival time). When managers are ambiguity-neutral (Grenadier and Weiss 1997), two of the four strategies dominate for very rapid or very slow innovation. For example, in markets prone to rapid innovation, leapfrog and laggard strategies dominate compulsive and buy-and-hold strategies. In this case, ambiguity-neutral managers are unlikely to adopt compulsive or buy-and-hold strategies. Meanwhile, managers who are averse to ambiguity consider all four strategies. For example, if the expected arrival time of a future innovation is more than 2.5 years, ambiguity-neutral managers exclude leapfrog and laggard strategies, whereas ambiguity-averse managers consider both strategies because they perceive the speed of innovation as ambiguous.

Second, regarding the profitability of a future innovation, ambiguity-averse managers delay their investment decisions until the future innovation arrives, at which point they perceive profitability to be less ambiguous. They bypass current innovation at its arrival time. Moreover, when ambiguity-averse managers believe that expected profitability is high (low), they are likely to adopt future (current) innovation. Compared with ambiguity-neutral managers, ambiguity-averse managers' strategies are significantly affected by the high or low profitability of future innovation.

Furthermore, we examine innovation strategies in a variety of contexts. When a current innovation becomes outdated, managers consider compulsive and buy-and-hold

[4] Hereafter, innovations refer to technological innovations.

strategies to be more important than when they are not exposed to the risk of outdatedness. This is because they are concerned about losing the value of the option to adopt current innovation. We also examine disputes arising within management due to ambiguity differences. Here, we examine the effects of such disputes on innovation strategies using a Nash bargaining game. Leapfrog and laggard strategies become more dominant than when management agrees on an innovation strategy. Thus, managers are likely to wait for future innovation and adopt current or future innovation. Disputes about innovation strategies caused by differences in ambiguity require managers to take time to attempt to cooperate, which can delay a decision on a strategy for a current innovation. Consequently, the probability of adopting a compulsive or buy-and-hold strategy decreases.

We also examine the impact of volatility on technological progress. We find that when an innovation process is volatile, ambiguity-averse managers are interested in the level of ambiguity and adopt either the leapfrog or laggard strategy. Finally, we discuss the optimal level of ambiguity. In the case of rapid innovation, it is relatively less important to determine whether the level of ambiguity is optimal. However, in the case of slow innovation, whether the level of ambiguity is optimal is crucial.

The rest of this paper is structured as follows. The next section reviews the literature on innovation and ambiguity, and notes the relationship between technological and financial innovations. This section presents an introductory example of ambiguity-averse managers' innovation strategies. The following section develops a model in which managers face ambiguity about the state of an innovation and describes four strategies for adopting current and future innovations. Then, under ambiguity, we derive formulas for the values of the options to upgrade or adopt current innovation, and we provide the optimal threshold for adopting the current innovation. The final three sections of the paper describe the effects of ambiguity on innovation adoption strategies, extend the results to other scenarios, and conclude the paper.

Background and introductory example

In our discussion of studies on innovation and ambiguity, we focus on technological innovation strategies. However, technological and financial innovations are connected because technological progress stimulates financial innovation, and technology-based firms have an impact on the financial industry. Before describing our formal model, we show how ambiguity-averse managers' innovation strategies differ from those of ambiguity-neutral managers.

Background

Related literature

This study contributes to the recent literature on innovation under ambiguity. According to Coiculescu et al. (2022), ambiguity (or ambiguity aversion) reduces innovation investment, whereas risk (or risk aversion) increases investment. In contrast to Coiculescu et al. (2022), Beauchêne (2019) shows that ambiguity aversion increases the likelihood of firms investing in innovation. These two studies make different assumptions when deriving their findings. The model developed by Coiculescu et al. (2022) considers innovation investment for firms with an ambiguity-averse manager. For such managers, the perceived probability of a bad state (i.e., the likelihood of innovation failure) is higher, resulting in relatively less investment in R&D. By contrast, Beauchêne (2019) considers the business-stealing effect on two firms. Here, an ambiguity-averse firm makes investment decisions based on the worst-case scenario, in which a competitor's innovation activity succeeds. This business-stealing effect reduces the firm's profit while increasing the competitor's profit, inducing an ambiguity-averse firm to invest more in projects.

Unlike these studies, we focus on the impact of ambiguity on a firm's strategy for adopting current and future innovations. While the aforementioned studies examine the relationship between R&D investment and ambiguity, this study investigates how ambiguity-averse managers adopt innovation strategies. To do so, we use Choquet ambiguity to extend the model of Grenadier and Weiss (1997). Numerous studies have used Choquet ambiguity to investigate the effects of ambiguity on managers (e.g., Kim 2021) and investors in financial markets (e.g., Driouchi et al. 2020). There are several advantages to using the Choquet ambiguity approach. First, developing a real-options model under ambiguity is relatively simple. The Choquet–Brownian motion defined in the Choquet ambiguity can be expressed as a general Brownian motion with a mean and variance that are functions of one parameter. This parameter, which represents the degree of managers' perceived ambiguity (and ambiguity aversion), allows us to model the state of the innovation arrival process under ambiguity. Second, Choquet ambiguity enables us to incorporate the case under risk. When the Choquet ambiguity parameter is restricted to a particular value, we obtain a model with no ambiguity. As a result, it is easy to compare firms' innovation strategies under ambiguity with those under risk (i.e., the absence of ambiguity).

Regarding the optimal decision to adopt an innovation, our model is related to that of Farzin et al. (1998). They show that the uncertainty of an innovation process significantly affects the decision to adopt the innovation (a new technology), even though there is no uncertainty about future market conditions. The optimal decision rule indicates a slower rate of innovation adoption when compared with the net present value rule. Our model emphasizes the importance of uncertainty about innovation by focusing on ambiguity rather than risk as uncertainty, as in Farzin et al. (1998).

This study also adds to the literature on the effects of Choquet ambiguity on corporate financial decisions. Agliardi et al. (2015, 2016) first analyze the price and conversion decision of convertible bonds under Choquet ambiguity, and then demonstrate that when managers face ambiguity, a reverse pecking order of financing appears. Kim (2021) recently shows that the leverage ratio is negatively related to ambiguity, and that ambiguity is important for risk management. We contribute to this body of literature by investigating ambiguity's effects on innovation investment.

Technological and financial innovations

As previously stated, technological and financial innovations are connected.[5] Frame, Wall, and White (2018) note that technological progress stimulates financial innovation and has altered the environment of traditional financial intermediaries such as banks.

[5] Financial innovations are innovations that provide new products to satisfy financial system participants' demands and reduce costs and risks (Frame and White 2004).

Fintech refers to technological innovations in financial industries and activities (International Monetary Fund: IMF 2022). Fintech firms use technology to provide financial services (Frame, Wall, and White 2018). Security and verification technologies have a significant impact on the financial industry. For example, decentralized finance (DeFi) is a fintech platform that offers a new type of financial intermediation. Because all transactions are written using blockchain technology, no central intermediary is required.

This section summarizes the effects of fintech on banking. According to the Bank for International Settlements (2018), three innovative fintech services are credit, payments, and investment management. The first is peer-to-peer (P2P) lending or marketplace lending.[6] Marketplace lenders connect with borrowers through online lending platforms rather than traditional financial intermediaries. Fintech firms can provide this type of financial service due to machine learning and big data, which allows them to assign credit scores to borrowers by analyzing their risk using large credit datasets. Since 2007, P2P lending has grown rapidly. Traditional banks must compete with P2P lenders like LendingClub, SoFi, and Upstart. Tang (2019) shows that by serving inframarginal borrowers, P2P lending in the United States has become a substitute for bank lending.

The verification of transactions is the basis of bank payment services. All transactions can be recorded in a distributed ledger using blockchain technology. Cryptocurrencies based on this technology, such as Bitcoin, are used as payment tools and investment assets. Hence, blockchain technology can verify transactions without the involvement of trusted intermediaries such as banks (Frame, Wall, and White 2018). Furthermore, non-financial firms, such as Apple, Google, and PayPal provide payment services through their own payment systems. The third innovative service of fintech firms is investment management services. For example, technological progress has enabled robo-advisors to provide customized investment advice rather than human advisors. Moreover, automated investment firms (e.g., Betterment and Wealthfront) compete with traditional financial firms (e.g., Charles Schwab).[7]

Non-financial and traditional financial firms compete for financial services due to technological innovations. According to Berk and DeMarzo (2019), competition stimulates financial innovation and reshapes the financial industry. Hence, although we focus on technological innovation strategies, we expect our results to be related to financial innovation strategies.

Introductory example and strategies for financial innovations

This section provides an introductory example of intuitive cases of ambiguity-neutral and ambiguity-averse managers' innovation strategies. Unlike ambiguity-neutral managers, ambiguity-averse managers face uncertain situations, in which the probability distribution of the outcomes is uncertain. Ambiguity-averse managers overweigh (underweigh) the probability of bad (good) outcomes (Tversky and Kahneman 1992).

Managers can invest in current or future innovation. A future innovation arrives randomly with an expected arrival time of $\mathbb{E}(T)$. Managers will either adopt current

[6] For details of the structure of P2P lending, see PricewaterhouseCoopers (2015).

[7] CNBC, "Robo-advisors are growing in popularity. Can they really replace a human financial advisor?" https://cnb.cx/3frUTWv, January 2022.

innovation or wait for future innovation. Ambiguity-neutral managers perceive future innovation's arrival time as $\mathbb{E}(T)$. By contrast, ambiguity-averse managers perceive the arrival time as $\mathbb{E}(T) + \varepsilon$, where the distribution of ε is unknown to them. Suppose they anticipate that the value of ε is either 1 or -1.

