Managing Innovation Risks in a Competitive Setting: A Decision Analysis Approach

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We characterize optimal sourcing and output quantity decisions in an analytical model of launching an innovative product in the market. The value of the innovation is ex ante uncertain, inducing *operational risk* (of under- or over-production) and *downside risk* (of innovation having negative impact on the product value, as determined by the market). In addition, the innovator is facing *spillover risk* (of competitor adopting the innovation). We show that innovator's optimal decision may involve voluntary exposure to spillover risk which is traded off for either market leadership position (as a consequence of competitor eliminating its operational risk) or for mitigating downside risk. Timing of decisions is critical in obtaining our results and is modeled by contrasting expected profits stemming out of Cournot and Stackelberg competitions. We use classical decision analysis concepts of *real options*, which allows for decision delay in exchange for eliminating operational risk, and *insurance*, which enables trading-off differences in risk exposure to mitigate downside risk, to establish the optimal decisions of the expected profit maximizing innovator.

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1. Introduction

Firms are increasingly specializing in their core competences, which makes them rely on partners and/or outsource important business functions and other value-adding processes. This adds complexity to managerial decision-making as decisions may not be compartmentalized to a functional area, and thus require understanding of their impacts on various aspects of the business. Moreover, since decisions often include engaging outside entities whose objectives might not be perfectly aligned with the firm, most decisions require addressing strategic considerations.

As an illustration, in many industries firm's proprietary knowledge is one of the most valuable assets, and is arguably the core asset for several of the most valuable firms in the world (such as Alphabet or Apple). Managerial decisions about this asset inherently affect other business functions and processes, and often involve outside partners and even competitors. One important aspect is knowledge spillover—in sourcing-related interactions between a firm and its supplier, some of the firm's proprietary knowledge could be exposed to the supplier.[1] In this paper we show that spillover risk does not need to be mitigated, and can instead be leveraged to improve profitability, especially if the nature of the engagement includes other uncertainties evolving over time.

We take the innovator's perspective and develop an analytical model that recommends optimal course of action. More precisely, we identify profit-maximizing decisions of an innovator who is managing a product innovation with ex-ante uncertain success in a competitive market. Before this uncertainty is resolved, the innovator needs to decide on the output quantity and on the supplier of the product. The core uncertainty of the innovator's supplier decision is exposure to *spillover risk*, i.e., the risk that a competitor will gain access to the innovation. We establish that the innovator's optimal decision is not necessarily geared towards mitigating spillover risk, and could in fact involve voluntary exposure to spillover risk by providing access to the innovation to a competitor in exchange for managing other risks of bringing the innovation to market. Specifically, we identify two additional risks associated with product innovation that can be traded-off with the spillover risk in the innovator's optimal decision. The *operational risk* is the risk of over or under-producing, and it arises when production quantity decision has to be made before uncertainty of innovation's success is resolved.[2] The *downside risk* is the risk due to potentially negative (market) outcome of the innovation. The key driver behind establishing the optimal trade-offs between these risks is the timing of the competitor's decisions: whether to adopt the innovation (if provided the access) and the competitor's output quantity. We show that the innovator's decision on whether to provide access to innovation to the competitor (via voluntary exposure to spillover risk) is of critical importance as it induces the optimal response by the competitor in terms of timing of its own decisions. We formally establish these results by using decision analysis concepts of *real options*, which allows for decision delay in exchange for resolving uncertainty and thereby can help eliminate operational risk, and *insurance*, which enables trading off differences in risk exposure and thereby can help mitigate downside risk.

In Section 2, we introduce the model of the innovator's strategic decision-problem. The *innovator* V has no production capability and has to choose either a *competitor-supplier* C or a non-competitor supplier. C has its own product and competes with the innovator in the market. By choosing to source from C, V voluntarily gives the access to the innovation to C, i.e., it voluntarily exposes itself to the spillover risk. On the other hand, by choosing a non-competitor supplier, V denies C the access to innovation.[3] The timing of V's and C's output quantity decisions is modeled either by Cournot competition (if chosen simultaneously, where V and C are market co-leaders) or by Stackelberg competition (if chosen sequentially, where V is the Stackelberg/market leader and C is the Stackelberg/market follower). The value of innovation is uncertain at the time V has to make supplier choice decision and commit to output quantity. This uncertainty is resolved once the innovative product hits the market, and V's profits are then realized. We assume that V (and C) maximizes expected profits. (In Section 5, we discuss relaxing this modeling assumption.)

In Section 3, we describe the structure of V's decisions that exploit interconnectedness of V's spillover risk and C's operational risk. We show that V's optimal decision involves voluntary exposure to spillover risk by providing access to innovation to C in exchange for C voluntarily delaying its adoption and output quantity decisions. We establish that this voluntary exposure to spillover risk is V's optimal decision when the expected value of innovation is not too large and when C's operational risk is high. In such settings, it is optimal for C to give up market co-leadership in exchange for the operational flexibility of deciding on the output quantity of its own product after the value of innovation is realized. This flexibility can be thought of as the *real option value of waiting* for C. Moreover, we show that the value of this real option could be a dominant factor in V's decision. Specifically, even if C is significantly less capable than another non-competitor supplier available to V, it may be optimal for V to source from C. This seemingly counterintuitive optimal decision leading to voluntary exposure to spillover risk by sourcing from a less capable supplier C who is facing a large operational risk, suggests that managing innovation and spillover risk cannot be done in isolation, and it requires understanding and optimally exploiting tradeoffs with other interraleted risks that not just V, but its counterparties may be facing.

The key reason for the existence of tradeoff between V accepting exposure to spillover risk and C eliminating its operational risk lies in the fact that the real option of waiting is available to C only if it has access to innovation, and granting this access is V's decision. However, if C has access to the innovation after it becomes available in the market (i.e., if V does not need to grant access), we show that V loses its leverage, i.e., the real option is naturally available to C regardless of V's access decision.[4] In Section 4, we focus on V's optimal decision when access to innovation does not require cooperation with V once the innovation becomes available in the market. With V being unable to benefit from C's operational risk exposure, we show that it could be optimal for V to voluntary expose itself to *early* spillover risk in order to mitigate downside risk of innovation.[5] We establish that this voluntary exposure to *early* spillover risk is V's optimal decision when downside risk is high for V, but operational risk and downside risk combined are not too high for C.[6] This voluntary exposure to spillover risk by V and early innovation adoption by C can be viewed as an *insurance* against downside risk for V, "paid" by giving up its market leadership. Hence, exploiting these tradeoffs between spillover risk and downside risk might be necessary for managing innovation optimally.

In our analysis, we deliberately isolate operational risk (Section 3) and downside risk (Section 4) which allows us to identify and interpret optimal innovation management strategies that leverage voluntary exposure to spillover risk. Specifically, classical decision analysis concepts arise naturally: real options are utilized to optimally exploit trade-off involving competitor's operational risk exposure, while insurance is used to optimize trade-off involving downside risk. In addition to these situations, we provide a full characterization of V's optimal decisions, by establishing and classifying equilibria of an associated game. Interestingly, the structure of equilibrium strategies critically depends on the nature of the uncertainty of the value of the innovation. Our results provide guidance on optimal innovation management decisions in more complex settings that combine and extend these risks and that have a more nuanced market dynamics. In Section 5, we discuss these and other assumptions and show that qualitative insights we derive in this paper appear to be robust to such enrichments of the model (yet are exceedingly difficult to tackle analytically).[7]

1.1. Related Literature

The research question considered in this paper is similar in flavor to the decision analysis literature on adoption of technology/innovation (e.g., McCardle 1985, Mamer and McCardle 1987, Kornish 2006, Kornish and Keeney 2008, Ulu and Smith 2009, Smith and Ulu 2012, Jose and Zhuang 2013, Ulu and Smith 2016). As in that literature, exploiting the tradeoff between uncertainty and decision timing plays an important role in our analysis.[8] Specifically, we leverage the flexibility of delaying decisions in exchange for resolving uncertainties which is the basic concept of real options in an R&D context (e.g., Dixit and Pindyck 1994, Smith and Nau 1995, Trigeorgis 1996, Pennings and Lint 1997, Huchzermeier and Loch 2001, Santiago and Vakili 2005). Also, we utilize the basic idea of risk pooling via insurance (a well-studied topic combining decision analysis and risk management; e.g., Schlesinger and v.d. Schulenburg 1987, Chiu 2005, Dong and Tomlin 2012, Serpa and Krishnan 2016), which in our model enables sharing downside risk of the uncertain value of an innovation. Finally, we contribute to the growing literature that incorporates game-theoretic approaches into decision analysis (e.g., Lichtendahl and Winkler 2007, Hausken and Zhuang 2011, Cheung and Zhuang 2012, Kwon et al. 2015, Payappalli et al. 2017).

There is a stream of literature on R&D and innovation management (e.g., Krishnan and Zhu 2006, Gaimon 2008, Ramachandran and Krishnan 2008, Krishnan and Ramachandran 2011, Chao and Kavadias 2013, Chao et al. 2014, Hutchison-Krupat and Chao 2014), and an even larger literature in economics and strategy on intellectual property, knowledge spillover, and patents, all of which are related to innovation spillover (e.g., Pakes and Griliches 1980, Griliches 1981, Jaffe 1986, Acs et al. 2002). The focus therein is on managing and/or valuing such intellectual properties via patents and other protection mechanisms. Our focus and approach are different: we consider settings in which decisions involving knowledge spillover are multi-faceted, and, instead of separating a decision, we manage the risks by exploiting tradeoffs among multiple dimensions of the decision problem. Thus, our approach to managing such risks has a distinct decision analytic flavor and is relevant when relying on intellectual property protections alone is proved to be ineffective. In particular, our analysis establishes that in some settings a voluntary exposure to innovation spillover emerges in the profit-maximizing equilibrium, which is similar to insights in some recent papers on strategic disclosure of innovations or patents (e.g., Pacheco-de Almeida and Zemsky 2012, Hu et al. 2017).

We argue that in many situations managing spillover risk is inseparable from strategic sourcing decisions, and build a model to exploit the interconnectedness of risk management and sourcing decisions. A related approach in operations management investigates strategic sourcing with knowledge spillover from a number of perspectives. Knowledge spillover may have a negative impact on a firm if it somehow benefits a competitor—either a competing firm that sources from the same supplier (Qi et al. 2015, Agrawal et al. 2016), or the supplier itself if it also competes with the buying firm in the market (Chen and Chen 2014). Conversely, knowledge spillover may also have a positive impact if the knowledge obtained by the supplier improves its efficiency or yield (Kotabe et al. 2003).

