Investment Efforts Under Complementary Sourcing: The Role of Market Risk and Endogenous Pricing

Problem definition: Complementary sourcing, where a product depends on both a supplier's and a manufacturer's engineering and production efforts, is ubiquitous in modern supply chains. A unique feature of complementary sourcing is that efforts by one party enhance the marginal value of the other party's efforts. While this positive spillover effect can benefit both parties, it is well established in the literature that it paradoxically induces a first-mover disadvantage; neither party is willing to exert efforts ex ante, resulting in significant lost opportunities for improving sourcing performance. The question we consider in this paper is whether the first-mover disadvantage is a valid concern in more realistic sourcing environments where the market is risky and price is endogenous. **Methodology/results**: We analyze a sequential-investment model and investigate how market risk and endogenous pricing affect the first-mover disadvantage. In the presence of market risk, the first mover may face greater market uncertainty than the second mover, and thus is at an apparent disadvantage. Surprisingly, we find the introduction of market risk can favor the first mover. In effect, the presence of market risk weakens the second mover's ability to free ride on the first mover's investment, which increases the leverage of the first mover. This finding persists with exogenous pricing even if the first mover has weak power. **Managerial implications**: Our results suggest that the first-mover disadvantage identified in the extant literature ignores the operational aspect of practical sourcing environments, and sourcing managers should recognize that advance effort investment is often beneficial in more realistic complementary sourcing environments.

Key words: complementary sourcing, effort investment, market risk, pricing

1. Introduction

Complementary sourcing occurs when the efforts of suppliers improve the marginal benefits of the manufacturer's and vice versa. Examples of complementary sourcing abound in practice and show up in various forms such as investment in specialized equipment (Song and Di Benedetto 2011), component and architectural innovation (Rosell 2015), sequential innovation (Buccafusco et al. 2018), and research and development (Krishnan et al. 2019). While investment efforts from both suppliers and manufacturers improve product demand, there is an inherent first-mover disadvantages when the strategy choice of players are positively related (Gal-Or 1985). The reason is that the second mover can undercut the first mover by under-investing in efforts, partly free riding on the positive spillover effect created by the first mover. Due to such inherent first-mover disadvantage, the full benefit of complementary sourcing may not be always realized in practice. For example, Dyer (1997) observes that suppliers may be unwilling to invest unless manufacturers invest first to "purchase the specialized assets", which is then used by suppliers as a safeguard to protect against the hazards of opportunism. More broadly, the received wisdom suggests that first movers are often disadvantaged due to "free rider effects, resolution of technological uncertainty, shift in technology or customer needs" (Brink 2016).

Yet paradoxically, even under considerable technology or market risk, many suppliers or manufacturers nevertheless lead (and benefit from) investments in product innovations in a complementary sourcing context. We premise that, while technological or market uncertainty appears to worsen first-mover disadvantages, it could, however, induce second movers to invest more when the market turns out to be promising. Thus, contrary to the received wisdom, instead of worsening the first-mover disadvantage, in expectation technology/market uncertainty may ameliorate or even reverse the first-mover disadvantage.

Intuitively, the key tradeoff regarding whether a firm should lead the investment is as follows: on the one hand, the second mover will free ride the investment from the first mover due to the complementary nature of the investment; on the other hand, the first mover can accrue price-setting power and clear the market uncertainty to attract more investment from the second mover than what the second mover would have invested under uncertain market conditions. While the former puts the first mover in a disadvantage, the latter will provide a first-mover advantage in expectation. Therefore, technology and market uncertainty can, somewhat surprisingly, help to reverse the first-mover disadvantage and serve as an incentive for firms to invest first.