We begin with a market with rapid innovation. For example, the expected arrival time of a future innovation is one year. Ambiguity-neutral managers are willing to wait because they do not consider ambiguity in future innovation and believe that it will arrive in one year. Ambiguity-averse managers believe that the arrival time of future innovation is longer than that perceived by the market and ambiguity-neutral managers. In other words, ambiguity-averse managers overweigh the likelihood of a relatively long arrival time, so their perceived value of ε is 1. Compared to ambiguity-neutral managers, they consider strategies that adopt current innovation to be more important.

Next, we consider a market with slow innovation, where future innovation is expected to arrive in three years. In this case, ambiguity-neutral managers focus on strategies that adopt the current innovation. Ambiguity-averse managers overweigh the likelihood of arrival in less than three years; that is, they perceive the value of ε as -1. Hence, unlike ambiguity-neutral managers, ambiguity-averse managers cannot ignore strategies for adopting future innovation. In this case, ambiguity leads to ambiguity-averse managers considering strategies for adopting both current and future innovations. The innovation strategies of ambiguity-averse managers are more diverse and complicated than those of ambiguity-neutral managers. In the following section, we formalize this result and examine several cases of such innovation strategies.

Before moving on to a formal model, consider how this example relates to the financial innovation strategies of a recent innovation: P2P lending platforms.[8] As previously stated, traditional financial institutions (e.g., banks) compete in credit markets with non-financial firms (e.g., P2P lenders). Thakor (2020) demonstrates that P2P lenders will not replace banks, but rather divide the banks' market share in credit markets. He also asserts that banks will have their own P2P lending platforms or will acquire platforms from other P2P lenders. This is very similar to the financial innovation of internet banks in the mid-1990s. Traditional banks acquired these banks at the time; for example, the Royal Bank of Canada acquired the first internet-only bank, Security First Network Bank and Wells Fargo merged with Norwest (Nath et al. 2001).

Considering P2P lending platforms as a recent financial innovation, we need to continue tracking the stance of traditional banks. Notwithstanding, our framework allows for the implications of banks' strategies for P2P lending platforms. Acquiring an existing P2P lending platform can be considered as adopting the current innovation. By contrast, having their own P2P lending platforms can be viewed as adopting a future innovation because banks require upgraded technologies to develop their own P2P lending platforms that are superior to the existing platforms. Recently, there have been rapid financial innovations. The preceding example indicates that if managers are averse to ambiguity, they consider current innovation to be more important; thus, they are more likely to acquire an existing P2P lending platform. Hence, we expect managers' ambiguity to be a determinant of banks' financial innovation strategies.

[8] I appreciate the Editor's suggestion of the connection between this example and a recent financial innovation.

Model

Modeling technological progress under ambiguity

A firm's managers (i.e., decision-makers) are ambiguous about the likelihood of an innovation arriving. This is due to their inability to obtain complete information about the innovation, resulting in biased estimates of the probability distributions for innovation. Before modeling the arrival of an innovation under ambiguity, we begin with the model of Grenadier and Weiss (1997), in which managers are neutral to the ambiguity of the innovation process. They assume that a log-normal diffusion process X characterizes a state of innovation:

$$dX_t = \alpha X_t dt + \sigma X_t dZ_t, \tag{1}$$

where α is the expected percentage change in X, σ is the conditional standard deviation per unit time, and Z_t denotes the standard Brownian motion at time t. When the state of an innovation reaches a certain threshold, the innovation arrives. The firm must then decide whether to adopt the current innovation or wait for a future one.

Unlike Grenadier and Weiss (1997), we consider that managers face ambiguity about the state of an innovation because they lack information about the expected change and standard deviation of the innovation's state. As in Driouchi et al. (2020), we use the Choquet ambiguity described by a Choquet–Brownian motion.[9] Ambiguity-averse managers perceive the state of innovation:

$$dX_t = (\alpha + m\sigma) X_t dt + \sigma n X_t dB_t, \tag{2}$$

where $m = 2c - 1$, $n = 2\sqrt{c(1-c)}$, and B_t represents a standard Brownian motion. The parameter c represents managers' ambiguity perception ($0 < c \leq 0.5$).[10] If $c = 0.5$, then the expected percentage change and standard deviation of the innovation state are reduced to α and σ, respectively. In other words, the process is reduced to that of Grenadier and Weiss (1997). When the parameter of managers' perceived ambiguity decreases, their perceived ambiguity (i.e., overweighing the likelihood of bad outcomes) increases.[11] In other words, as c falls below 0.5, managers' perceived ambiguity rises. Because of this ambiguity, ambiguity-averse managers perceive the innovation state's behavior as in Eq. (2), whereas ambiguity-neutral managers perceive it as in Eq. (1).

Innovation strategies

When the state of an innovation, X_t, hits a threshold, X_h, from below, a future innovation arrives. Let T be the first hit time of X_t to the threshold X_h; that is, $T = \inf\{t : X_t \geq X_h\}$. Next, we describe the firm's innovation adoption and migration strategies for innovation, as well as the payoffs and costs associated with these strategies. At time zero, the current innovation (denoted by I_C) arrives. The firm can then take between two actions: 1) adopt the current innovation; or 2) bypass the current innovation and wait for a future innovation.

[9] For details, see Kast, Lapied, and Roubaud (2014).

[10] Under Choquet ambiguity, c takes a value between zero and one. When managers seek ambiguity (i.e., ambiguity-loving managers), the parameter takes a value between 0.5 and 1. In general, because managers are ambiguity-averse (Lee 2017), we consider that the parameter c takes a value between 0 and 0.5.

[11] Under Choquet ambiguity, capacity indicates the ambiguity perceived by managers and their attitude toward the ambiguity (Agliardi et al. 2016; Driouchi et al. 2020).

If managers adopt the current innovation, the payoff is $P_0 - C_e$, where P_0 and C_e denote the current innovation's value and cost, respectively. Let T denote the arrival time of future innovation (I_F). At time T, the strategy will depend on which of them managers choose at time zero. First, suppose that managers adopt I_C at time zero. These managers also have two strategies: 1a) upgrade I_C to I_F, or 1b) hold onto I_C. If managers upgrade the current innovation, then the payoff is $P_T - P_0 - C_u$. As in Grenadier and Weiss (1997), the distribution P_T is assumed to follow a normal distribution with a mean $P_0 + \mu$ and variance ν^2. The value of I_F is P_T and the cost of upgrading is C_u. If managers still hold at time T, no cash flow is added. Strategies 1a) and 1b) are referred to as compulsive and buy-and-hold, respectively. In other words, to pursue a compulsive strategy, managers purchase both I_C and I_F. The buy-and-hold strategy means that managers adopt only I_C. If managers adopt the leapfrog strategy, they bypass I_C but purchase I_F. When adopting the laggard strategy, managers buy the I_C when I_F arrives.

Second, suppose that managers bypass I_C at time zero. In this case, they can choose from two strategies: 2a) jump to the future (new) innovation, I_F, or 2b) purchase the current (previous) innovation I_C. When managers leapfrog to I_F, the payoff is $P_T - C_l$. If managers bypass I_C at time zero, but purchase it at time T, then the payoff is $P_0 - C_d$. Strategies 2a) and 2b) are called leapfrog and laggard strategies, respectively. We also consider the cost conditions. The early adoption cost of I_C is higher than that of I_C: $C_d \leq C_e$. In addition, the total cost of adopting I_C at time zero and upgrading to I_F at time T is higher than that of leapfrogging to I_F: $C_l < C_e + C_u$. These conditions ensure the absence of adoption arbitrage.

Options to upgrade or adopt early under ambiguity

We consider two options available to managers: upgrading from I_C to I_F, and adopting I_C as soon as the current innovation arrives. Managers value the option to upgrade from current to future innovation. Because there is no interim cash flow from this option, the Bellman equation (e.g., Dixit and Pindyck 1994) for this upgrade option value, $F(X_t)$, is given by:

$$F(X_t) = e^{-rdt}\mathbb{E}[F(X_t + dX_t)]. \tag{3}$$

The value of the upgrade option for $X_t < X_h$ is

$$F(X_t) = A_1 \left(\frac{X_t}{X_h}\right)^{\beta(c)}, \tag{4}$$

where A_1 and $\beta(c)$ are given in the Appendix.