A notable common assumption in this literature is that the transferred knowledge has a positive value which is certain and known (Chen and Chen 2014). This might be the case if the involved knowledge improves the manufacturing of an existing product or the delivery of an existing service. In this paper, however, we allow for the value of innovation to be uncertain, i.e., we focus on innovations that introduce a new or improved product or service, and thus have ex-ante uncertain values that are rooted in consumer experiences, which cannot be accurately estimated prior to actual consumption, including the sourcing stage.

Another important distinction of our model stems from the structure of the firms' equilibrium strategies which critically depend on the timing of the counterparty's decisions. To capture timing of firms' decisions, we incorporate the classic setting of Cournot versus Stackelberg competition which are commonplace in the economic literature (e.g., Gal-Or 1985, Saloner 1987, Hamilton and Slutsky 1990, Maggi 1996) and are often used as a modeling tool in the operations literature (e.g., Arya et al. 2007, Ramachandran and Krishnan 2008, Bhaskaran and Ramachandran 2011, Wang et al. 2013). In particular, in contrast with most models of sourcing from a competitor-supplier (e.g., Arya et al. 2007) which assume that a competitor-supplier is always the Stackelberg follower, in our model the competitor-supplier makes a strategic decision to be a Cournot co-leader or the Stackelberg follower, thereby endogenizing the time-to-market decision through this binary choice.

2. Model

We consider a profit-maximizing *innovator* V holding a product innovation. V is bringing the product innovation to market, and needs to make a sourcing decision that consists of two interrelated choices: i) choosing a supplier; ii) choosing output quantity for the innovative product. In particular, V needs to decide on sourcing from either a *competitor-supplier* C (a competitor in the end-product market who is also a potential supplier for V) or a non-competitor-supplier S (who is not a competitor in the end-product market and focuses only on production). In addition, V needs to decide the output quantity q_V to order from the chosen supplier.

Definition 1 (Spillover Risk). The principal risk that V faces is that of innovation *spillover risk*, i.e., the risk of a competitor adopting the innovation on their product (thereby eliminating the competitive advantage V might have). Specifically, if V were to source from C, it would provide the access to the innovation to its competitor, i.e., V would expose itself to spillover risk. □

When making a decision, V needs to take into account that C is also a profit-maximizing firm, which competes with its conventional product in the end product market. Thus, C's decisions are of critical importance for V's decision-making (and vice versa). In particular, V's optimal decision needs to take into account several aspects of C's actions: *i*) C's adoption decision i.e., whether to adopt V's innovation on its conventional product (provided C has the access to the innovation); *ii*) C's output quantity decision q_C, i.e., the output quantity for its product; *iii*) timing of C's adoption and quantity decisions.

We introduce parameter $\pi \geq 0$ to capture the value that the innovation adds to the conventional product. The key feature of our model is that π is ex-ante uncertain and is realized after the innovative product is introduced to the market. Thus, the value of innovation π is modeled as a random variable with cumulative distribution function F over a finite support, with mean $\mu \geq 0$, and variance σ^2.

The market size is $a > 0$, and the market clearing prices are $p_R = a - q_V - q_C$ for the conventional product, and $p_I = a + \pi - q_V - q_C$ for the innovative product. On the cost side, we assume V faces the same exogenous market wholesale price w when sourcing from either C or S.[9] Furthermore, without loss of generality, we abstract away and normalize unit production cost to zero for both conventional and innovative products. Both V and C's decisions are driven by the objective of maximizing expected profits, denoted by Π_V and Π_C, respectively.[10] To ensure positive output quantities, we assume $a > \max\{3w, 2(\mu - w)\}$.[11]

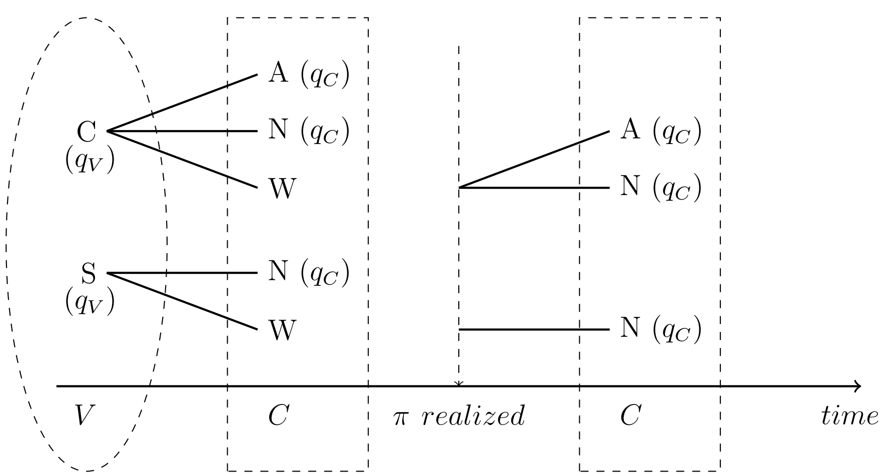


Figure 1 **Sequence of decisions**

Figure 1 illustrates the sequence of decisions. First, V chooses either C or S as its supplier for the innovative product. V also decides on order quantity q_V. Note that V's decisions (marked in the dashed oval) are necessarily made before realization of π, which happens after V's product hits the market. Whereas, C's decisions (marked in the dashed rectangles) can be made either before or after realization of π.

If V sources from C (C branch in Figure 1), it exposes itself to the spillover risk. With the access to the innovation, C has three possible choices: adopting the innovation and making the output quantity decision ("A (q_C)"); not adopting the innovation and making the output quantity decision ("N (q_C)"); or waiting and delaying its decisions until after π is realized ("W"). If C chooses to wait and delay the adoption decision (i.e., C chooses W), it needs to decide between A and N, and make quantity decision q_C after π is realized.

If V sources from S (S branch in Figure 1), it avoids spillover risk as C does not have the access to the innovation.[12] In particular, C has only two possible choices: making the output quantity decision ("N (q_C)"); or delaying its decision until after π is realized ("W"). If C chooses to delay its decision (i.e., C chooses W), it makes the output quantity decision q_C after π is realized.

Note that π is realized after V's innovative product hits the market, so V's profit is affected not only by the realization of π but also by the timing of C's decisions. In particular, if C makes the decisions before realization of π (A or N), V engages in a simultaneous Cournot duopoly competition (i.e., V and C are market co-leaders). On the other hand, if C decides to delay its decisions until after π is realized (WA or WN), V engages in a Stackelberg duopoly competition (i.e., V is the Stackelberg leader and C is the Stackelberg follower). In this case, V would have the first-to-market advantage as the result of C delaying its market entry decisions. Note that our use of either Cournot and Stakelberg competition models, captures the effect of timing of C's decision in a rudimentary way: C makes its adoption and quantity decision either before or after π is realized (and market clears according to either Cournot or Stackelberg competition, respectively).[13] The ability to capture the tradeoff between C's option to benefit from delaying decisions at the expense of also having to delay market entry, is another important feature of our model.

Note that, as standard in the analysis of Cournot and Stackelberg duopoly competitions (e.g., Saloner 1987, Hamilton and Slutsky 1990), the output quantities q_V and q_C in our model are uniquely determined by C's choice of A, N, WA or WN. Therefore, we simplify exposition by omitting derivations of these quantities whenever unambiguous.

Finally, note that since V's decision depends on decisions of a competing counterparty C, it is natural to cast the described setting as a game and study the equilibrium behavior of the firms, i.e., the firms' optimal decisions correspond to their mutual best responses in the game. In particular, V and C are the players of the game. V has two actions, C and S. C has at most four actions depending on V's action: A, N, WA and WN. (Note that q_V and q_C are uniquely determined by the actions of C.) The payoffs of the firms are determined by the equilibrium outcomes. We represent the outcomes in the XY format where the first single character X denotes V's action, and Y denotes C's action that jointly define XY outcome. For example, CWA corresponds to the outcome in which V sources from C, and C decides to wait and then adopt. We use this notation in superscript to denote ex-ante expected profits in the described outcome for V and C, respectively; e.g., Π_V^{CWA} and Π_C^{CWA}. In what follows, we call this game *incremental innovation game*.[14]

3. Managing Operational Risk: Real Option Value of Waiting

In this section we show that V's optimal decision may involve voluntary exposure to spillover risk. More precisely, we characterize settings (i.e., parameters of our model) in which sourcing from C is V's optimal decision. The key idea is that V's choice of supplier allows trading V's voluntary exposure to spillover risk for C's delayed market entry. The latter may be optimal for C, as it allows eliminating another type of risk C is facing.

Definition 2 (Operational Risk). Since the value of innovation π is uncertain, V and C (if it has access to and adopts the innovation) face the risk of under- or over-production due to choosing their output quantities before π is realized. We call this risk *operational risk*. Since operational risk is directly related to the uncertainty of the value of the innovation, we quantify it using the variance of π. Thus, operational risk is measured by σ^2. □

While operational risk is inevitable for V, C may eliminate it by delaying the output quantity decision q_C until after the uncertainty of the value of the innovation is resolved, i.e., after π is realized. (Note that this corresponds to C's WA decision.) Thus, managing operational risk for C reduces to a *real options* problem: benefit of resolving uncertainty before making the output quantity decision needs to be compared with the cost of the delayed market entry.

In order to present and characterize V's optimal decisions, we first need to describe C's optimal decisions. Note that some of C's decisions are always suboptimal in the sense they are always *dominated* by another decision at C's disposal. (For example, if V were to source from C, C's decision N would be suboptimal.) Consequently, these dominated decisions can be eliminated from our analysis. Note that eliminating dominated decisions is equivalent to eliminating corresponding outcomes in the incremental innovation game.

The following lemma identifies the dominated outcomes, and also provides optimal expected profits of V and C for all non-dominated outcomes.

Lemma 1. *Outcomes CN, CWN and SWN are dominated by CA, CWA and SN, respectively. The optimal expected profits for outcomes CA, CWA, and SN are:*

$$\Pi_V^{CA} = (a+\mu-2w)^2/9, \quad \Pi_C^{CA} = (a+\mu+w)^2/9 + w(a+\mu-2w)/3, \tag{CA}$$

$$\Pi_V^{CWA} = (a+\mu-2w)^2/8, \quad \Pi_C^{CWA} = (a+\mu+2w)^2/16 + \sigma^2/4 + w(a+\mu-2w)/2, \tag{CWA}$$

and

$$\Pi_V^{SN} = (a+2\mu-2w)^2/9, \quad \Pi_C^{SN} = (a-\mu+w)^2/9. \tag{SN}$$

3.1. Real Option Value of Waiting

In this section, we show that V can leverage spillover risk to "sell" C a real option for managing operational risk, which in turn creates value for itself should C exercise it.

Since there is operational risk, C needs to evaluate trading off its market position (co-leader or follower) against being able to optimally choose its output quantity q_C after π is realized (thereby eliminating its operational risk). Note that the latter is possible only when C can choose WA. This operational flexibility of decision delay can be viewed as a *real option value of waiting*. The following proposition establishes C's optimal decision if given the access to the innovation, i.e., if V sources from it.