A case in point is the investment efforts between ASML and TSMC. ASML supplies precision lithography equipment to TSMC and other chip makers. By 2014, ASML invested about 2.8 billion in extreme ultra-violet (EUV) lithography (LaPedus 2014), even though the outlook of the EUV technology was highly uncertain, which "leaves continued investment in lithography and very expensive manufacturing process technology with increasingly uncertain future demand" (Sperling 2018). By 2016, however, seeing EUV is on the verge of being feasible with commercial production, TSMC announced its plan for risk production at 7nm process with EUV (Wikipedia 2022). In 2020 TSMC approved spending of $15.1 billion on EUV (Shilov 2020), with additional 28 billion in 2021 (Hwang and Lee 2021). ASML is currently the leading supplier for EUV scanners and charges between $120 \sim 180$ million dollars for each scanner.[1]

The above example shows that leading investments, while risky, may induce large subsequent investments. Interestingly, an earlier research by Eisenhardt and Tabrizi (1995) found empirically that a focal firm is better off investing early and involve the supplier later for less predictable products while leveraging the supplier early for more predictable products. This suggests that the effect of market risk on the first-mover disadvantage is more nuanced than intuitions might suggest. Note that economists and organizational science researchers in general link environmental [market]

[1] The EUV scanner is a 'raw tool' that requires significant process investments at chip makers such as TSMC, and hence the massive capital investments required. While TSMC did invest in ASML's EUV technology in 2012, it invested only about 345 million (Tyson 2012). At that time, TSMC was not convinced that ASML's EUV was commercially viable (Maire 2021). At the end of 2021, the P/E ratio is about 48 for ASML and 32 for TSMC.

uncertainty with first-mover disadvantage under horizontal competition, i.e., market uncertainty has deleterious effects on first movers when they compete for market dominance, see for example Liberman and Montgomery (1988), Dobrev and Gotsopoulos (2010). In a complementary sourcing setting considered here, however, firms face trade-offs that differ fundamentally from those in horizontal competition. As such, one cannot directly borrow insights from the economics and organizational science literature, which leads to our above observation that the effect of market risk can be ambiguous on first mover disadvantage.

Based on the above observations, we develop an analytical model that captures market risk and endogenous pricing, two key operational factors in complementary sourcing that have not been investigated in extant literature on first mover disadvantages. Our model is general enough that it can be interpreted in many different settings, from strategic collaboration to assets co-location. Leveraging this simple model, we analyze how these operational factors influence the first-mover disadvantage established in the literature. The classic study such as Gal-Or (1985) therefore does not directly apply in this more practical, operational setting.

Our study reveals some important insights into the first-mover disadvantage phenomena in a practical sourcing environment. First, as discussed above, consider a complementary sourcing setting where the manufacturer invests first before the supplier does. The manufacturer can strategically set wholesale price and leverage its own effort level to influence the supplier's effort. While the manufacturer's effort level is complementary to the supplier's, the wholesale price is not (i.e., all else being equal a higher price benefits the supplier but hurts the manufacturer and vice versa). The manufacturer therefore has two conflicting incentives when setting the purchase price: lower the price to save on the sourcing costs or raise the price to encourage the supplier to exert higher effort. The wholesale price set by the manufacturer, therefore, works in conjunction with its own effort levels to influence the supplier's efforts.

Second, expanding on existing studies, we show that, in absence of market risk, first-mover disadvantage largely persists even if the first mover can strategically set wholesale price – unless the complementary effect is relatively small. Hence, pricing power alone typically cannot compensate for the first-mover disadvantage such that firms would still be reluctant to make advanced investment in a complementary sourcing environment.

Third, when the market is risky, then the first-mover disadvantage is either significantly attenuated or completely reversed - regardless of whether the manufacturer can dictate the wholesale price. Part of the intuition is that the presence of market risk fundamentally changes the effect of manufacturer's investment on the supplier effort. If the market turns out to be better than expected the supplier's effort will increase (a positive effect) but if the market turns out to be worse than expected the supplier effort will decrease (a negative effect). These effects are typically not symmetric, but overall the supplier's investment effort becomes more "efficient" which may spillover to the manufacturer. This suggests that being a first mover in a risky market environment can be significantly beneficial even if the first mover cannot dictate wholesale price. Finally, our results can be extended to alternative settings, where the wholesale price is exogenous (with fixed, arbitrary margins), market risk remains unresolved before subsequent investment, and market selling price can be endogenously set.