Next, we deal with the option to adopt current innovation. As in Grenadier and Weiss (1997), managers adopt current innovation when the state of innovation X_t hits X_l from above ($X_l < X_h$). The value of the option to adopt the current innovation is:

$$G(X_t) = (P_0 - C_e + F(X_l))p_l(X_t) + Kp_h(X_t), \tag{5}$$

where K is given in the Appendix. Furthermore, $p_l(X_t)$ and $p_h(X_t)$ are given by:

$$p_l(X_t) = \frac{X_t^{\beta(c)}X_h^{\gamma(c)} - X_t^{\gamma(c)}X_h^{\beta(c)}}{X_l^{\beta(c)}X_h^{\gamma(c)} - X_l^{\gamma(c)}X_h^{\beta(c)}}; p_h(X_t) = \frac{X_t^{\gamma(c)}X_l^{\beta(c)} - X_t^{\beta(c)}X_l^{\gamma(c)}}{X_l^{\beta(c)}X_h^{\gamma(c)} - X_l^{\gamma(c)}X_h^{\beta(c)}}, \tag{6}$$

As in Goldstein et al. (2001), $p_l(X_t)$ $(p_h(X_t))$ is the present value of a claim that pays \$1 when X_t hits X_l (X_h) before hitting X_h (X_l). The optimal threshold X_l satisfies the following equation:

$$\begin{aligned} &\frac{(P_0 - C_e + F(X_l))\left(\beta(c)X_l^{\beta(c)}X_h^{\gamma(c)} - \gamma(c)X_l^{\gamma(c)}X_h^{\beta(c)}\right)}{\Sigma(c)} \\ &\quad + \frac{K(\gamma(c) - \beta(c))X_l^{\beta(c)+\gamma(c)}}{\Sigma(c)} - \beta(c)F(X_l) = 0, \end{aligned} \tag{7}$$

where

$$\Sigma(c) = X_l^{\beta(c)}X_h^{\gamma(c)} - X_l^{\gamma(c)}X_h^{\beta(c)}. \tag{8}$$

It is straightforward to numerically calculate the optimal threshold X_l using Eq. (7).

Different innovation environments lead to different strategies. For example, managers are less likely to adopt a current innovation and more likely to wait for future innovation in an environment where future innovation arrives rapidly. Furthermore, managers' perceptions of an innovation's arrival influence their innovation strategies. This is due to the fact that the perceived speed of innovation by ambiguity-averse managers varies depending on the degree of ambiguity. To investigate how managers' perceptions of ambiguity affect their innovation adoption strategies, we analyze the probability of adopting each of the four strategies (compulsive, buy-and-hold, leapfrog, and laggard).

Let *PC*, *PB*, *PL*, and *PG* denote the probabilities of adopting the compulsive, buy-and-hold, leapfrog, and laggard strategies, respectively. Let τ be the first hit time of X_t to threshold X_l; that is, $\tau = \inf\{t : X_t \leq X_l\}$. By definition, *PC* and *PB* are calculated only when managers adopt the current innovation early, that is, when $\tau < T$. Because managers adopt a compulsive strategy if the payoff of the upgrade option is positive, *PC* is given by:

$$\text{Prob}\left\{\tau < T \text{ and } P_T - P_0 - C_u \geq 0\right\} \tag{9}$$

If the payoff of the upgrade option is less than zero, managers adopt a buy-and-hold strategy; thus *PB* is given by

$$\text{Prob}\left\{\tau < T \text{ and } P_T - P_0 - C_u < 0\right\} \tag{10}$$

Managers who do not adopt an innovation early ($\tau \geq T$) have two choices when a future innovation arrives: adopt the future innovation (a leapfrog strategy) or adopt the current innovation (a laggard strategy). Managers compare their payoffs to choose one of the two strategies. The payoff from the leapfrog strategy is $P_T - C_l$, whereas the payoff from the laggard strategy is $P_0 - C_d$. Hence, *PL* and *PG* are given by:

$$\text{Prob}\left\{\tau \geq T \text{ and } P_T - C_l \geq P_0 - C_d\right\} \tag{11}$$

and

$$\text{Prob}\{\tau \geq T \text{ and } P_T - C_l < P_0 - C_d\} \tag{12}$$

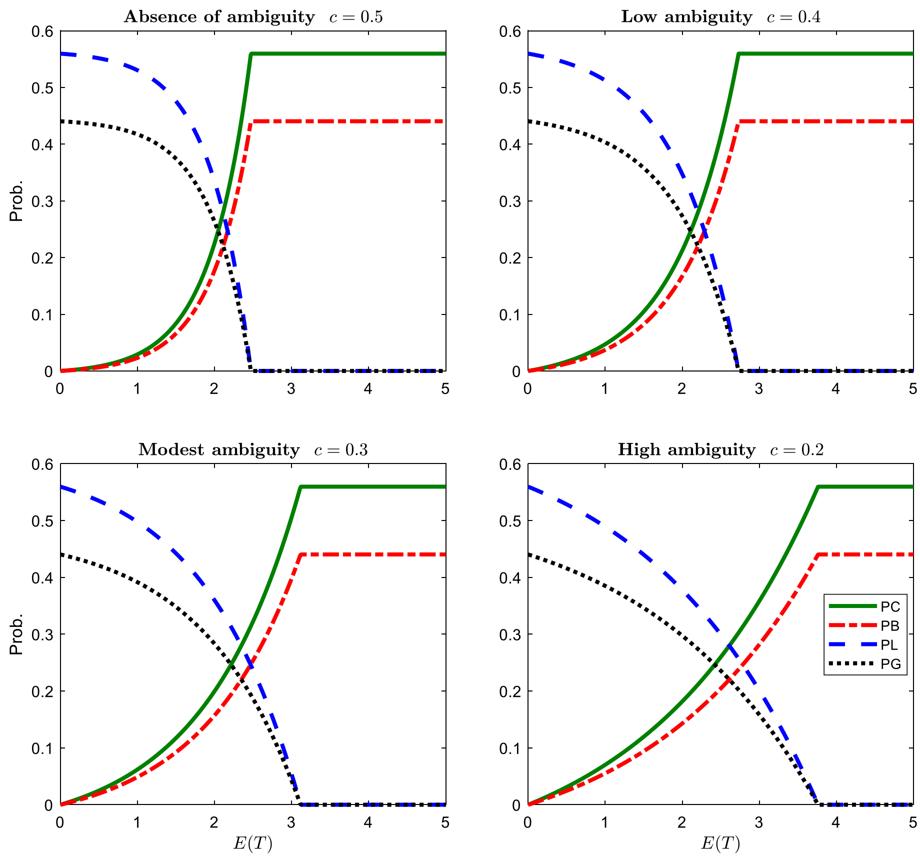

Fig. 2 Probabilities of the four strategies under ambiguity when the expected arrival time, $\mathbb{E}(T)$, varies. *PC*, *PB*, *PL*, and *PG* represent the probabilities of pursuing compulsive, buy-and-hold, leapfrog, and laggard strategies, respectively. The parameter *c* represents the degree of ambiguity perceived by managers. When $c = 0.5$, ambiguity is absent, implying that managers are neutral toward ambiguity. The upper left figure shows Fig. 1 of Grenadier and Weiss (1997). As *c* decreases, the degree of ambiguity increases. When $c = 0.2$, the degree of ambiguity is the highest. Leapfrog and laggard strategies dominate in a market with rapid innovation (low $\mathbb{E}(T)$), whereas compulsive and buy-and-hold strategies dominate in a market with slow innovation (high $\mathbb{E}(T)$)

These four probabilities are affected by managers' perceptions of ambiguity, *c*. In the Appendix, we provide the formulas for the four probabilities. The following section discusses the implications of innovation strategies under ambiguity.

Effects of ambiguity on innovation strategies

We follow the work of Grenadier and Weiss (1997) to examine the impact of ambiguity on innovation strategies. First, we examine the probabilities of adopting the four strategies, given the expected arrival time of future innovation ($\mathbb{E}(T)$), that is, the speed of innovation.[12] Second, we investigate the probabilities of the four strategies when future innovation's expected profitability (μ) varies. We employ the results of Grenadier and

[12] From Eq. (2), the expected arrival time of the future innovation is given by $\mathbb{E}(T) = \frac{1}{\alpha + m\sigma - \frac{\sigma^2 n^2}{2}} \ln\left(\frac{X_h}{X}\right)$.

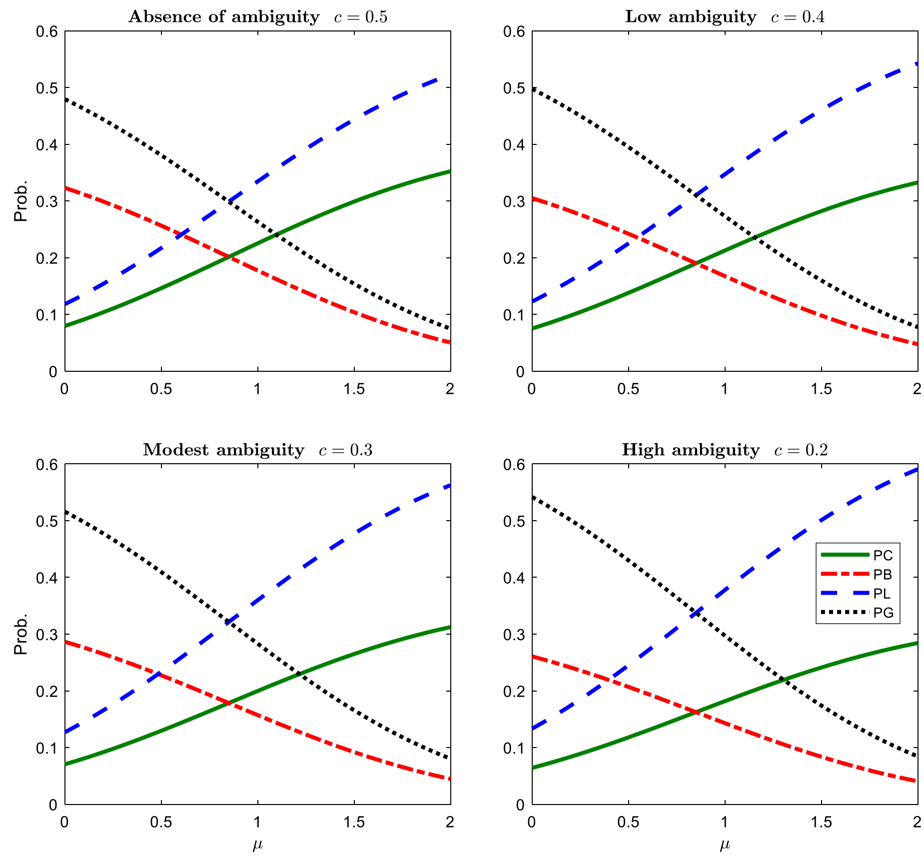

Fig. 3 Probabilities of the four strategies under ambiguity when the profitability of the future innovation, μ, varies. *PC*, *PB*, *PL*, and *PG* represent the probabilities of pursuing compulsive, buy-and-hold, leapfrog, and laggard strategies, respectively. Parameter *c* represents the degree of ambiguity perceived by managers. When $c = 0.5$, ambiguity is absent, implying that managers are neutral toward ambiguity. The upper left figure illustrates Fig. 2 in Grenadier and Weiss (1997). As *c* decreases, the degree of ambiguity increases. Here, $c = 0.2$ represents the highest degree of ambiguity perceived by managers. As the profitability of future innovation increases, *PC* and *PL* increase, whereas *PB* and *PG* decrease