LEMMA 2. *Suppose V sources from C. For any μ_C, there exists a threshold Σ^2 such that C's optimal decision is WA if and only if $\sigma^2 \geq \Sigma^2$.*

Regions of C's optimal decisions described by Lemma 2 are illustrated in Figure 2. The result establishes the existence of a threshold value on the amount of operational risk C is facing, so that the real option value of waiting has a positive value for C. Clearly, larger uncertainty σ^2, more valuable is information about the realized value of π.

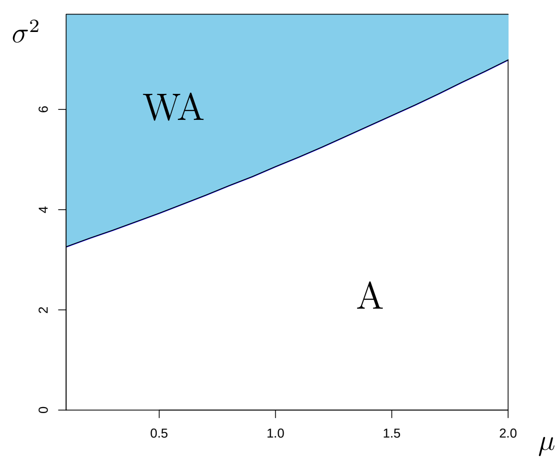


Figure 2 C**'s WA and A decision regions in** μ **and** σ^2 **when** $a = 10$ **and** $w = 3$

V may benefit from the real option as it is created only if V decides to source from C. It suggests that V needs to account for this real option value when evaluating the possibility of sourcing from C. V may effectively "sell" the real option to C, who in return willingly "pays" for the option by giving up market co-leadership. This suggests that V may strategically source from C despite (and in fact because of) spillover risk.

We next formally establish that V's optimal decision can in fact be sourcing from C, which implies voluntary exposure to spillover risk.

PROPOSITION 1. *There exist thresholds M_e and Σ^2 such that if $\mu < M_e$ and $\sigma^2 > \Sigma^2$, it is optimal for V to source from C.*

Proposition 1 suggests that V may want to source from C even if there is spillover risk. V's incentive to voluntarily expose itself to spillover risk lies in unlocking the real option value of waiting for C. However, V benefits from this decision only if C exercises the option, i.e., only if C's best response is WA. Thus, both the expected value of the innovation cannot be large ($\mu < M_e$), and uncertainty cannot be low ($\sigma^2 > \Sigma^2$): if μ were large, V would source from S and not expose itself to spillover risk; if operational risk σ^2 were small, C would not exercise the option and would adopt immediately. In other words, V chooses C only if it can "sell" the real option of waiting to C in exchange for market leadership (which is secured only if C exercises the option, i.e., chooses WA), thus indirectly benefiting from it as well.

3.2. Heterogeneous Supplier Capabilities

In this section we investigate the impact of supplier capabilities on V's optimal decision. In particular, supplier capability captures how well a supplier can manufacture the innovative product. Consequently, supplier capability may affect the success of V's innovation, i.e., the realization of π depends on supplier choice. We incorporate this in our model by differentiating distribution of π, depending on supplier choice. We denote the mean, μ_C or μ_S, and the variance, σ_C^2 or σ_S^2, of the distribution of π, depending on whether V is sourcing from C or S, respectively. We also define *capability ratio* of C and S as $\alpha = \mu_C/\mu_S$. Note that $\alpha > 1$ ($\alpha < 1$) suggests that C is more (less) capable than S.

In the extreme case in which S cannot produce the innovative product (i.e., $\mu_S = \sigma_S^2 = 0$), V sources from C. Intuitively, if supplier capability ratio $\alpha = \mu_C/\mu_S$ is large enough, i.e., if C is sufficiently more capable supplier than S, V should source from C. This is formalized in the following Proposition.

PROPOSITION 2. *Let supplier capability ratio $\alpha > 2$. It is optimal for V to source from C.*

The proposition establishes that V is exposing itself to spillover risk, as long as C is at least twice as capable supplier as S (independent of all other model parameters). When V sources from C, it bears the risk that C may immediately adopt the innovation and share half of the newly created value. However, if sourcing from C generates twice or more value in expectation than sourcing from S, then this offsets the potential loss due to innovation spillover.

Interestingly, if S is a more capable supplier than C ($\alpha < 1$), it might not be optimal for V to source from S regardless of how much more capable is S, i.e., regardless of how small is $\alpha > 0$.

PROPOSITION 3. *Let $0 < \mu_C < \mu_S$. There exist a, w, σ_C^2 and σ_S^2 such that it is optimal for V to source from C.*

V's decision to source from C unlocks the real option value of waiting for C, and if it is optimal for C to exercise the option in response, C would concede market leadership to V, thereby creating benefit for V. It turns out that this benefit for V could be unbounded, and may offset any capability disadvantage that C has as a supplier. Therefore, Proposition 3 suggests that the value of the real option to V could potentially dominate the cost of spillover risk.

We conclude the section by providing a complete characterization of V's optimal decision (allowing C and S to have different capabilities). First we characterize both firms' optimal decisions i.e., equilibrium behavior of the firms in the incremental innovation game. We use notation (X;Y,Z) to denote strategy profiles, where X is V's action, Y is C's action(s) if V sources from C, and Z is C's action(s) if V sources from S.

LEMMA 3. *There exist thresholds $M > 0$, $\Sigma^2 > 0$, and K, $1 < K < 2$, such that the equilibrium in the incremental innovation game is*

1. *(C;A,N), if $\sigma_C^2 < \Sigma^2$ and $\alpha > 2$;*
2. *(S;A,N), if $\sigma_C^2 < \Sigma^2$ and $\alpha < 2$;*
3. *(C;WA,N), if $\sigma_C^2 > \Sigma^2$, and $\alpha > K$ or $\mu_C < M$;*
4. *(S;WA,N), if $\sigma_C^2 > \Sigma^2$, $\alpha < K$ and $\mu_C > M$.*

Given the equilibrium conditions in Lemma 3, Proposition 4 follows immediately, and characterizes the optimal decision of V.

PROPOSITION 4. *There exist thresholds $M > 0$, $\Sigma^2 > 0$, and K, $1 < K < 2$, such that it is optimal for V to source from C (i.e., to voluntarily exposure itself to spillover risk), if*

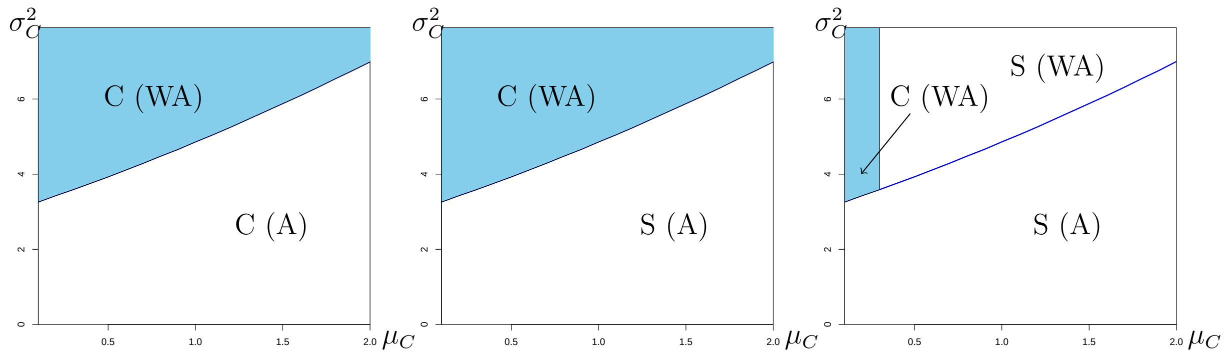
1. *$\alpha > 2$, or*
2. *$\sigma_C^2 > \Sigma^2$, and $\alpha > K$ or $\mu_C < M$.*

Furthermore, it is optimal for V to source from S, if

1. *$\sigma_C^2 < \Sigma^2$ and $\alpha < 2$, or*
2. *$\sigma_C^2 > \Sigma^2$, $\alpha < K$ and $\mu_C > M$.*

The parameter regions supporting V's optimal decisions for a selection of different supplier capability ratio values α are illustrated in Figure 3. (C's optimal decisions contingent on V sourcing from it are marked in the parentheses.)

Proposition 4 suggests that there are two types of situations in which it is optimal for V to source from C. The first is when C's capability is much superior than S's ($\alpha > 2$). The second is when operational risk is high ($\sigma_C^2 > \Sigma^2$). In this case, if offered the real option of waiting, C would wait for



(a) $\alpha > 2$ (b) $K < \alpha < 2$ (c) $\alpha < K$

Figure 3 **V's decision regions for different α values when $a = 10$ and $w = 3$**

the uncertainty of the value of the innovation to be resolved and thereby concede market leadership to V. In other words, C would "exercise" the real option of waiting. This means that it might be optimal for V to unlock this value by sourcing from C and effectively "selling" the real option of waiting to C, as it offsets the loss due to innovation spillover. Thus, V sources from C either because of its superior capability ($\alpha > K$ where $K < 2$), or if the expected value of innovation is not large ($\mu_C < M$) which limits the loss due to innovation spillover. When none of the above conditions holds, V's optimal decision is to source from S.

In summary, the principal tradeoff V is facing differs based on the level of operational risk that C is facing (measured by σ_C^2). When this risk is low, V faces a straightforward tradeoff between the expected benefit from selecting a more capable supplier and the cost due to the exposure to innovation spillover. When operational risk is high, however, V sourcing from C would unlock the real option of waiting, which benefits V, should C choose to "exercise" the option and delay its market entry. Thus V may source from C, effectively "selling" the real option of waiting to C in exchange for market leadership. This effect profoundly changes the tradeoff faced by V when making the sourcing decision, and could have a substantial impact on V's expected profit. In fact, this value could be the main driver for V's sourcing decision: V may voluntarily expose itself to spillover risk and source from C, even if S is a (significantly) more capable supplier than C.

3.3. An Illustration: Incremental Innovations

The key aspect of our analysis so far is that the adoption of the innovation requires the access in the sourcing stage, i.e., C can adopt the innovation only if V sources from it. Such modeling fits the types of innovations that tend to be technological in nature, i.e., the innovation requires a cutting-edge manufacturing technology.

An example of such innovation is Retina Display which was introduced by Apple at launch of iPhone 4. The essence of this innovation lies in the technology that increases screen resolution. The Retina Display used in the iPhone 4 was manufactured by LG, a competitor of Apple in the smartphone market (AppleInsider 2010). Note that Retina Display brought an incremental improvement to iPhone 4 (compared to earlier iPhone models) as it did not compromise any existing iPhone features or functionality. Thus, we refer to this type of innovation as *incremental innovation*, as it typically enhances but does not replace existing functionality (so that $\pi \geq 0$), and is often technological in nature (so that it cannot be easily adopted without access, and supplier capability matters).