Our findings echo the earlier examples (e.g., ASML and TSMC in EUV technology, manufacturers investing early before involving suppliers for less predictable products) and have important implications for complementary sourcing strategies: firms can be better off by making advanced investment in a complementary sourcing environment - not despite of market risk, but rather because of market risk's effect on curbing the first mover disadvantage. Therefore, firms should carefully assess their sourcing requirements, and when strong complementary effects exist, firms should not be discouraged by making early investment due to the commonly received belief on first-mover disadvantages. The complementary effects also serve as an effective safeguard to limit the first mover's pricing power and curb opportunism on the second mover in a typical sourcing setting where first mover can strategically set wholesale price and market is risky. In fact, even if the first mover does not bring pricing power, leading investment effort can be beneficial in presence of market risk.

1.1. Other Related Literature

This research is closely related to the extensive literature in strategic supplier collaboration. In general, such collaborations often happen in both directions: either a supplier or a manufacturer can initiate strategic collaboration. As such, we discuss the related literature through the lens of vertical channel interaction, which typically refers to supplier-retailer or supplier-manufacturer interactions with regard to pricing or ordering quantity decisions. These interactions are complementary when a decision choice by one party enhances the marginal value of the decision choice by the other party. Besides Gal-Or (1985), Lee and Staelin (1997) examines a setting where the decision choices involve pricing commitment in which both a supplier and a retailer set their respective price margins in response to the other. They found that if their margin responses are negatively related (i.e., an increased margin by one player induces a decreased margin by the other), then it is advantageous to be a first mover, while if margin responses are positively related, the opposite is true.[2] The

[2] The notion of the first-mover (dis-)advantage has attracted significant attention in economics, organizational science, and marketing science literature. These streams of literature focus on horizontal competition where firms compete for market dominance, which differs from our setting where firms invest efforts to improve market demand. Hence we do not detail this literature here but point interested readers to Liberman and Montgomery (1988), Kerin et al. (1992), Dobrev and Gotsopoulos (2010), and Querbes and Frenken (2017) for more details and references therein.

theory thus suggests that, under complementary sourcing, the manufacturer (and the supplier) will be unwilling to make investment ex ante due to first-mover disadvantage. This predication, however, ignores practical considerations in a typical sourcing relationship, most notably the pricing decisions and the presence of market risk when making investment decisions. We extend the above literature by considering such more practical sourcing environments.

From a more traditional supply chain perspective, researchers have empirically examined the factors that influence a buyer's investments with suppliers (Anderson and Weitz (1992), Eisenhardt and Tabrizi (1995), Dyer (1997), Krause and Ellram (1997), Krause (1997), Forker et al. (1999), Dyer and Nobeoka (2000), Humphreys et al. (2004), and Modi and Mabert (2007)). This literature provides a conceptual and empirical foundation for examining buyer and supplier joint improvement efforts. Note that our findings partly corroborate empirical findings in Eisenhardt and Tabrizi (1995) by showing that firms should lead investment when market uncertainty is large, that is, a focal firm is better off investing early and involve the supplier later for less predictable products. Recently, Bhaskaran and Krishnan (2009) consider a setting where vertical supply chain members may share development cost (investment sharing) and development work (innovation sharing), and they find that investment sharing is more attractive for products that are new to market while innovation sharing is more attractive when members have similar capabilities. They do not examine first-mover or second-mover disadvantages, however, since they assume the efforts are independent (non-complementary) and hence the investment sequence has no impact on either party's innovation effort. This research complements the above literature on two fronts. First, it expands the manufacturer's strategy to include both effort and pricing choices, which exhibit different complementarity effects in encouraging a supplier's effort. Second, it considers a more realistic setting where investment decisions are made under higher market risk for the first mover than that for the second mover who can observe market demand with better resolution. These two expansions allow a more nuanced understanding of the vertical channel interactions in complementary sourcing.