Weiss (1997) as benchmarks when analyzing the effects of ambiguity on probabilities. Their results are obtained under risk, that is, when managers are ambiguity-neutral.[13]

The base-case parameter values come from Grenadier and Weiss (1997): $\alpha = 0.05;\ \sigma = 0.05;\ r = 0.07;\ X_0 = 1;\ \mu = 1;\ \nu = 1;\ P_0 = 1;\ C_e = 0.825;\ C_d = 0.8;\ C_l = 1.65;$ and $C_u = 0.85$. In addition, an ambiguity parameter must be chosen. Following Agliardi et al. (2015), we set the ambiguity parameter, *c*, to 0.5 (no ambiguity), which corresponds to the case of Grenadier and Weiss (1997), 0.4 (low ambiguity), 0.3 (moderate ambiguity), and 0.2 (high ambiguity).

Figure 2 depicts how the expected arrival time of a future innovation influences the probabilities of the four strategies under ambiguity.[14] We find that *PL* and *PG* dominate *PC* and *PB* for rapid innovation and vice versa for slow innovation. When $\mathbb{E}(T)$ has a

[13] The upper left figures of Figs. 2 and 3 show the strategies of ambiguity-neutral managers. The two figures replicate Figs. 1 and 2, respectively, of Grenadier and Weiss (1997).

[14] Following Grenadier and Weiss (1997), we change $\mathbb{E}(T)$ by increasing the threshold X_h.

low value (i.e., rapid innovation), the probability of bypassing the current innovation at its arrival time is high. This is because if managers expect a future innovation to arrive soon, they are likely to wait and prefer to either adopt a laggard or leapfrog strategy. By contrast, when $\mathbb{E}(T)$ is high (i.e., slow innovation), managers focus on the current innovation. Hence, the probabilities of adopting the current innovation, *PC* and *PB*, are high.

In the case of Grenadier and Weiss (1997), ambiguity-neutral managers (upper left figure), as $\mathbb{E}(T)$ increases, *PL* and *PG* decrease dramatically, whereas *PC* and *PB* increase sharply. These four strategies are highly sensitive to innovation speed. When $\mathbb{E}(T)$ is one year, the sum of the probabilities that ambiguity-neutral managers ($c = 0.5$) adopt either the leapfrog or laggard strategy is approximately 95%. However, when $\mathbb{E}(T)$ is 2.5 years, the sum of the probabilities of the two strategies is zero. This implies that if $\mathbb{E}(T)$ is greater than 2.5 years, ambiguity-neutral managers choose either *PC* or *PB*.

By contrast, because ambiguity-averse managers perceive information on the speed of innovation as ambiguous, they consider all four strategies, even for very rapid or very slow innovation. In other words, they are more cautious than ambiguity-neutral managers when adopting an innovation strategy. For example, for markets prone to rapid innovation ($\mathbb{E}(T) = 1$), the values of *PC* and *PB* for ambiguity-averse managers ($c = 0.2$; lower right figure) are more than double those for ambiguity-neutral managers. The sum of *PC* and *PB* for ambiguity-averse managers is more than 12%. In addition, ambiguity-averse managers consider leapfrog and laggard strategies until $\mathbb{E}(T)$ is 3.8 years, whereas ambiguity-neutral managers exclude both strategies after 2.5 years. In markets with slow innovation, the dominance of compulsive and buy-and-hold strategies weakens when managers are ambiguity-averse.[15]

Relative to ambiguity-neutral managers, ambiguity-averse managers consider all strategies for adopting an innovation across a broader range of expected future innovation arrival times. Ambiguity-averse managers do not believe they have accurate information about the speed of an innovation and thus consider more strategies than ambiguity-neutral managers.

This result can be extended to explain why the growth rate of innovations varies across countries.[16] Investments in innovation in developing countries are more likely to be ambiguous than those in developed countries. Compared to managers in developed countries, managers in developing countries face obstacles in terms of human capital, low firm capabilities, and a lack of financial support from the government (e.g., Cirera and Maloney 2017), resulting in a low level of innovation adoption. From our result that ambiguity-averse managers consider all innovation strategies, we infer that managers in developing countries need to make greater efforts to adopt innovations. According to Korinek et al. (2021), developing countries should focus on "steering the adoption of innovation" rather than "steering innovation." Developing countries may have a lower growth rate than that produced by innovations.

[15] For example, suppose that the expected arrival time of the future innovation is three years. When managers perceive a high degree of ambiguity ($c = 0.2$), the probabilities that they adopt the leapfrog or laggard strategies are about 20% and 16%, respectively. However, when managers are neutral to ambiguity, both probabilities are zero.

[16] I am thankful to the reviewer for suggesting this extension.

Figure 3 shows how the expected profitability of future innovation influences the four strategy probabilities under ambiguity. The expected profitability of future innovation, μ, describes the significance of future innovation. In markets where future innovation is significant (i.e., high μ), managers are more likely to pursue future innovation. In other words, the probability of adopting a leapfrog or compulsive strategy increases as the expected profitability of future innovation increases. By contrast, for markets where future innovation is expected to be less profitable, *PG* and *PB* are greater than *PL* and *PC*; that is, the laggard and buy-and-hold strategies dominate the leapfrog and compulsive strategies.

Even for ambiguity-averse managers, we find a similar pattern (three figures, except for the upper left figure). However, when the profitability of future innovation is low (high), the discrepancy between *PG* and *PB* (*PL* and *PC*) increases as managers' perceived ambiguity grows (i.e., c decreases). When ambiguity-averse managers expect a low level of profitability for future innovation, they are more likely to pursue a laggard strategy. However, when they expect a high profitability for future innovation, they are more likely to adopt a leapfrog strategy. Taken together, ambiguity induces ambiguity-averse managers to delay investment decisions until future innovation arrives, at which point they perceive profitability to be less ambiguous. Hence, ambiguity-averse managers adopt current (future) innovation when they believe that the expected profitability of future innovation is significantly low (high). This tendency increases as perceived ambiguity increases. When compared with ambiguity-neutral managers' strategies (Grenadier and Weiss 1997), ambiguity-averse managers' strategies are significantly affected by a high or low level of μ.

Extensions

This section discusses several extensions to this study. First, we examine the case where the option to adopt a current innovation can become outdated (or obsolete). We then examine strategies for adopting innovation when ambiguity leads to disputes among managers about innovation strategies. Furthermore, we discuss volatility impacts and the optimal level of ambiguity.

Strategies when innovations become outdated

Following Grenadier and Weiss (1997), we examine four innovation adoption strategies. We assume that even if managers do not adopt current innovation, they can do so after the arrival of future innovation. However, in many cases, as time passes, the current innovation becomes outdated and a firm may miss out on adopting it. For example, Kodak, Commodore Computers, Grundig, and Polaroid missed the innovation moment because they focused only on the current business management.[17]

This subsection considers the risk of being outdated and examines its effects on strategies for adopting innovations. To incorporate the outdatedness (or obsolescence) of innovation, we employ the approaches of Morellec and Schürhoff (2011) and Hackbarth et al. (2014) in which investment opportunities can be obsolete. Suppose that if

[17] Financial Times, "The danger in missing the innovation moment." https://www.ft.com/content/b2ef363c-31c4-11e4-b377-00144feabdc0, September 2014.