Note that the key result we establish in Proposition 1, i.e., V "selling" a real option to C for managing operational risk, critically depends on the fact that the innovation cannot be adopted by C without the access in the sourcing stage. Specifically, if C can adopt the innovation after V's product is available in the market (even if V sources from S), the real option is always available to C, so V does not necessarily need to trade the access to the innovation to unlock it.

We close this section by demonstrating critical importance of the access to the innovation for establishing optimality of V's voluntary exposure to spillover risk. To that end, consider the setting in which C does not need the access to the innovation in the sourcing stage and can adopt the innovation once it hits the market. In other words, consider the setting in which C has one additional choice: C can choose WA (i.e., wait and then adopt) even if V sources from S. The following proposition establishes that, if C and S have equal supplier capability, it could not be strictly optimal for V to expose itself to spillover risk, i.e., to source from C.

PROPOSITION 5. *Let $\mu_C = \mu_S = \mu$. If it is optimal for C to choose WA should V source from C, it would also be optimal for C to choose WA should V source from S.*

Proposition 5 holds because the real option of waiting is available to C, regardless of V's choice of supplier. Since V cannot profit from "unlocking" the option for C, there is no benefit from exposure to spillover risk, and hence eliminating spillover risk and choosing S is $V's$ optimal decision.[15]

4. Managing Downside Risk: Insurance Value of Immediate Adoption

In this section, we investigate the setting in which the access to the innovation is not required for adoption, i.e., C can adopt V's innovation after the innovative product is available in the market even if V sources from S. In such setting, as established in Proposition 5, V can no longer leverage the real option of waiting for managing C's operational risk to create additional value for both C and itself. However, by extending the bounded support of the random variable π (representing the value of innovation) to include negative values, we identify another type of risk that V can manage by voluntary exposure to spillover risk.

Allowing for π to be negative is not just a theoretical construct. For example, consider the on-screen keyboard innovation introduced by Apple at the launch of the first iPhone. The on-screen keyboard had gradually replaced the hardware keyboard, but in fact there was serious doubt about market success at its introduction. For example, PC World (2007) asserted that *"for any feature that requires text input, the iPhone displays an on-screen keyboard that you can toggle between QWERTY text keys and numbers/symbols. It's still no match for the hardware keyboard you get on a BlackBerry or Treo".* The essence of the innovation was in the design concept, as the on-screen keyboard was not novel at the time but Apple was the first to introduce it with smartphones. Interestingly, given iPhone's phenomenal success, Apple's smartphone competitors followed suit and adopted and incorporated on-screen keyboard to their products.

We refer to this type of innovation, that can potentially negatively impact other product features and functionality, as *disruptive innovation*. (Note that allowing $\pi < 0$ is needed to capture such innovations.) We next introduce a risk that is naturally associated with disruptive innovations.

DEFINITION 3 (DOWNSIDE RISK). Since introducing a disruptive innovation to the market might negatively affect market demand, V and C (if adopting innovation before π is realized) face the risk of a negative realized value of innovation π. We call this risk *downside risk*. While downside risk is inevitable for V, C may eliminate it by delaying its adoption decision. In particular, if C delays its adoption decision, it can resort to the conventional product should π turn out to be negative. Thus, the ex-ante value of innovation for C, should it choose W, is $\pi_+ = \max\{\pi, 0\}$. We denote the mean and variance of π_+ by μ_+ and σ_+^2, respectively. Clearly, $\mu_+ \geq \mu$ and $\sigma_+^2 \leq \sigma^2$. We further define $\Delta\mu = \mu_+ - \mu$ to quantify the downside risk via the impact of negative outcomes on the expected value of the innovation. □

We next analyze V's optimal innovation management decision in the presence of downside risk. Note that V's optimal decision in this setting focuses solely on trading-off spillover risk and downside risk.[16] Analogous to our analysis in Section 3, the decisions in this setting can be interpreted as a game. We refer to this game *disruptive innovation game*. (The sequence of decisions is illustrated in Figure 4.)

In order to present and characterize V's optimal decisions, similar to the analysis in Section 3 we first need to describe C's optimal decisions. Note that some of C's decisions are always suboptimal in the sense they are always dominated by another decision at C's disposal. (For example, if V were to source from C, C's decision N would be suboptimal.) Consequently, these dominated decisions can be eliminated from our analysis. Again, since C's decisions are contingent on V's decisions, eliminating dominated decisions is equivalent to eliminating corresponding outcomes in the disruptive innovation game.

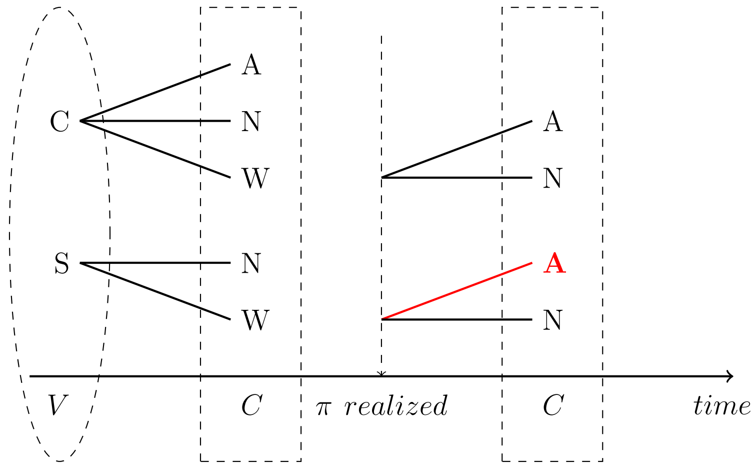


Figure 4 **Sequence of decisions in the disruptive innovation game**

In order to eliminate an uninteresting case in which C has no incentive to adopt the innovation, throughout this section we make an additional technical assumption that guarantees a large enough expected value μ of the innovation. This assumption ensures that the innovation is attractive enough for C to wait and then potentially adopt it (i.e., to choose decision WA), when V sources from S. Specifically, it suffices to assume that $\mu > (a - 2w)/7$.[17]

The following lemma identifies the dominated outcomes, and also provides optimal expected profits of V and C for all non-dominated outcomes. (Note that we slightly abuse the notation and abbreviate multiple outcomes and decisions so that a pair of actions AB is denoted by A/B. For example, WA/N denotes C's decision to Wait (W) and then adopt (A) if π turns out to be positive, or not adopt (N) if π turns out to be negative. CWA/N denotes the pair of outcomes CWA and CWN, and C/SWA denotes the pair of outcomes CWA and SWA.)

LEMMA 4. *Outcomes CN and SN are dominated by CA and SWA/N, respectively. The optimal expected profits for outcomes CA, CWA/N and SWA/N are:*

$$\Pi_V^{CA} = (a + \mu - 2w)^2/9, \quad \Pi_C^{CA} = (a + \mu + w)^2/9 + w(a + \mu - 2w)/3, \tag{CA}$$

$$\Pi_V^{CWA/N} = (a{+}2\mu{-}\mu_+{-}2w)^2/8, \quad \Pi_C^{CWA/N} = (a{-}2\mu{+}3\mu_+{+}2w)^2/16{+}\sigma_+^2/4{+}w(a{+}2\mu{-}\mu_+{-}2w)/2, \tag{CWA/N}$$

and

$$\Pi_V^{SWA/N} = (a + 2\mu - \mu_+ - 2w)^2/8, \quad \Pi_C^{SWA/N} = (a - 2\mu + 3\mu_+ + 2w)^2/16 + \sigma_+^2/4, \tag{SWA/N}$$

4.1. Early Innovation Spillover as an Insurance

In this section, we show that V can leverage spillover risk to "buy" an insurance from C for managing downside risk, which creates value for both C and itself.

In the incremental innovation game, C is facing operational risk of under- or over-production, but no downside risk. By contrast, in this disruptive innovation game, both operational and downside risks may exist. This strengthens C's incentive to delay its decisions until after the uncertainty of the value of the innovation is resolved, as C can resort to the conventional product should the value of the innovation π turn out to be negative. Therefore, in the disruptive innovation game, the real option of waiting is valuable to C not just because it allows eliminating operational risk (if choosing output quantity after π is realized; identical to the incremental innovation game), but also because it allows eliminating downside risk (if choosing the conventional product after π turns out to be negative).

Despite this, the following lemma shows that C may still choose to *immediately* adopt the innovation and enter the market before the uncertainty of the value of the innovation is resolved, should V source from it. Recall that $\Delta\mu = \mu_+ - \mu$ measures a disruptive innovation's downside risk.

LEMMA 5. *Suppose V sources from C in the disruptive innovation game. For any μ, there exist thresholds D_C and Σ_+^2 such that C's optimal strategy is A if and only if $\Delta\mu < D_C$ and $\sigma_+^2 < \Sigma_+^2$.*

Lemma 5 shows that when both downside risk and remaining operational risk after eliminating downside risk are low ($\Delta\mu < D_C$ and $\sigma_+^2 < \Sigma_+^2$; meaning that the overall risk is low), C would bear both risks and immediately adopt the innovation (before π is realized) in order to obtain market co-leadership. When either of the two risks is high, C would delay its adoption and quantity decisions until after the uncertainty is resolved. Regions of C's optimal decisions described by Lemma 5 are illustrated in Figure 5.

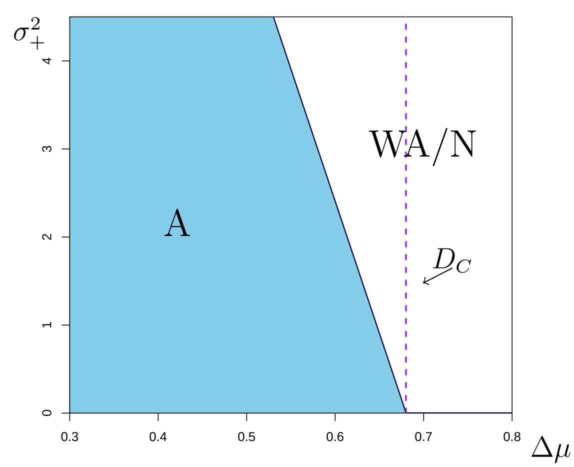


Figure 5 C**'s A and WA/N decision regions in** $\Delta\mu$ **and** σ_+^2 **when** $a = 10$, $w = 3$ **and** $\mu = 6$

Recall that in the incremental innovation game V may strategically source from C to expose itself to spillover risk and enable C to adopt its innovation, in anticipation that C will choose to delay its decisions until π is realized, thus conceding market leadership to V. In other words, V may "sell" the real option of waiting to C in exchange for market leadership. However, in this disruptive innovation game, C can adopt the innovation after the product is available in the market, even if V does not source from C. Furthermore, V's sourcing from C would also enable C to choose A, i.e., immediately adopt the innovation. The key question, then, is whether V has any incentive to voluntarily expose itself to this *early* innovation spillover risk. Lemma 6 characterizes the equilibria of the disruptive innovation game, and Proposition 6, which immediately follows from Lemma 6, provides an affirmative answer to this question.