Pricing is another important consideration that affects investment in complementary sourcing. Krishnan et al. (2019) note that technology component suppliers often wonder whether downstream finished-product manufacturers "price these products high enough to extract the surplus of high-end-consumers for their own profit maximizations, resulting in less incentive for the suppliers to invest in innovation." Furthermore, when a manufacturer (or supplier) leads effort investments, it may also strategically set wholesale price besides its own effort levels to influence the other party's subsequent effort investments. While in practice the wholesale price is often negotiated between manufacturers and suppliers, the pricing power is typically positively influenced by the party that leads investments early (Dou 2016, Liozu 2019). Interestingly, the complementary nature of the sourcing relationship offers an automatic safeguard that limits the first-mover's ability to exploit its pricing power. Therefore, even if the first mover could strategically set wholesale price, it would not fully exploit the pricing power to extract all supply chain profits. Indeed, Schiele et al. (2011) empirically find that supplier innovation does not necessarily lead to higher prices. Nevertheless, even limited pricing power can still soften the first-mover disadvantage since it can at least partially attenuate the free-riding effect.

In sum, there is a vast literature in strategic collaboration that recognizes the phenomenon of first-mover disadvantage when the strategy choice of players are positively related. We refine this received wisdom by considering practical operational factors (i.e., pricing power and market risk) in a typical sourcing environment. We show that first-mover disadvantage can be significantly attenuated and oftentimes reversed when these operational factors are incorporated. Surprisingly, market risk does not aggravate but rather attenuate or reverse first-mover disadvantage. As such, manufacturers and suppliers should carefully examine their sourcing environments: if the market is risky, efforts are strongly complementary, and the first mover has pricing power, then advanced investment can be significantly beneficial.

The remainder of the paper is organized as follows. Section 2 describes the model setup and Section 3 examines the base setting with endogenous wholesale price. Section 4 explores the alternative settings with exogenous (fixed) wholesale prices, persistent market risks, and endogenous market selling price, respectively. Section 5 sums up our discussion and offers suggestions for future studies. All proofs are given in the (abridged) Appendix. Some auxiliary technical analyses (Sections A3 - A7) are contained in an unabridged version of the Appendix.

2. The Model

In this section we lay out the model context and introduce relevant parameters. Consider a manufacturer that designs and sells a product with a set of measurable performance attributes. The manufacturer procures some critical design and manufacturing work from a supplier; hence the product performance attributes are jointly influenced by both the manufacturer's and the supplier's investment efforts. The investment efforts of the manufacturer and the supplier contribute to different aspects of the product performance, and these different aspects may interact to influence the user experience of the product and hence the desirability of the product. It is worth pointing out that the manufacturer's and the supplier's investment efforts should be broadly interpreted: they can represent research and development efforts, engineering and design efforts, asset co-location efforts, or forecasting and planning efforts, as long as these efforts help to improve the end product performance.

Let $u(x_m, x_s)$ denote the user experience of the product, where x_m and x_s are the performance attributes contributed by the manufacturer and the supplier, respectively. These performance attributes are directly influenced by the effort levels invested by the manufacturer and the supplier. Without loss of generality, we scale the performance attributes of the product to be the same as the investment efforts, and hence x_m and x_s can also be equivalently viewed as investment efforts. In what follows we use the term performance attributes and effort levels interchangeably. Naturally, the user experience increases in both aspects of performance attributes x_m and x_s, i.e., $u'_m \geq 0$ and $u'_s \geq 0$. We assume diminishing marginal benefit in performance attributes, i.e., $u''_m \leq 0$ and $u''_s \leq 0$. Further, the performance attributes can exhibit complementary effect, i.e., $u''_{ms} \geq 0$. All concave supermodular functions satisfy the above conditions. For analytical clarity, we adopt the simplest form of $u(x_m, x_s)$ as a linear function of x_m and x_s with a constant marginal interaction term, i.e., $u(x_m, x_s) = x_m + x_s + \alpha x_m x_s$. Parameter $\alpha \geq 0$ captures the complementary effect. If $\alpha = 0$, then there is no complementary effect, and the user experience is captured by the sum of performance attributes (investment efforts). In contrast, when $\alpha > 0$, user experience is elevated beyond the sum of performance attributes. Investment efforts by the manufacturer and the supplier are costly, and, consistent with common assumption in the literature, we assume that such costs are convex and take the quadratic form, i.e., $e_i = \frac{1}{2}x_i^2$ for $i \in \{m, s\}$.