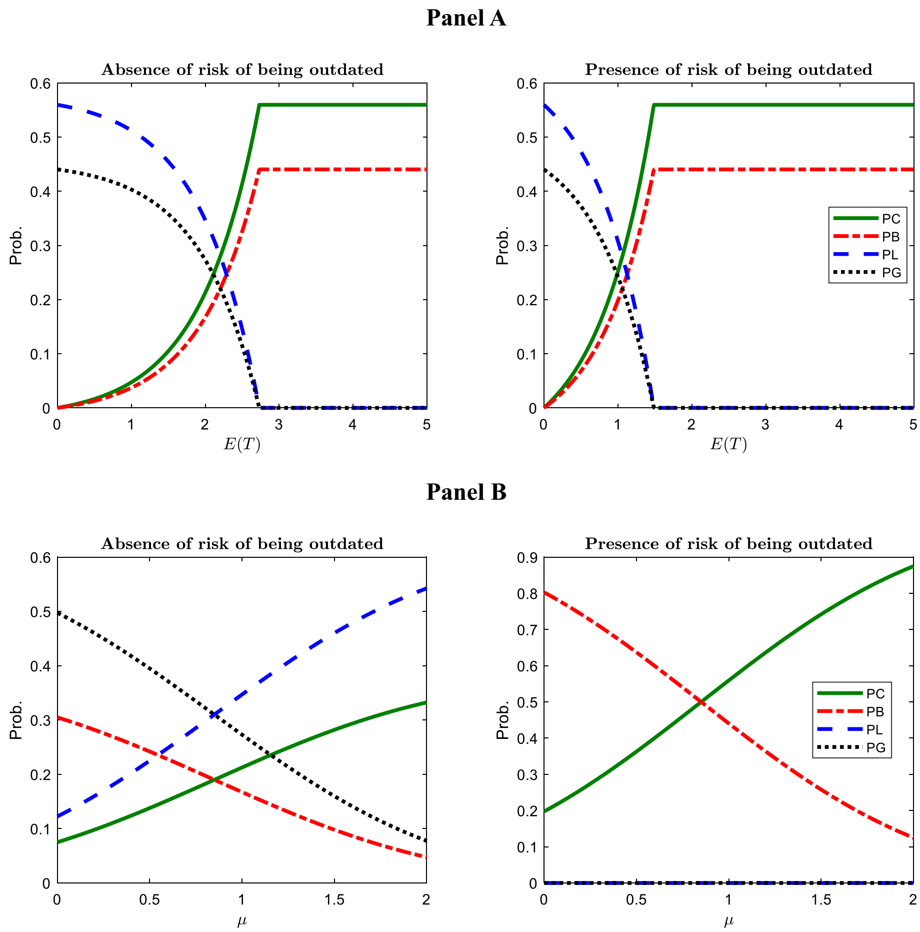

Fig. 4 Risk of being outdated: Probabilities of the four strategies under ambiguity. *PC*, *PB*, *PL*, and *PG* represent the probabilities of pursuing compulsive, buy-and-hold, leapfrog, and laggard strategies, respectively. To obtain conservative results, we choose a low level of ambiguity ($c = 0.4$) as managers' perceived ambiguity. Panels A and B show the innovation strategies for varying $\mathbb{E}(T)$ and for varying μ, respectively. Compared with no risk of being outdated (left graphs), the risk of being outdated increases *PC* and *PB* (right graphs)

managers do not adopt a current innovation, it may become outdated and they may miss out on adopting it later. With probability λdt over a short period dt, the innovations become outdated. In the presence of innovation outdatedness, the Bellman equation for the option value of adopting the current innovation, $G(X_t)$ provides:

$$rG(X_t) = \frac{1}{2}\sigma^2 n^2 X_t^2 G''(X_t) + (\alpha + m\sigma)X_t G'(X_t) + \lambda(0 - G(X_t)). \tag{13}$$

Compared to the case in which an opportunity to adopt the current innovation does not become outdated, as discussed in the previous section, Eq. (13) has the additional term $\lambda(0 - G(X_t))$, which represents the effect of innovation outdatedness on the option value of adopting the current innovation.

Similar to Eq. (5), the value of the option to adopt current innovation in the presence of innovation outdatedness is:

$$G(X_t) = (P_0 - C_e + F(X_l))p_l^\lambda(X_t) + Kp_h^\lambda(X_t) \quad (14)$$

where $p_l^\lambda(X_t)$ and $p_h^\lambda(X_t)$ are provided in the Appendix. To examine the effect of innovation outdatedness, we use 10% as the risk of being outdated as in Hackbarth et al. (2014). Figure 4 shows that the risk of being outdated increases the probability of adopting compulsive and buy-and-hold strategies.[18] As expected, managers who face the risk of being outdated are more cautious when considering strategies for adopting current innovation than managers who do not face such risk. Even in markets with rapid future innovation (Panel A), the values of *PC* and *PB* sharply increase when the risk of being outdated exists. Without the risk of being outdated, managers can adopt current innovation at any time. However, in the presence of such a risk, managers can lose the value of the option to adopt the current innovation. If they do so, managers cannot compare current innovation to future innovation if the former becomes outdated when the latter arrives. Furthermore, the effects of the risk of being outdated on the four probabilities are significant for various levels of profitability (Panel B). The changes in *PC* and *PB* increase with profitability. In addition, for varying profitability, *PG* and *PL* have values of less than 12%. Hence, when innovations can become outdated, managers are more likely to adopt the current innovation and then consider whether to upgrade later or hold on to it.

Microsoft Corporation's development of a media player called Zune to unseat Apple's iPods in the music market is an example of outdated innovation and missed opportunities.[19] However, despite being regarded as a superior product by technology experts, the Zune ended up disappearing from the market. Apple's iPod had already attracted music buyers five years before the Zune was released in 2006. Zune could not take them from iPod users, and its hardware was discontinued in 2011. This case is an example of supporting our finding that managers are more likely to adopt current innovation when they anticipate it will become outdated (or obsolete).

Disputes about strategies within management due to ambiguity difference

Our main results are derived under the assumption that management has agreed on a strategy. However, this may not be the case. For example, in our study, differences in perceptions of ambiguity within the management lead to disputes about innovation strategies. Suppose there are two people on a firm's management team or a chief executive officer (CEO) board: an executive director with the right to make a final decision on strategy and a department director who analyzes innovations and plans innovation strategies. There is a difference in their perceived ambiguity, which is denoted by d_a. If a dispute does not result in cooperation, it may be detrimental to the firm. Therefore, the value of adopting the current innovation for the executive director is $(1 - d_a)G(X_l)$. Because the executive director takes all of the value, the department director receives

[18] To be conservative in our result, we use a low level of ambiguity ($c = 0.4$) as perceived ambiguity.

[19] Reuters, "Microsoft to phase out unsuccessful Zune player." https://www.reuters.com/article/microsoft-zune-idCNN1418111320110314, May 2011.

nothing. Note that if there is no difference in ambiguity between them, that is, $d_a = 0$, then the loss of the option value does not occur.

Both parties attempt to cooperate, because cooperation results in a higher total value for the firm. To analyze this case, we use a Nash bargaining game.[20] The bargaining game between them determines the sharing rule for the value of the innovation option. The bargaining powers of the executive director and department director are $1 - \eta$ and η ($0 \leq \eta < 1$), respectively. If they cooperate in the current innovation strategy, they share the initial option value $G(X_l)$, without any loss. Let w represent the sharing rule for option value. The incremental value to the executive is equal to $(1 - w)G(X_l) - (1 - d_a)G(X_l)$, which is the difference between the shared value to the executive director and the value without cooperation. The incremental value of the department director is $wG(X_l) - 0$. The optimal sharing rule is obtained as follows.

$$w^* = argmax((1 - w)G(X_l) - (1 - d_a)G(X_l))^{1-\eta}(wG(X_l))^\eta \tag{15}$$

Solving the problem delivers the optimal sharing rule as:

$$w^* = d_a\eta \tag{16}$$

Therefore, through cooperating, the value to the executive director is $(1 - w^*) G(X_l) = (1 - d_a\eta)G(X_l)$, and the value to the department director is $w^*G(X_l) = d_a\eta G(X_l)$. The sum of the two values is $G(X_l)$, implying that cooperation provides the entire option value without loss.

Because the executive director has the right to make the final decision on the adoption of innovation strategies, we need to examine how differences in ambiguity and cooperation affect the optimal threshold for adopting the current innovation. Let $G_c(X_t)$ be the option value for the executive director after cooperation. Similar to the derivation of $G(X_t)$, we obtain:

$$G_c(X_t) = (1 - d_a\eta)(P_0 - C_e + F(X_l))p_l(X_t) + Kp_h(X_t) \tag{17}$$

The optimal threshold for adopting the current innovation satisfies the following equation:

$$\begin{aligned}(1 - d_a\eta)&\frac{(P_0 - C_e + F(X_l))\left(\beta(c)X_l^{\beta(c)}X_h^{\gamma(c)} - \gamma(c)X_l^{\gamma(c)}X_h^{\beta(c)}\right)}{\Sigma(c)} \\ &+ \frac{K(\gamma(c) - \beta(c))X_l^{\beta(c)+\gamma(c)}}{\Sigma(c)} - \beta(c)F(X_l) = 0\end{aligned} \tag{18}$$

If d_a is equal to zero, Eq. (18) becomes Eq. (7). In this case, the optimal threshold with cooperation is equal to the optimal threshold when the managers' opinions coincide.

To examine the effect of the difference in perceived ambiguity within the management, we choose 0.05 and 0.5 as the values of d_a and η, respectively. Panel A of Fig. 5 shows that when disputes about strategies exist, the dominance of the leapfrog and laggard strategies becomes strong. Panel B of Fig. 5 shows a similar pattern. Here, disputes within the management significantly decrease the values of *PC* and *PB*, whereas changes in the values of

[20] Fan and Sundaresan (2000) and François and Morellec (2004) use a Nash bargaining game to value corporate securities upon default.