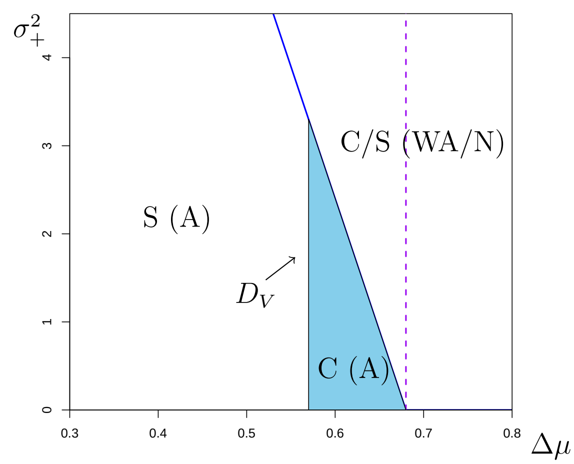


Figure 6 V**'s decision regions in** $\Delta\mu$ **and** σ_+^2 **for** $a = 10$, $w = 3$ **and** $\mu = 6$

LEMMA 6. *There exist thresholds* $D_V < D_C$ *and* Σ_+^2 *such that the equilibrium of the disruptive innovation game is*

1. *(C;A,WA/N), if* $D_V < \Delta\mu < D_C$ *and* $\sigma_+^2 < \Sigma_+^2$*;*
2. *(S;A,WA/N), if* $\Delta\mu < D_V$ *and* $\sigma_+^2 < \Sigma_+^2$*;*
3. *(C;WA/N,WA/N) or (S;WA/N,WA/N), if* $\Delta\mu > D_C$ *or* $\sigma_+^2 > \Sigma_+^2$*.*

Given the equilibrium conditions in Lemma 6, Proposition 6 characterizes V's optimal decisions.

PROPOSITION 6. *There exist thresholds* $D_V < D_C$ *and* Σ_+^2 *such that it is optimal for* V *to source from* C *(i.e., to voluntarily expose itself to early spillover risk), if* $D_V < \Delta\mu < D_C$ *and* $\sigma_+^2 < \Sigma_+^2$*. Furthermore, it is optimal for* V *to source from* S*, if* $\Delta\mu < D_V$ *and* $\sigma_+^2 < \Sigma_+^2$*. Finally,* V *is indifferent between* C *and* S*, if* $\Delta\mu > D_C$ *or* $\sigma_+^2 > \Sigma_+^2$*.*

The regions for V's optimal decisions in $\Delta\mu$ and σ_+^2 are illustrated in Figure 6. In particular, Proposition 6 establishes that it may indeed be optimal for V to source from C, i.e., to voluntarily expose itself to spillover risk, in anticipation of C's immediate adoption. Recall that in this disruptive innovation game, C can choose WA/N, regardless of V's sourcing decision. The WA/N decision enables C to eliminate both downside risk and operational risk and potentially gain advantage over V in terms of the product value: V and C have an equally good product if π turns out to be positive, but C has a better product than V if π turns out to be negative (because C resorts to the conventional product, corresponding to $\pi_+ = 0$). V can try to mitigate this disadvantage by sourcing from C, thereby exposing itself to spillover risk by offering C an opportunity for immediate adoption. If C indeed adopts immediately, it will gain market co-leadership position but will need to assume the same risks as V. It can be interpreted as C's choice to assume higher risk than it needs to in exchange for market co-leadership position. Thus, C is effectively offering insurance to V (in the sense of eliminating V's disadvantage in terms of risk), and V in return forfeits its market leadership position. For the CA outcome to emerge, V needs to value eliminating this risk disadvantage more than its market leadership advantage, provided that C values its market position disadvantage more than its risk advantage. This is the case when downside risk is substantial ($\Delta\mu > D_V$), so that the insurance is more valuable to V than its market leadership advantage, but the overall risk is limited (as illustrated by the region below the diagonal line in Figure 6), so that C would bear the risks in exchange for market co-leadership.

If operational risk is low ($\sigma_+^2 < \Sigma_+^2$) but downside risk is too low ($\Delta\mu < D_V$), C is willing to provide the insurance to V in exchange for the market co-leadership, but the insurance has little value to V. Therefore, V's priority is in securing its market leadership and preventing early innovation spillover. In this case, V sources from S and forces C to be the market follower.

On the other hand, if either operational risk or downside risk is high ($\sigma_+^2 > \Sigma_+^2$ or $\Delta\mu > D_C$), the real option of waiting becomes valuable, so WA/N is C's optimal decision. In other words, when either operational risk or downside risk is high, market co-leadership position is not valuable enough to C to justify assuming the risks, i.e., A is not C's optimal decision. Consequently, absent this insurance option, V is indifferent between C and S.

In summary, the principal tradeoff V is facing in the disruptive innovation game depends on the level of risk exposure. When the overall risk is high, C would not offer insurance to V, making V indifferent between C and S. However, when the overall risk is low, C is willing to assume the risk and by doing so give up its risk advantage over V, which effectively offers insurance to V (that negative realization of π will not put it at disadvantage relative to its market competitor C). Thus, it might be optimal for V to source from C (if downside risk is substantial), effectively unlocking the value of this insurance at the expense of giving up early innovation exclusivity and its market leadership.

5. Model Extensions

In this section, we discuss robustness of our key findings with respect to modifications and relaxations of several assumptions of our model.

5.1. Market Clearing: Cross-Product Impact

Recall that market clearing prices in our model are $p_R = a - q_V - q_C$ for the conventional product, and $p_I = \pi + a - q_V - q_C$ for the innovative product. Thus, the uncertain value of innovation π adds a premium to the market clearing price of the innovative product, but it does not affect the price of the conventional product. However, one might want to consider a model in which the introduction of the innovative product to the market also impacts the market clearing price of the conventional product. Such model would correspond to the setting in which consumers who are willing to pay more (less) for the innovative product, are likely willing to pay less (more) for the conventional product. This cross-product impact can be incorporated in our model by setting the market clearing price for the conventional product at

$$\tilde{p}_R = a - \pi - q_V - q_C.$$

First, in the disruptive innovation game, such cross-product impact can be captured by simply changing the definition of π_+ from $\max\{\pi, 0\}$ to $|\pi|$, without any changes in the analysis. Therefore, V's decision to source from C is still driven by the value of insurance, i.e., risk sharing. In fact, the insurance is even more valuable to V in this setting with cross-product impact on market clearing prices: when C waits and resorts to the conventional product due to a negative realization of π, the difference between the market clearing price of the innovative product and the conventional product, $\tilde{p}_R - p_I = 2\pi$, is double the corresponding difference $p_R - p_I = \pi$ in our model.

Incorporating the cross-product impact on market clearing prices has a more substantial effect on the analysis in the incremental innovation game. This is because $\tilde{p}_R$ depends on π and is ex-ante uncertain, which introduces operational risk for C even if it does not have access to the innovation, i.e., if V sources from S. Consequently, if V were to source from S, C's decision of WN would not necessarily be suboptimal, i.e., SWN is no longer a dominated outcome. This means V could potentially get the first-to-market advantage even if V sources from S. Nevertheless, the equilibrium (C;WA,N), in which V voluntarily exposes itself to spillover risk and thereby creates a real option of waiting for C who in turn gives up market leadership to V, does emerge in this setting, too.

Proposition 7. *Consider the incremental innovation game with market clearing prices p_I and $\tilde{p}_R$, and with $\mu_C = \mu_S = \mu$ and $\sigma_C^2 = \sigma_S^2 = \sigma^2$. There exist thresholds M^*, Σ^2 and Σ^{2*} such that, if $\mu < M^*$ and $\Sigma^2 < \sigma^2 < \Sigma^{2*}$, the equilibrium is (C;WA,N), i.e., it is optimal for V to source from C and voluntarily expose itself to spillover risk.*

Proposition 7 establishes that the result of Proposition 1 extends to this more complex market-clearing setting. (Figure 7 illustrates the equilibrium regions for an instance with $\mu_C = \mu_S = \mu$ and $\sigma_C^2 = \sigma_C^2 = \sigma^2$.) The main difference is the new constraint for C to choose N if V sources from S:

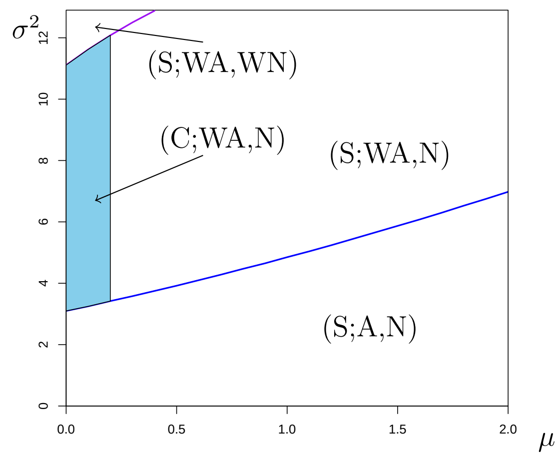


Figure 7 The equilibrium region of (C;WA,N) in μ and σ^2 when $a = 10$ and $w = 3$

an upper bound Σ^{2*} on operational risk σ^2 that C is facing. This difference is the consequence of the fact that the real option of waiting now has two components contributing to its value: the component, as in the original model, in the case of adoption (and this part of the option is available to C only if V chooses to source from C), and the "new" component, emerging only in this setting because of the cross-product impact, due to C facing operational risk even in the case with no access to the innovation. The "new" component is always available to C and does not depend on V's actions. Intuitively, V should not be able to benefit from the latter component of C's real option, i.e., potential for V benefiting from making this option available to C is limited by the value of the former component.

Thus, V's decision to source from C is based on evaluating one limited component of the real option value of waiting to C and comparing the benefit of possibly securing market leadership position to sourcing from S without exposing itself to spillover risk.

We stop short of providing closed-form full characterizations of equilibria and V's optimal decisions that would be analogous to the results of Lemma 3 and Proposition 4, primarily because the proofs would require more than straightforward modifications and extensions. Thus, we conclude by pointing out that we have established the existence of V's voluntary exposure to spillover risk in exchange for the real option value of waiting in this setting. This strongly suggests robustness of the optimality of such decision for a larger class of market-clearing models, i.e., our main insight that the optimal way to manage spillover risk might be voluntary exposure, is robust to a richer set of modeling choices of market-clearing.