Market demand is uncertain, which is influenced by the product's intrinsic performance as well as the market 'taste' of the product category. For example, the product may be a particular type of vehicle. The demand for this vehicle will be influenced by (a) the performance attributes or features of this vehicle and (b) the market taste for this category of vehicles. We scale the performance attributes and market taste such that the lesser of these two factors determines the actual market demand for the product. For example, a product with high performance but low market taste would see its demand curbed by market taste. On the other hand, a product with low performance but high market taste would see its demand curbed by product performance. Let ϵ denote the market taste of the particular product category, then the market demand can be expressed as:

$$d(x_m, x_s, \epsilon) = \mu \min\{u(x_m, x_s), \epsilon\} = \mu \min\{x_m + x_s + \alpha x_m x_s, \epsilon\},$$

where μ is a scaling parameter for market size. Note that ϵ can be broadly interpreted as a market risk term that captures the uncertain market environment or factors external to the product itself but nevertheless limits the demand for that product.

Let r denote the unit profit for each product sold, and w denote the unit wholesale price paid by the manufacturer to the supplier. We normalize the supplier's unit production cost to zero, therefore w is the supplier's net unit profit. The manufacturer's unit production cost is subsumed in r. The sequence of events are as follows.

(a) Either the manufacturer or the supplier decides to make an effort investment first, which we label as the first mover. The first mover also strategically sets the wholesale price along with its effort investment, and these two decisions are made before market risk uncertainty ϵ is resolved.

(b) After observing the first mover's effort level and the wholesale price w, the second mover decides its effort investment level conditional on the realized market risk uncertainty ϵ.

(c) The manufacturer and the supplier fulfill market demand as much as possible at per unit profits of r and w, respectively.

In the above sequence of events, the second mover observes market demand uncertainty before making its effort investment decision. This approximates practical scenarios when the second mover has much better information about the market condition as compared to the first mover. Thus, our formulation offers an upper bound on the second-mover advantage in complementary sourcing. We now formulate the decision problems for the manufacturer and the supplier. For ease of exposition, we focus on the case where the manufacturer is the first mover and the supplier is the second mover. The other case can be similarly formulated. The manufacturer's decision problem is:

$$\pi_m^* = \max_{0\leq w\leq r, x_m\geq 0} \mathsf{E}_\epsilon\left[(r-w)d(x_m, x_s(x_m, w|\epsilon), \epsilon)\right] - \frac{1}{2}x_m^2, \tag{1}$$

where $x_s^*(w, x_m|\epsilon)$ is given by the maximizer to the supplier's problem (2) described below. Specifically, for any given x_m, w, and realized market risk uncertainty ϵ, the supplier's problem is:

$$\pi_s^* = \max_{x_s\geq 0} \pi_s(x_s|x_m, w, \epsilon) = \max_{x_s\geq 0} wd(x_m, x_s, \epsilon) - \frac{1}{2}x_s^2. \tag{2}$$

We note that the above simple model captures essential aspects of complementary sourcing: the parameter α signifies the strength of the complementary effect between the manufacturer's and the supplier's investment efforts; the market uncertainty ϵ captures market risks that the first mover face when making its effort investment and pricing decisions; the quadratic cost term captures the fact that the marginal cost of investment effort is increasing; and the wholesale price is endogenized to capture the fact that the first mover that makes advance investment is more likely to accumulate pricing power. Yet, this simple model allows us to demonstrate the nuanced effects of operational risk and pricing power on the first-mover disadvantage documented in the literature.

The above model makes three assumptions: (1) first mover decides the wholesale price, (2) second mover observes realized market risk before investing in efforts, and (3) retail price is exogenous. While these three assumptions are naturally satisfied in many cases, there are cases where these assumptions may not hold. We therefore also study several variants of the above model in subsequent sections: fixed wholesale price in §4.1, persistent market uncertainty for second mover in §4.2, and endogenous retail price in §4.3.