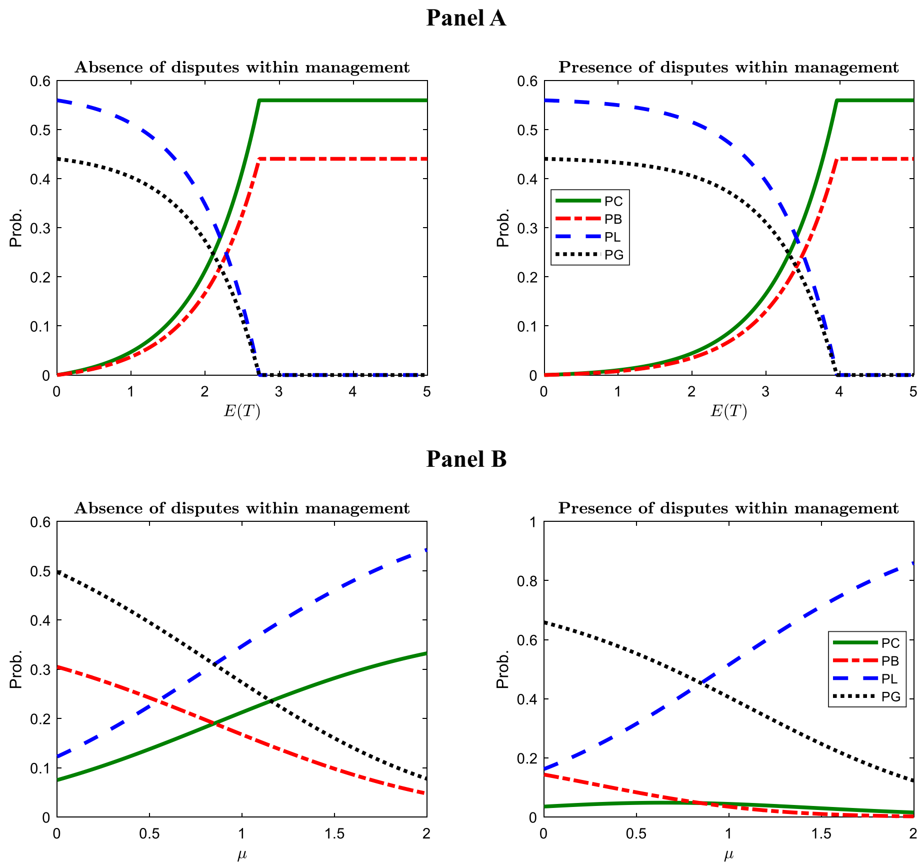

Fig. 5 Disputes within management: Probabilities of the four strategies under ambiguity. *PC*, *PB*, *PL*, and *PG* represent the probabilities of pursuing compulsive, buy-and-hold, leapfrog, and laggard strategies, respectively. To obtain conservative results, we choose a low level of ambiguity ($c = 0.4$) as executive managers' perceived ambiguity. Panels A and B show the innovation strategies for varying $\mathbb{E}(T)$ and for varying μ, respectively. Compared with no disputes within management (left graphs), *PL* and *PG* rise but *PC* and *PB* decline when disputes are present (right graphs)

PL and *PG* are small. These results imply that managers are more likely to wait for a future innovation and then adopt one of the two innovations rather than adopting the current one. Disputes about strategies due to ambiguity require managers to take time to cooperate, causing them to delay a decision on which strategy to adopt, thus reducing the likelihood that they immediately adopt the current innovation (compulsive and buy-and-hold strategies). Hence, differences in perceived ambiguity within management increase the likelihood that managers will pursue leapfrog and laggard strategies across all degrees of ambiguity.

In addition, disputes and diverse opinions regarding innovation strategies are important for successful innovation. The power of diversity must be supported by management cooperation. According to Pisano (2015), innovation strategies that integrate and align perspectives within management (i.e., cooperation within management) are indispensable to successful innovations. Without these factors, diversity becomes detrimental to innovation. In line with Feng and Xiao (2022), cooperation within management is required for consistent innovation strategies. Hence, diversity and cooperation are not mutually exclusive but rather complementary to successful innovation.

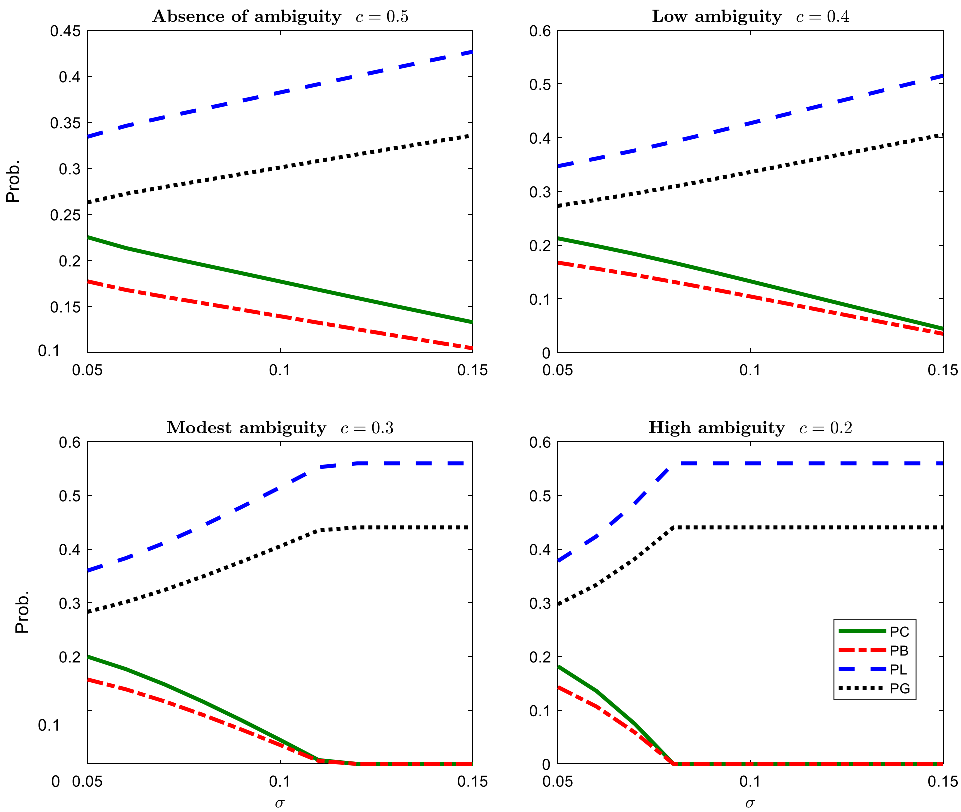

Fig. 6 Volatility impacts: Probabilities of the four strategies under ambiguity when the volatility of the state of innovation, σ, varies. *PC*, *PB*, *PL*, and *PG* represent the probabilities of pursuing compulsive, buy-and-hold, leapfrog, and laggard strategies, respectively. Parameter *c* represents the degree of ambiguity perceived by managers. When $c = 0.5$, ambiguity is absent, implying that managers are neutral toward ambiguity. As *c* decreases, the degree of ambiguity increases. The case $c = 0.2$ represents the highest degree of ambiguity that managers perceive. When there is no ambiguity or the degree of ambiguity is low, *PL* and *PG* increase, but *PB* and *PC* decrease as the volatility of the state of innovation increases. When the degree of ambiguity is modest or high, the four probabilities remain constant beyond a certain level of σ

We also interpret our results as managers' innovation strategies when there are diverse opinions, leading to disputes within management. The two graphs on the left side of Fig. 5 illustrate innovation strategies without diverse opinions and disputes. By contrast, our results (the two graphs on the right side of Fig. 5) show managers' innovation strategies when there are disputes within management. Hence, diversity and cooperation are important determinants of successful innovation strategies. Our result has implications for managers' behavior regarding innovation strategies under the framework in which diverse opinions and disputes arise from different degrees of ambiguity.

Volatility impacts

In addition to the analysis by Grenadier and Weiss (1997), we examine the probabilities of the four strategies concerning volatility (σ) in the state of innovation. This is because the volatility of the innovation process perceived by ambiguity-averse managers (σn) differs from that of ambiguity-neutral managers (σ). Figure 6 illustrates how the volatility of the innovation state affects the four probabilities of the innovation strategies under ambiguity. Regardless of the level of ambiguity, *PL* and *PG* are greater than *PC* and *PB*. In contrast to

Table 1 Option values across the level of ambiguity

	High level of ambiguity			Modest level of ambiguity			Low level of ambiguity		
$\mathbb{E}(T)$	X_h	X_l	Option value	X_h	X_l	Option value	X_h	X_l	Option value
0.0	1.000	0.967	1.157	1.000	0.961	1.157	1.000	0.956	1.157
0.5	1.010	0.939	1.123	1.015	0.927	1.120	1.020	0.917	1.119
1.0	1.019	0.948	1.090	1.029	0.941	1.086	1.040	0.935	1.083
1.5	1.029	0.958	1.058	1.044	0.954	1.052	1.060	0.953	1.048
2.0	1.039	0.967	1.028	1.060	0.968	1.020	1.081	0.972	1.016
2.5	1.049	0.976	0.999	1.075	0.982	0.990	1.102	0.991	0.986
3.0	1.059	0.985	0.972	1.091	0.997	0.963	1.123	1.000	0.959
3.5	1.070	0.995	0.946	1.107	1.000	0.938	1.145	1.000	0.933
4.0	1.080	1.000	0.922	1.123	1.000	0.914	1.168	1.000	0.908
4.5	1.090	1.000	0.900	1.139	1.000	0.890	1.191	1.000	0.884
5.0	1.101	1.000	0.878	1.156	1.000	0.867	1.214	1.000	0.861

X_h represents the threshold at which a future innovation arrives and this value corresponds to the expected time of its arrival. X_l represents the optimal threshold at which managers invest optimally in the current innovation. "Option value" is the sum of the values of the options, F and G, given the values of X_h and X_l. "High," "Modest," and "Low" levels of ambiguity correspond to $c = 0.2, 0.3$, and 0.4, respectively

the speed of innovation ($\mathbb{E}(T)$), the leapfrog and laggard strategies always dominate the compulsive and buy-and-hold strategies across all volatility ranges. Furthermore, the leapfrog strategy has the highest probability of adoption for each level of volatility.