5.2. Real Option Value of Waiting with Downside Risks

In the incremental innovation game we require that the value of innovation $\pi \geq 0$, i.e., there is no downside risk, $\Delta\mu = \mu_+ - \mu = 0$. In this section we discuss the robustness of our findings with respect to this assumption. Thus, we consider the incremental innovation game, but allow for the value of the innovation π to turn negative.

Providing full closed-form characterizations of equilibria and V's optimal decisions in such extended setting is challenging due to C's operational risk (either stemming from π or π_+), depending on the outcomes. However, with the additional assumption that C and S have the same capability, we can characterize settings in which voluntary exposure to spillover risk is V's optimal decision.

PROPOSITION 8. *Consider the incremental innovation game with $\pi_+ \neq \pi$, and with $\mu_C = \mu_S = \mu$ and $\sigma_C^2 = \sigma_S^2 = \sigma^2$. There exist thresholds M_e, D_+ and Σ_+^2 such that, if $\mu < M_e$, $\Delta\mu < D_+$ and $\sigma_+^2 > \Sigma_+^2$, the equilibrium is (C;WA/N,N), i.e., it is optimal for V to source from C and voluntarily expose itself to spillover risk.*

Note that C's decision is WA/N instead of WA in the original model, because C does not adopt the innovation if π turns out to be negative. Also note that, since C and S have the same capability, V would not source from C if it would immediately adopt the innovation, so outcome CA is dominated by SN. The intuition behind the result of Proposition 8 is similar to the intuition behind results presented in Section 3. The only caveat is related to the existence of downside risk $\Delta\mu$, which needs to be limited. With limited downside risk, the market leadership is valuable enough to V, despite the possibility of the value of innovation π turning negative (thereby giving market advantage to C's conventional product). The equilibrium region for (C;WA/N,N) in $\Delta\mu$ and σ_+^2, with fixed $\mu < M_e$, is depicted in Figure 8.

Finally, note that Proposition 8, together with results of Section 3, suggests that voluntary exposure to spillover risk could be V's optimal decision in the incremental innovation game, not just if one is to relax the assumption $\pi \geq 0$ but also if there are small enough differences in supplier capabilities (because profit functions are continuous and small changes will not affect ordering of profits for different outcomes).

5.3. Insurance Value of Immediate Adoption with Small Expected Values

In our analysis for the disruptive innovation game in Section 4, we assumed that the expected value of innovation is sufficiently large, i.e., $\mu > (a - 2w)/7$. This restriction simplifies our analysis because $\mu > (a - 2w)/7$ ensures that C's decision N, if V sources from S, is always suboptimal. If, however,

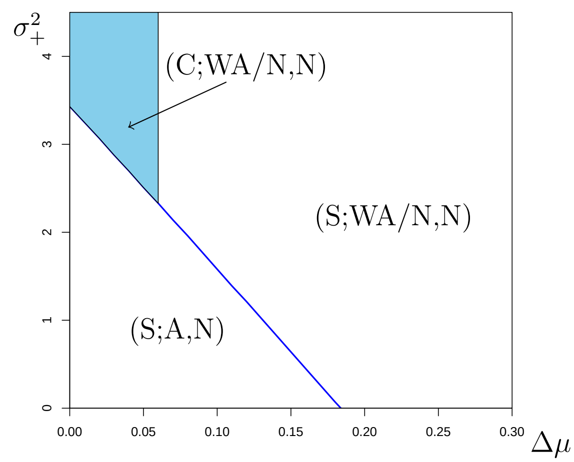


Figure 8 The equilibrium region of (C;WA/N,N) in $\Delta\mu$ and σ_+^2 when $a = 10$, $w = 3$ and $\mu = 0.2$

$\mu < (a-2w)/7$, N could be suboptimal if $\Delta\mu$ and σ_+^2 are sufficiently large. In this section, we relax the restriction on the expected value of innovation, μ. The following proposition establishes that outcome CA (strategy profile (C;A,WA/N)) may still arise in the equilibrium, i.e., V's optimal decision is to source from C and voluntary exposure to early spillover risk.

Proposition 9. *Consider the disruptive innovation game, there exists $\Delta\mu$, σ_+^2 and $\mu \leq (a-2w)/7$ such that such that CA is the equilibrium outcome, i.e., it is optimal for V to source from C and voluntarily expose itself to early spillover risk.*

Thus, the constraint on μ that ensures existence of V voluntarily exposing itself to spillover risk in exchange for sharing downside risk with C (that could be interpreted as "buying" insurance from C) can be relaxed further.

5.4. Risk Attitudes

The key driver behind our findings lies within exploiting tradeoffs between decision timing and various risks firms are facing. In particular, the focus is on managing spillover risk, and downside risk and operational risk play a critical role in deriving optimal decisions. In order to focus on these risks, isolate the structure of optimal decisions, and provide a clear interpretation of our findings, we assume that both V and C are expected profit maximizers, i.e., we assume they are risk-neutral. Given smoothness of profit functions for both firms in all of the outcomes, our qualitative findings are robust to small deviations from risk-neutrality. On the other hand, incorporating risk attitudes that are substantially different from risk-neutrality would make the analysis of Sections 3 and 4 analytically intractable, even if attentions were limited to some well-known classes of utility functions.

One possible generalization is to allow both V and C to be risk-averse, which is a typical assumption in the decision analysis literature (although it has also been argued that firms whose shareholders are well-diversified should be aiming toward risk-neutral decision-making; see Smith 2004). In such case, C's real option value of waiting increases in both incremental and disruptive innovation games. This suggests that results of Section 3, yielding our principal insight that V's optimal decision may involve exploiting tradeoff of spillover risk and C's operational risk, should be further strengthened. However, V's value of insurance of immediate adoption increases with risk-aversion. Thus, results of Section 4 yielding our principal insight that V's optimal decision may involve exploiting the tradeoff of spillover risk and downside risk could either be strengthened or weakened, depending on the relative degrees of risk-aversion of the two firms. For example, in the extreme case in which V is infinitely risk-averse but C is almost risk-neutral, it would be optimal for V to source from C as long as C would share downside risk by adopting the innovation before the uncertainty of the value of the innovation is resolved.

Another possible generalization could allow for V to be risk-seeking (as suggested and argued in the entrepreneurship literature, e.g., McMullen and Shepherd 2006). In this case, V would value the insurance aspect of innovation spillover less and would consequently have less incentive to source from C, i.e., this could weaken the principal tradeoff we established between spillover risk and downside risk (Section 4). On the other hand, in the incremental innovation game, a risk-seeking V would not necessarily have a weaker incentive to source from C as the limited negative effects of spillover risk might be easily offset by "risk reward" of seizing market leadership position in the market where profits are driven by the ex-ante uncertain value of innovation π.

These straightforward observations suggest that our main insights about innovation spillover risk management would hold even if firms are not expected profit maximizers. We also note that the analysis with the risk-neutrality assumption provides an important and natural benchmark.

6. Conclusion

In this paper we develop an analytical model to study optimal decisions of an innovator facing a competitor-supplier in the presence of spillover risk. The value of innovation is ex-ante uncertain, and depends on the market acceptance.

We argue that an innovator's decisions regarding innovation management are inherently interwoven with other important managerial decisions, such as optimizing order quantities and strategizing in order to secure a favorable market position. We show that the uncertainty of the value of the innovation and the interconnectedness of these decisions provide an opportunity for improvement in managing spillover risk. Specifically, we identify and exploit tradeoffs among spillover risk, C's operational risk, and V's downside risk that stem out of the ex-ante uncertainty of the value of the innovation, and timing of decisions that impact market clearing and consequently the firm's expected profits. (Table 1 summarizes differences between the two types of risk in our model.)

Type of Risks	*Spillover Channel*	*Value of Innovation*	*Supplier Capabilities*
C's operational risk	Sourcing	$\pi \geq 0$	Differentiated: (μ_C, σ_C^2), (μ_S, σ_S^2)
V's downside risk	Sourcing or Market	$\mu >> 0$	Identical: $(\mu,\ \sigma^2)$

Table 1 Trading off spillover risk with operational risk or downside risk

With operational risk, we find that it may be optimal for the innovator to voluntarily expose itself to spillover risk by sourcing from the competitor-supplier. If so, the competitor-supplier has a real option value of waiting, i.e., of delaying output quantity decision until the uncertainty of the value of the innovation is resolved. In doing so, the innovator will expose itself to innovation spillover but will secure the first-to-market position. This turns out to be the innovator's optimal decision when C's operational risk is high (and thus the real option is valuable) and the expected value of innovation is not too large (so the loss from innovation spillover is limited).

With downside risk, we find that it may be optimal for the innovator to voluntarily expose itself to *early* spillover risk by sourcing from the competitor-supplier. The reason for the innovator's willingness to source from the competitor-supplier and thereby expose itself to the early innovation spillover risk, is the attractiveness of eliminating its potential disadvantage in the market competition (as the competitor-supplier would not be able to resort to the conventional product should the value of the innovation turn out to be negative). For this to be the innovator's optimal decision, the insurance must be more valuable to the innovator than its market leadership position. Therefore, it emerges when the overall risk (i.e., downside risk plus operational risk) is limited (so that the insurance is available), but downside risk is not negligible (so that the insurance is valuable).

While our parsimonious model might appear stylized, it allows us to isolate important aspects of the problem and provide clean prescriptive solutions. Furthermore, our findings appear to be robust, suggesting that the insights would prevail in models that incorporate specific details of a particular business context. An important takeaway from the approach presented in this paper is the idea of *not* decomposing a multi-faceted decision problem, but exploiting tradeoffs across different facets and different parties. This is the key driver behind our analysis. It is plausible that a similar approach could be applied to other complex managerial decision-making problems.

Appendix: Proofs

This appendix collects proofs of all formal statements in the paper. Note that derivations and relationships among various inequalities in several proofs below are established using Mathematica, and can readily be replicated. (The files are available upon request.)

Proof of Lemma 1. It is evident that outcome CN and CWN are dominated by CA and CWA, respectively, as the value of innovation π cannot be negative. We derive the ex-ante expected profits of V and C in outcome CA, CWA, SN and SWN, and show that outcome SN dominates outcome SWN.