Whereas ambiguity-neutral managers perceive volatility as σ, ambiguity-averse managers perceive volatility as σn (Eq. (2)), which is a function of their perceived ambiguity. When perceived ambiguity is low ($c = 0.4$; upper right figure), ambiguity-averse managers' strategies are similar to those of ambiguity-neutral managers: PL and PG increase, but PC and PB decrease with volatility. However, the likelihood of these four strategies being adopted by ambiguity-averse managers is more sensitive to volatility. Importantly, when their perceived ambiguity is greater than or equal to a moderate level ($c = 0.2$ or 0.3; two lower figures), PL and PG (PC and PB) increase (decrease) and remain constant. Beyond a certain level of volatility, the four probabilities are constant, that is, they are irrelevant to the volatility level.[21] Furthermore, PC and PB are close to zero. The greater the perceived ambiguity, the more this observation manifests itself. Hence, in this case, the effects of perceived ambiguity outweigh those of volatility when ambiguity-averse managers adopt innovation strategies. When volatility is high, ambiguity-averse managers concentrate on their perceived ambiguity and adopt either a leapfrog or laggard strategy.

Optimal degree of ambiguity

In the main analysis, we examined strategies for adopting innovation under various levels of ambiguity perceived by managers. In this section, we discuss the optimal level of ambiguity. The optimal level of ambiguity is chosen to maximize the sum of the values of the options (F and G) to adopt innovations. To compute the values of the options,

[21] For example, consider a modest degree of ambiguity ($c = 0.3$). The figure shows that the four probabilities do not change when the volatility is higher than 12%. If managers perceive the highest degree of ambiguity ($c = 0.2$) and the volatility is greater than 7%, then their strategies for adopting innovation are unrelated to the level of volatility.

we need information on the threshold X_h at which a future innovation arrives, whereas threshold X_l is optimally determined. In our setting, the threshold X_h is related to the expected arrival time, $\mathbb{E}(T)$. Hence, we examine the optimal ambiguity level when the value of $\mathbb{E}(T)$ (i.e., the value of X_h) is given.[22]

Table 1 displays the optimal threshold, X_l, and option values. Note that as the threshold X_h increases (i.e., $\mathbb{E}(T)$ increases), the value of the option to upgrade from the current innovation to a future innovation decreases because future innovation arrives late. In addition, as the expected time of arrival, $\mathbb{E}(T)$ increases, the optimal threshold, X_l increases. This means that managers adopt the current innovation earlier as technological progress is slower. Hence, an increase in X_h (or $\mathbb{E}(T)$) results in a decrease in both option values.

We observe that the higher the level of ambiguity, the higher the option value. The difference in option values across levels of ambiguity is small when $\mathbb{E}(T)$ is low. In other words, in the case of rapid innovations, the level of ambiguity is relatively less important. However, as $\mathbb{E}(T)$ (or X_h) increases, the differences in the option values due to ambiguity become greater. In this case, whether or not the level of ambiguity is optimal matters. In this subsection, we address the basic form of the optimal level of ambiguity. In future research, we expect to explore the optimality of ambiguity in the process of adopting innovation.

Conclusion

Innovation is a strong driver of outperformance. However, firms find it difficult to maintain innovation initiatives without innovation strategies. When firms adopt innovation strategies, they must consider ambiguity, an important characteristic of innovation. Recent literature shows that ambiguity significantly impacts innovation investments and corporate decisions. In line with the literature, we examine how ambiguity influences the innovation strategies of ambiguity-averse managers. We derive the values of the real options for innovation strategies and the probabilities of strategies under ambiguity. This has several implications. Ambiguity-averse managers perceive the innovation process as ambiguous. When compared to ambiguity-neutral managers, ambiguity-averse managers consider various innovation strategies for a wider range of future innovation arrival times. They also delay their decision to invest in innovations until the profitability of future innovation becomes less ambiguous. High or low profitability significantly affects ambiguity-averse managers' strategy.

We also extend the basic setting to various cases. Managers who are exposed to the risk of being outdated consider compulsive and buy-and-hold strategies more important. When there are disputes within the management due to ambiguity differences, the leapfrog and laggard strategies become more dominant. Furthermore, when the volatility of the innovation process is high, ambiguity is a dominant factor in the innovation strategies of ambiguity-averse managers. When technological progress is slower, it is relatively more important to determine whether the level of ambiguity is optimal.

We believe that our study provides the first step toward connecting innovation strategies with ambiguity. This study can be extended to financial innovations, such as traditional bank strategies for online P2P lending platforms. Bank managers' perceived

[22] For example, the expected time of two years corresponds to the following values of X_h: 1.039 ($c = 0.2$), 1.060 ($c = 0.3$), and 1.081 ($c = 0.4$).

ambiguity toward financial innovations affects their strategies, whether they acquire an existing P2P lending platform (adopt a current innovation) or develop an upgraded platform system (adopt a future innovation). We leave empirical and case studies based on our results to future research.

Appendix

Derivation of $F(X_t)$

From Eq. (3), $F(X_t)$ has the following general solution:

$$F(X_t) = A_F X_t^{\beta(c)} + B_F X_t^{\gamma(c)} \tag{19}$$

where

$$\beta(c) = \frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\alpha + m(c)\sigma}{\sigma^2}\right)^2 + \frac{2r}{n(c)^2\sigma^2}}, \tag{20}$$

and

$$\gamma(c) = \frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2} - \sqrt{\left(\frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2}\right)^2 + \frac{2r}{n(c)^2\sigma^2}}. \tag{21}$$

The solution has the following boundary conditions:

$$F(0) = 0, \tag{22}$$

$$F(X_h) = \mathbb{E}[\max(P_T - P_0 - C_u, 0)]. \tag{23}$$

The option value is worthless as X_t approaches zero, implying that B_F should be zero. The value of $F(X_t)$ at the threshold, X_h, is equal to the expected payoff from upgrading the current innovation. The right-hand side of Eq. (23) becomes $(\mu - C_u)N((\mu - C_u)/\nu) + \nu n((\mu - C_u)/\nu)$. Because B_F is zero, Eq. (23) becomes

$$A_F X_h^{\beta(c)} = (\mu - C_u)N\left(\frac{\mu - C_u}{\nu}\right) + \nu n\left(\frac{\mu - C_u}{\nu}\right). \tag{24}$$

Substituting Eqs. (22) and (24) into Eq. (19) yields Eq. (4) and

$$A_1 = \left[(\mu - C_u)N\left(\frac{\mu - C_u}{\nu}\right) + \nu n\left(\frac{\mu - C_u}{\nu}\right)\right]. \tag{25}$$

Derivation of $G(X_t)$

The Bellman equation for the option value of adopting the current innovation, $G(X_t)$ yields the following equation:

$$0 = \frac{1}{2}\sigma^2 n^2 X_t^2 G''(X_t) + (\alpha + m\sigma)X_t G'(X_t) - rG(X_t). \tag{26}$$

Equation (26) has the general solution:

$$G(X_t) = AX_t^{\beta(c)} + BX_t^{\gamma(c)}. \tag{27}$$

Equation (27) satisfies the following three boundary conditions:

$$G(X_l) = P_0 - C_e + F(X_l), \tag{28}$$

$$G'(X_l) = F'(X_l), \tag{29}$$

$$G(X_h) = \mathbb{E}[\max(P_T - C_l, P_0 - C_d)]. \tag{30}$$

The first condition represents the value-matching condition at the threshold, X_l. The second condition is the smooth-pasting condition at X_l. The third condition shows the value of $G(X_t)$ when X_t hits the threshold, X_h. From Eqs. (28) and (30), we determine the coefficients A and$B$, as follows:

$$A = \frac{1}{X_l^{\beta(c)}X_h^{\gamma(c)} - X_l^{\gamma(c)}X_h^{\beta(c)}}\left[(P_0 - C_e + F(X_l))X_h^{\gamma(c)} - KX_l^{\gamma(c)}\right], \tag{31}$$

$$B = \frac{1}{X_h^{\beta(c)}X_l^{\gamma(c)} - X_l^{\beta(c)}X_h^{\gamma(c)}}\left[(P_0 - C_e + F(X_l))X_h^{\beta(c)} - KX_l^{\beta(c)}\right], \tag{32}$$

where K denotes $\mathbb{E}[\max(P_T - C_l, P_0 - C_d)]$. Substituting Eqs. (31) and (32) into Eq. (27) yields the formula for $G(X_t)$ in Eq. (5).