Outcome CA:

V sources from C, and V and C engage in Cournot competition without product differentiation. In this situation, V and C output q_V and q_C simultaneously prior to realization of π. The ex-ante expected profits of V and C are

$$\Pi_V^{CA} = (\mu + a - q_V - q_C)q_V - wq_V, \quad \Pi_C^{CA} = (\mu + a - q_V - q_C)q_C + wq_V. \tag{1}$$

By the first order condition, (1) yields the best responses of V and C as

$$BR_V(q_C) = (\mu + a - w - q_C)/2, \quad BR_C(q_V) = (\mu + a - q_V)/2. \tag{2}$$

Solving $BR_V(q_C)$ and $BR_C(q_V)$ from (2) jointly, we obtain the optimal output quantities

$$q_V = (a + \mu - 2w)/3, \quad q_C = (a + \mu + w)/3. \tag{3}$$

Plugging in the optimal quantities q_V and q_C from (3) into (1), the resulting optimal ex-ante expected profits are

$$\Pi_V^{CA} = (a + \mu - 2w)^2/9, \quad \Pi_C^{CA} = (a + \mu + w)^2/9 + w(a + \mu - 2w)/3, \tag{CA}$$

Outcome CWA:

V sources from C, and V and C engage in Stackelberg competition without product differentiation. Since the uncertainty of the value of the innovation is resolved when C produces, it could output quantity q_C^π based on the observed value of innovation π. Its profit Π_C^π is

$$\Pi_C^\pi = (\pi + a - q_V - q_C^\pi)q_C^\pi + wq_V. \tag{4}$$

By the first order condition, C's best response given q_V is

$$BR_C^\pi(q_V) = (\pi + a - q_V)/2. \tag{5}$$

On the other hand, V has to produce facing the uncertainty of the value of the innovation. It outputs q_V with respect to the expected value of innovation μ_C, and in response to the expected quantity of C. Its expected profit is

$$\Pi_V^{CWA} = (\mu_C + a - q_V - E[BR_C^\pi(q_V)])q_V - wq_V. \tag{6}$$

Plugging in C's best response and then optimizing (6) with respect to q_V, we obtain

$$q_V = (a + \mu_C - 2w)/2. \tag{7}$$

Substituting q_V from (7) into C's best responses in (5) and then taking expectation, we obtain

$$E[q_C^\pi] = (a + \mu_C + 2w)/4. \tag{8}$$

Given q_V from (7) and $E[q_C^\pi]$ from (8), the optimal ex-ante expected profits of V and C are

$$\Pi_V^{CWA} = (a + \mu - 2w)^2/8, \quad \Pi_C^{CWA} = (a + \mu + 2w)^2/16 + \sigma^2/4 + w(a + \mu - 2w)/2. \tag{CWA}$$

Outcome SN:

V sources from S, and V and C engage in Cournot competition with product differentiation. In this situation, V and C output q_V and q_C prior to the realization of π. V and C's ex-ante expected profits are

$$\Pi_V^{SN} = (\mu + a - q_V - q_C)q_V - wq_V, \quad \Pi_C^{SN} = (a - q_V - q_C)q_C. \tag{9}$$

By the first order condition, (9) yields the best responses functions

$$BR_V(q_C) = (\mu + a - w - q_C)/2, \quad BR_C(q_V) = (a - q_V)/2. \tag{10}$$

Thus, the optimal quantities are

$$q_V = (a + 2\mu - 2w)/3, \quad q_C = (a - \mu + w)/3. \tag{11}$$

Substituting the optimal quantities q_V and q_C from (11) into (9) yields the optimal ex-ante expected profits as

$$\Pi_V^{SN} = (a + 2\mu - 2w)^2/9, \quad \Pi_C^{SN} = (a - \mu + w)^2/9. \tag{SN}$$

Outcome SWN:

V sources from S, and V and C engage in Stackelberg competition with product differentiation. Since C cannot adopt the innovation even if it waits, C would produce q_C to maximize

$$\Pi_C^{SWN} = (a - q_V - q_C)q_C. \tag{12}$$

By the first order condition, C's best response given q_V is

$$BR_C(q_V) = (a - q_V)/2. \tag{13}$$

On the other hand, given C's best response, V would produce q_V to maximize

$$\Pi_V^{SWN} = (\mu + a - q_V - BR_C(q_V))q_V - wq_V. \tag{14}$$

Plugging in C's best response and then optimizing (14) with respect to q_V, we obtain

$$q_V = (a + 2\mu - 2w)/2. \tag{15}$$

Substituting q_V from (15) into C's best response in (14), we obtain

$$q_C = (a - 2\mu + 2w)/4. \tag{16}$$

Substituting q_V from (15) and q_C from (16) into (12) and (14) yields the optimal ex-ante expected profits of V and C as

$$\Pi_V^{SWN} = (a+2\mu-2w)^2/8, \quad \Pi_C^{SWN} = (a-2\mu+2w)^2/16. \tag{SWN}$$

One can check that assumption $a > \max\{3w, 2(\mu - w)\}$ which ensures positive output quantities implies $\Pi_C^{SN} = (a-\mu+w)^2/9 > (a-2\mu+2w)^2/16 = \Pi_C^{SWN}$.

□

Proof of Lemma 2. Given the ex-ante expected profits in Lemma 1, C would choose WA if and only if $\Pi_C^{WA} > \Pi_C^A$. One can check that the inequality holds if $\sigma^2 > \Sigma^2 = 7(a+\mu-2w)^2/36$. Thus, C would choose A, otherwise.

□

Proof of Proposition 1. Given the ex-ante expected profits in Lemma 1, one can check that when $\Pi_C^{WA} > \Pi_C^A$ (*i.e.*, $\sigma^2 > \Sigma^2 = 7(a+\mu-2w)^2/36$ follows from Lemma 2), $\Pi_V^{CWA} > \Pi_V^{SN}$ if $\mu_C < M_e = (6\sqrt{2}-7)(a-2w)/23$. However, when $\Pi_C^{WA} < \Pi_C^A$, it is always $\Pi_V^{CA} < \Pi_V^{SN}$.

□

Proof of Propositions 2, 3, 4 and Lemma 3. Let $\mu = \mu_C$ (μ_S) and $\sigma^2 = \sigma_C^2$ (σ_S^2) for the corresponding expected profits of V and C in Lemma 1. We first show Lemma 3 as it provides the complete characterization of equilibrium behavior, and then Propositions 2, 3 and 4 follow immediately.

Lemma 3: (C;A,N) is the equilibrium if and only if $\Pi_C^{CA} > \Pi_C^{CWA}$ and $\Pi_V^{CA} > \Pi_V^{SN}$. (S;A,N) is the equilibrium if and only if $\Pi_C^{CA} > \Pi_C^{CWA}$ and $\Pi_V^{SN} > \Pi_V^{CA}$. (C;WA,N) is the equilibrium if and only if $\Pi_C^{CWA} > \Pi_C^{CA}$ and $\Pi_V^{CWA} > \Pi_V^{SN}$. (S;WA,N) is the equilibrium if and only if $\pi_C^{CWA} > \Pi_C^{CA}$ and $\Pi_V^{SN} > \Pi_V^{CWA}$. One can check these inequalities hold respectively under the conditions in *(i)*, *(ii)*, *(iii)* and *(iv)*, where $K = 4(a+2w)[(8+9\sqrt{2})a - 2(8+3\sqrt{2})w]/(49a^2+20aw-92w^2)$, $M = \alpha(a-2w)[6\sqrt{2}(-32+9\alpha^2)|\alpha-2| + (16-9\alpha)|32-9\alpha^2|]/[(-32+9\alpha^2)|32-9\alpha^2|]$ and $\Sigma^2 = 7(a+\mu_C-2w)^2/36$.

□

Proof of Proposition 5. Note that $\Pi_C^{SWA} = \Pi_C^{CWA}$ in Lemma 1. Since $\pi > 0$, it is clear that $\Pi_C^{CA} > \Pi_C^{SN}$. Therefore, if $\Pi_C^{CWA} > \Pi_C^{CA}$, then $\Pi_C^{SWA} > \Pi_C^{SN}$.

□

Proof of Lemma 4. It is evident that outcome CN is dominated by CA as the expected value of innovation μ is positive. We derive the ex-ante expected profits of V and C in outcome CA, CWA/N, SN and SWA/N, and show that outcome SWA/N dominates SN (under the assumption that $\mu > (a-2w)/7$).

Outcome CA:

V sources from C, and V and C engage in Cournot competition. The ex-ante expected profits are derived simply by replacing μ_C with μ in Π_V^{CA} and Π_C^{CA} in Lemma 1:

$$\Pi_V^{CA} = (a+\mu-2w)^2/9, \quad \Pi_C^{CA} = (a+\mu+w)^2/9 + w(a+\mu-2w)/3, \tag{CA}$$

Outcome CWA/N:

V sources from C, and V and C engage in Stackelberg competition. Since the uncertainty of the value of the innovation is resolved, and it could resort to the conventional product, when C produces, it could output quantity $q_C^{\pi_+}$ based on the observed value of innovation π. Its profit $\Pi_C^{\pi_+}$ is

$$\Pi_C^{\pi_+} = (\pi_+ + a - q_V - q_C^{\pi_+})q_C^{\pi_+} + wq_V. \tag{17}$$

By the first order condition, C's best response given q_V is

$$BR_C^{\pi_+}(q_V) = (\pi_+ + a - q_V)/2. \tag{18}$$

On the other hand, V has to produce facing the uncertainty of the value of the innovation. It outputs q_V with respect to the expected value of innovation μ_C, and in response to the expected quantity of C. Its expected profit is

$$\Pi_V^{CWA} = (\mu + a - q_V - E[BR_C^{\pi_+}(q_V)])q_V - wq_V. \tag{19}$$

Plugging in C's best responses and then optimizing (19) with respect to q_V, we obtain

$$q_V = (a + 2\mu - \mu_+ - 2w)/2. \tag{20}$$

Substituting q_V from (20) into C's best responses in (18) and then taking expectation, we obtain

$$E[q_C^{\pi_+}] = (a - 2\mu + 3\mu_+ + 2w)/4. \tag{21}$$

Given q_V from (20) and $E[q_C^{\pi_+}]$ from (21), the optimal ex-ante expected profits of V and C are

$$\Pi_V^{CWA/N} = (a + 2\mu - \mu_+ - 2w)^2/8, \quad \Pi_C^{CWA/N} = (a - 2\mu + 3\mu_+ + 2w)^2/16 + \sigma_+^2/4 + w(a + 2\mu - \mu_+ - 2w)/2, \tag{CWA/N}$$

Outcome SN:

V sources from S, and V and C engage in Cournot competition. The ex-ante expected profits are derived simply by replacing μ_S with μ in Π_V^{SN} and Π_C^{SN} in Lemma 1:

$$\Pi_V^{SN} = (a + 2\mu - 2w)^2/9, \quad \Pi_C^{SN} = (a - \mu + w)^2/9. \tag{SN}$$

Outcome SWA/N:

V sources from S, and V and C engage in Stackelberg competition. The ex-ante expected profits are the same as in outcome CWA/N, except that C has no profit from producing for V:

$$\Pi_V^{SWA/N} = (a + 2\mu - \mu_+ - 2w)^2/8, \quad \Pi_C^{SWA/N} = (a - 2\mu + 3\mu_+ + 2w)^2/16 + \sigma_+^2/4. \tag{SWA/N}$$

One can check that $\Pi_C^{SN} > \Pi_C^{SWA/N}$ if and only if $\mu < (a-2w)/7$, $\Delta\mu < 1/9(a - 7\mu - 2w)$ and $\sigma_+^2 < 1/36(7a^2 - 54a\Delta\mu - 81\Delta\mu^2 - 50a\mu - 54\Delta\mu\,\mu + 7\mu^2 - 4aw - 108\Delta\mu w - 68\mu w - 20w^2)$. Therefore, restricting $\mu > (a - 2w)/7$ ensures that $\Pi_C^{SN} < \Pi_C^{SWA/N}$ for any $\Delta\mu$ and σ_+^2.

□

Proof of Lemma 5. Given the ex-ante expected profits in Lemma 4, C would choose A if and only if $\Pi_C^A > \Pi_C^{WA/N}$. One can check that the inequality holds if and only if $\Delta\mu < D_C = [-3a - 3\mu - 2w + 4\sqrt{a^2 + 2a\mu + \mu^2 - aw - \mu w + 2w^2}]/9$ and $\sigma_+^2 < \Sigma_+^2 = [7a^2 - 81\Delta\mu^2 + 7(\mu - 2w)^2 - 18\Delta\mu(3\mu + 2w) - 2a(27\Delta\mu - 7\mu + 14w)]/36$. Thus, C would choose WA/N, otherwise.

□

Proof of Lemma 6 and Proposition 6. We first show Lemma 6 as it provides the complete characterization of equilibrium behavior, and then Proposition 6 follows immediately.

(C;A,WA/N) is the equilibrium if and only if $\Pi_C^{CA} > \Pi_C^{CWA/N}$ and $\Pi_V^{CA} > \Pi_V^{SN}$. (S;A,WA/N) is the equilibrium if and only if $\Pi_C^{CA} > \Pi_C^{CWA/N}$ and $\Pi_V^{SN} > \Pi_V^{CA}$. (C/S;WA/N,WA/N) is the equilibrium if and only if $\pi_C^{CWA/N} > \Pi_C^{CA}$. One can check these inequalities hold respectively under the conditions in *(i)*, *(ii)*, and *(iii)*, where $D_V = (2\sqrt{2} - 3)(a + \mu - 2w)/3$, $D_C = [-3a - 3\mu - 2w + 4\sqrt{a^2 + 2a\mu + \mu^2 - aw - \mu w + 2w^2}]/9$, and $\Sigma_+^2 = [7a^2 - 81\Delta\mu^2 + 7(\mu - 2w)^2 - 18\Delta\mu(3\mu + 2w) - 2a(27\Delta\mu - 7\mu + 14w)]/36$.

□

Proof of Proposition 7. Under this formulation, none of the four possible outcomes, namely, CA, CWA, SN and SWN, is uniformly dominated, and the equilibrium expected profits for the outcomes are:

$$\Pi_V^{CA} = (a + \mu_C - 2w)^2/9, \quad \Pi_C^{CA} = (a + \mu_C + w)^2/9 + w(a + \mu_C - 2w)/3, \tag{CA}$$

$$\Pi_V^{CWA} = (a + \mu_C - 2w)^2/8, \quad \Pi_C^{CWA} = (a + \mu_C + 2w)^2/16 + \sigma_C^2/4 + w(a + \mu_C - 2w)/2, \tag{CWA}$$

$$\Pi_V^{SN} = (a + 3\mu_S - 2w)^2/9, \quad \Pi_C^{SN} = (a - 3\mu_S + w)^2/9, \tag{SN}$$

and

$$\Pi_V^{SWN} = (a + 3\mu_S - 2w)^2/8, \quad \Pi_C^{SWN} = (a - 5\mu_S + 2w)^2/16 + \sigma_S^2/4. \tag{SWN}$$

(C;WA,N) is the equilibrium if and only if $\Pi_C^{CWA} > \Pi_C^{CA}$, $\Pi_C^{SN} > \Pi_C^{SWN}$ and $\Pi_V^{CWA} > \Pi_V^{SN}$. When $\mu_C = \mu_S = \mu$ and $\sigma_C^2 = \sigma_S^2 = \sigma^2$, one can check that those inequalities hold under the conditions in Proposition 8, where $M^* = (4\sqrt{2} - 5)(a - 2w)/21$, $\Sigma^2 = 7(a + \mu - 2w)^2/36$ and $\Sigma^{2*} = (7a^2 - 6a\mu - 81\mu^2 - 4aw + 84\mu w - 20w^2)/36$.

□

Proof of Proposition 8. Allowing π to be negative, the equilibrium expected profits for outcome CA, CWA/N and SN are:

$$\Pi_V^{CA} = (a + \mu_C - 2w)^2/9, \quad \Pi_C^{CA} = (a + \mu_C + w)^2/9 + w(a + \mu_C - 2w)/3, \tag{CA}$$

$$\Pi_V^{CWA/N} = (a + 2\mu_C - \mu_+ - 2w)^2/8, \quad \Pi_C^{CWA/N} = (a - 2\mu_C + 3\mu_+ + 2w)^2/16 + \sigma_+^2/4 + w(a + 2\mu_C - \mu_+ - 2w)/2, \tag{CWA/N}$$

and

$$\Pi_V^{SN} = (a + 2\mu_S - 2w)^2/9, \quad \Pi_C^{SN} = (a - \mu_S + w)^2/9. \tag{SN}$$

(C;WA/N,N) is the equilibrium if and only if $\Pi_C^{CWA/N} > \Pi_C^{CA}$ and $\Pi_V^{CWA/N} > \Pi_V^{SN}$. When $\mu_C = \mu_S = \mu$ and $\sigma_C^2 = \sigma_S^2 = \sigma^2$, one can check that those inequalities hold under the conditions in Proposition 9, where $M_e = (6\sqrt{2} - 7)(a - 2w)/23$, $D_+ = [(3 - 2\sqrt{2})a + (3 - 4\sqrt{2})\mu + (4\sqrt{2} - 6)w]/3$ and $\Sigma_+^2 = [7a^2 - 81\Delta\mu^2 + 7(\mu - 2w)^2 - 18\Delta\mu(3\mu + 2w) - 2a(27\Delta\mu - 7\mu + 14w)]/36$.

□

Proof of Proposition 9. Consider the following numerical example: $a = 12$, $w = 3$, $\Delta\mu = 0.389$, $\sigma_+^2 = 0.01$, and $\mu = 0.8$. In this example, $\mu = 0.8 < 0.857 = (a - 2w)/7$ which implies SN is not uniformly dominated. Under these parameter values, $\Pi_C^{CA} = 34.5378 > 34.5366 = \Pi_C^{CWA/N}$, $\Pi_C^{SWA/N} = 24.9201 > 22.4044 = \Pi_C^{SN}$ and $\Pi_V^{CA} = 5.13778 > 5.13762 = \Pi_V^{SWA/N}$. This leads to CA as the equilibrium outcome.

□

Endnotes

1. For example, Foxconn which manufactures electronic devices for many clients, raises concerns about knowledge spillover (Hsiao et al. 2016); Apple, a leader in the smartphone market, and Samsung, one of Apple's most important suppliers for smartphone components, had filed over 50 patent lawsuits against each other as of 2015 (Elmer-DeWitt 2015). These examples indicate that the sole focus on intellectual property protection, like patents and trademarks, has inherent limitations in complex multi-faceted international business interactions. (In some cases the underlying reasons are straightforward: innovations are not always patentable, and competitors can often find ways to circumvent patents as well.)

2. While the innovator is naturally exposed to this risk, a competitor adopting the innovation is able to avoid it.

3. For example, this setting resembles Apple's relationship with LG and Samsung who are often suppliers of most innovative/critical parts of the Apple's products (e.g., Retina display) and also main competitors with their own products (AppleInsider 2010).

4. Innovations that are technological in nature are harder to adopt without access in the production stage, as the success may significantly depend on the involved supplier's capabilities. For example, during launch of the iPhone 4, Apple worked closely with LG to develop the Retina Display, which had the highest pixel density to date and was considered an impressive technical feat. In contrast, success of innovations focusing on altering the product's design concept does not depend on the supplier capability and are easily accessible/replicable once the product is available in the market. For example, the original iPhone in 2007 featured touch-based interactions in lieu of conventional hardware keyboard-based interactions.

5. Doing away with hardware keyboard, in lieu of touch-based interactions and on-screen keyboard, was considered a risky decision at the time of iPhone introduction, with many reviews concluding that the touch-based experience was inferior to the conventional keyboard-based experience (PC World 2007). Another overused example is Coca-Cola's New Coke (introduced in 1985), which was an innovation meant to replace the classic Coke, but was met with abysmal consumer responses and subsequently reverted (Coca-Cola 2012).

6. C can eliminate downside risk by delaying adoption decision, hence the ex-ante uncertainty about the innovation success that V and C are facing are not identical (as discussed in Section 4.)

7. All proofs are relegated to the Appendix.

8. More generally, the impact of time on risk and uncertainty perceptions and estimates is a central theme of decision analysis and is widely studied from normative, prescriptive and descriptive perspectives (e.g., Abdellaoui et al. 2011, Baucells and Heukamp 2012, Festjens et al. 2015.)

9. Note that S makes no decisions in our model. S simply represents V's best outside for sourcing.

10. We deliberately abstract away from richer descriptions of market dynamics on both revenue and cost sides. This not only makes our analysis tractable, but also allows us to isolate the structure and provide decision analytic interpretations of V's optimal decisions that are driven by managing and leveraging exposure to innovation spillover risk. In Section 5 we show that our qualitative insights extend to richer modeling settings.

11. This technical assumption ensures large enough market and eliminates uninteresting and trivial settings in which C's optimal decision is to produce zero quantity if it cannot adopt V's innovation.

12. The access in the sourcing stage is required for the adoption of the innovation. Consequently, C cannot adopt the innovation, not only before but also after π is realized, i.e., even after V's product is available in the market.

13. Given that π is realized instantaneously once the innovative product hits the market, considering only two decision points is sufficient. However, if one were to learn about π over time, a different continuous time model would be required. In such model, it is not a priori clear how would market-clearing be modeled. Comparing equilibria of Cournot and Stackelberg duopoly competitions for capturing first-to-market advantage is common in the literature (e.g., Arya et al. 2007, Swinney et al. 2011).

14. Our proofs rely on establishing best responses in this game.

15. Note that it is a weakly optimal decision for V to source from C when C's optimal decision is WA regardless of V's decision. In such case, V is indifferent between C and S.

16. This is because access to disruptive innovation in the sourcing stage is not necessary for its adoption after it hits the market, and thus V cannot benefit from trading-off its exposure to spillover risk and C's elimination of operational risk.

17. The proof of Lemma 4 establishes sufficiency of this bound. We discuss relaxation of this assumption in Section 5.

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