We now determine K. Because $P_T = P_0 + \varepsilon$ and ε is normally distributed with mean μ and variance ν^2, K can be expressed as

$$K = \mathbb{E}\left[(P_0 - C_l + \varepsilon)I_{\{\varepsilon \geq C_l - C_d\}}\right] + \mathbb{E}\left[(P_0 - C_d)I_{\{\varepsilon < C_l - C_d\}}\right]. \tag{33}$$

The notation $I_{\{E\}}$ is an indicator function that takes the value of one if event E occurs, and the value of zero if the event does not occur. The second term in Eq. (33) is

$$(P_0 - C_d)N\left(\frac{\mu + C_d - C_l}{\nu}\right). \tag{34}$$

where the function $N(\cdot)$ is the cumulative standard normal distribution function. The first term of Eq. (33) is

$$(P_0 + \mu - C_l) + (C_l - C_d - \mu)N\left(\frac{C_l - C_d - \mu}{\nu}\right) + \nu N\left(\frac{C_l - C_d - \mu}{\nu}\right). \tag{35}$$

Therefore, K is the sum of Eqs. (34) and (35).

Derivation of the optimal threshold X_l

Differentiating $G(X_t)$ with respect to X_t yields

$$G'(X_t) = (P_0 - C_e + F(X_l))\frac{\partial p_l(X_t)}{\partial X_t} + K\frac{\partial p_h(X_t)}{\partial X_t}. \tag{36}$$

We can derive

$$\frac{\partial p_l(X_t)}{\partial X_t} = \frac{1}{\Sigma(c)}\left(\beta(c)X_t^{\beta(c)-1}X_h^{\gamma(c)} - \gamma(c)X_t^{\gamma(c)-1}X_h^{\beta(c)}\right), \tag{37}$$

$$\frac{\partial p_h(X_t)}{\partial X_t} = \frac{1}{\Sigma(c)}\left(\gamma(c)X_t^{\gamma(c)-1}X_l^{\beta(c)} - \beta(c)X_t^{\beta(c)-1}X_l^{\gamma(c)}\right). \tag{38}$$

The smooth-pasting condition at X_l (i.e., Eq. (29)) is:

$$(P_0 - C_e + F(X_l))\left.\frac{\partial p_l(X_t)}{\partial X_t}\right|_{X_t=X_l} + K\left.\frac{\partial p_h(X_t)}{\partial X_t}\right|_{X_t=X_l} = F(X_l)\frac{\beta(c)}{X_l}. \tag{39}$$

Hence, the optimal threshold, X_l, is a solution of Eq. (7).

The probabilities of adopting the strategies

Note that because P_T follows a normal distribution that does not depend on time, P_T is independent of τ and T. Hence, we express each probability in two parts.

$$PC = \text{Prob}\{\tau < T\} \times \text{Prob}\{P_T - P_0 - C_u \geq 0\} \tag{40}$$

$$PB = \text{Prob}\{\tau < T\} \times \text{Prob}\{P_T - P_0 - C_u < 0\} \tag{41}$$

$$PL = \text{Prob}\{\tau \geq T\} \times \text{Prob}\{P_T - C_l \geq P_0 - C_d\} \tag{42}$$

$$PG = \text{Prob}\{\tau \geq T\} \times \text{Prob}\{P_T - C_l < P_0 - C_d\} \tag{43}$$

By the definition of $p_l(X_t)$ of Equion (6), $p_l(X_t)$ can be expressed as

$$p_l(X_t) = \mathbb{E}\left[e^{-r\tau}\middle|\tau < T\right] \tag{44}$$

The probability $\text{Prob}\{\tau < T\}$ represents the probability that the state of an innovation hits the threshold, X_l before hitting the threshold, X_h. As in Hackbarth and Mauer (2012), we obtain $\text{Prob}\{\tau < T\}$ as follows:

$$Pr_1 \equiv \text{Prob}\{\tau < T\} = \lim_{r\to 0} p_l(X_t) = \lim_{r\to 0}\frac{X_t^{\beta(c)}X_h^{\gamma(c)} - X_t^{\gamma(c)}X_h^{\beta(c)}}{X_l^{\beta(c)}X_h^{\gamma(c)} - X_l^{\gamma(c)}X_h^{\beta(c)}} = \frac{X_t^{\delta(c)} - X_h^{\delta(c)}}{X_l^{\delta(c)} - X_h^{\delta(c)}} \tag{45}$$

where $\delta(c) = 1 - \frac{2(\alpha + m(c)\sigma)}{n(c)^2\sigma^2}$. When there is no ambiguity ($c = 0.5$), Eq. (45) is identical to that of Grenadier and Weiss (1997).[23] We obtain

$$Pr_2 \equiv \text{Prob}\{P_T - P_0 - C_u \geq 0\} = N\left(\frac{\mu - C_u}{\nu}\right) \tag{46}$$

[23] In Grenadier and Weiss (1997), this is represented by the notation, $H(X)$ on page 415, where γ should be $(2/\sigma^2)(\alpha - \sigma^2/2)$, rather than $-(2/\sigma^2)(\alpha - \sigma^2/2)$.

$$Pr_3 \equiv \text{Prob}\{P_T - C_l \geq P_0 - C_d\} = N\left(\frac{\mu + C_d - C_l}{\nu}\right) \tag{47}$$

Therefore, the probabilities of the four strategies are given by $PC = Pr_1 \times Pr_2$, $PB = Pr_1 \times (1 - Pr_2)$, $PL = (1 - Pr_1) \times Pr_3$, and $PC = (1 - Pr_1) \times (1 - Pr_3)$.

Strategies when innovations become outdated

Since the innovations become outdated with a probability λdt, the Bellman equation for the option value of adopting the current innovation, $G(X_t)$ provides:

$$G(X_t) = (1 - \lambda dt)\mathbb{E}\left[e^{-rdt}G(X_t + dX_t)\right]. \tag{48}$$

On the right-hand side, $G(X_t + dX_t)$ is expressed as $dG(X_t) + G(X_t)$ and e^{-rdt} approximates $1 - rdt$. Using Ito's lemma, Eq. (48) becomes Eq. (13). The general solution of Eq. (13) is:

$$G(X_t) = A_\lambda X_t^{\beta_\lambda(c)} + B_\lambda X_t^{\gamma_\lambda(c)}, \tag{49}$$

where

$$\beta_\lambda(c) = \frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2}\right)^2 + \frac{2(r+\lambda)}{n(c)^2\sigma^2}}, \tag{50}$$

and

$$\gamma_\lambda(c) = \frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2} - \sqrt{\left(\frac{1}{2} - \frac{\alpha + m(c)\sigma}{n(c)^2\sigma^2}\right)^2 + \frac{2(r+\lambda)}{n(c)^2\sigma^2}}. \tag{51}$$

The three boundary conditions for $G(X_t)$ are identical to Eqs. (28), (29), and (30) except that $F(X_t) = A_1(X_t/X_h)^{\beta_\lambda(c)}$. Similar to the derivation of $G(X_t)$ in the absence of outdatedness, we obtain A_λ and B_λ by replacing $\beta(c)$ and $\gamma(c)$ in Eqs. (31) and (32) with $\beta_\lambda(c)$ and $\gamma_\lambda(c)$, respectively. In addition, replacing $\beta(c)$ and $\gamma(c)$ in Eq. (6) with $\beta_\lambda(c)$ and $\gamma_\lambda(c)$, respectively, delivers $p_l^\lambda(X_t)$ and $p_h^\lambda(X_t)$. From this, we derive the option value to upgrade the current innovation into the future innovation when the risk of innovation outdatedness is present.

Sharing rule when disputes are present between management

When there is a dispute about which innovation strategy to adopt between the executive and the department directors, they attempt to cooperate. Here, we employ a Nash bargaining game to describe how both parties cooperate, thereby not destroying the value of the option to upgrade. In other words, the sharing rule, w, for the option value is determined by a bargaining game between them. If they cooperate in the current innovation strategy, then they share the initial option value $G(X_l)$ without any loss. The incremental values for the executive director and the department director are equal to $(1-w)G(X_l) - (1-d_a)G(X_l)$ and $wG(X_l) - 0$, respectively. The optimal sharing rule is derived from Eq. (15).

Let $f(w)$ be the term on the right-hand side of Eq. (15). Differentiating $f(w)$ delivers

$$f'(w) = G(X_l)(d_a - w)^{-\eta} w^{\eta-1}(d_a\eta - w). \tag{52}$$

The solution of $f'(w)$ is $d_a\eta$ and is denoted by w^*.[24] To check whether this solution is optimal, we differentiate $f(w)$ twice and arrange the terms:

$$f''(w) = G(X_l)(d_a - w)^{-\eta-1} w^{\eta-2}\left(-\eta(1-\eta)d_a^2\right). \tag{53}$$

Because $w^* = d_a\eta$ and $\eta < 1$, $d_a - w^*$ is positive. This implies that $f''(d_a\eta) < 0$. Therefore, w^* is the optimal sharing rule. Based on this sharing rule, the values for the executive and the department directors are $(1 - w^*)G(X_l) = (1 - d_a\eta)G(X_l)$ and $w^*G(X_l) = d_a\eta G(X_l)$, respectively.

Abbreviations

BCG	Boston consulting group
BMY	Bristol myers squibb
CAPEX	Capital expenditures
CEO	Chief executive officer
DeFi	Decentralized finance
IMF	International monetary fund
MSCI	Morgan stanley capital international
P2P	Peer-to-peer
R&D	Research and development

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[24] Here, d_a can be a solution of $f'(w)$. However, this solution is irrelevant to the bargaining powers of both parties, that is, a bargaining game. Hence, it is excluded as a sharing rule.

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