3. Analysis of the Base Model

To isolate the effects of market risk and wholesale pricing power, in what follows we first analyze a special case where there is no market risk, that is, ϵ is sufficiently large such that it would not limit market demand. This helps us to build intuition on how wholesale pricing power and market risk influences the first mover disadvantage in a complementary sourcing environment.

3.1. No Market Risk

The benchmark case of no market risk can be obtained by setting $\epsilon \to \infty$ (that is, there is no limit on potential product demand). We present and slightly extend the classic first-mover disadvantage result in Gal-Or (1985), which assumes symmetric payoff functions, to our model setting. This will then serve as a building block to subsequent analysis. Let subscript $\{m, s\}$ denote the manufacturer and the supplier, and superscript $\{M, S\}$ denote the cases when the manufacturer invests first and when the supplier invests first, respectively.

Lemma 1 (Gal-Or (1985)) *For any given fixed wholesale price $w \in [0, r]$, first-mover disadvantage persists in complementary sourcing, i.e., $\pi_m^{M*} \leq \pi_m^{S*}$ and $\pi_s^{S*} \leq \pi_s^{M*}$.*

The complementary nature of the manufacturer's and the supplier's investment efforts therefore create a paradoxical phenomenon. On the one hand, both parties benefit from the other's investment effort and hence both are better off with mutually increased investments. On the other hand, however, neither party has incentives to make investment before the other does since advance investment means lower profit as compared with late investment.

Now, consider the case where the first mover can strategically set the wholesale price to motivate the second mover to exert appropriate efforts. Intuitively, having the ability to set wholesale price should attenuate first mover disadvantage, since the first mover can exploit this pricing power for its own benefit. One might be concerned whether such a pricing power is feasible in practice since wholesale price is often negotiated between the supplier and the manufacturer. We shall show that the complementary nature of their investment efforts provides an intrinsic safeguard that limits the pricing power afforded to the first mover. As such, the wholesale price set by the first mover is more moderate than one might have anticipated.

Model (M): Manufacturer Moves First. The equilibrium investment efforts and optimal wholesale price can be obtained through backward induction. For any given manufacturer's effort investment and pricing decisions (x_m, w), the supplier's problem is to determine the optimal investment level $x_s^*(x_m, w)$ that maximizes its profit as described in (2), with $\epsilon = \infty$. It is straightforward to show that the optimal supplier effort is: $x_s^*(x_m, w) = \mu w(1 + \alpha x_m)$. Expecting the supplier's best response in investment effort $x_s^*(x_m, w)$, the manufacturer's problem is to determine the optimal investment effort and wholesale price, denoted as (x_m^M, w^M), to maximize its profit. Substituting $x_s^*(x_m, w) = \mu w(1 + \alpha x_m)$ into the objective function of (1), with $\epsilon = \infty$, we obtain the manufacturer's profit function as follows:

$$\pi_m(x_m, w) = (r - w)\mu \left(\mu w(1 + \alpha x_m)^2 + x_m\right) - \frac{1}{2}x_m^2. \tag{3}$$

The following proposition characterizes the manufacturer's and the supplier's optimal decisions.

Proposition 1 (Optimal Efforts) *When the manufacturer makes effort investment first, the optimal decisions in Model (M); i.e.,* (x_m^M, w^M, x_s^M)*, are determined as follows:*

1. *If* $\alpha r\mu \geq \sqrt{2}$*, then* $x_m^M = +\infty$*,* $w^M = \frac{r}{2}$*, and* $x_s^M = +\infty$*.*
2. *If* $\alpha r\mu < \sqrt{2}$*, then* $x_m^M = \bar{x}$*,* $w^M = \frac{r}{2} - \frac{\bar{x}}{2\mu(1+\alpha\bar{x})^2} := \bar{w}$*, and* $x_s^M = \mu\bar{w}(1+\alpha\bar{x})$*, where* $\bar{x}$ *is the unique positive root of:* $((\alpha r\mu)^2 - 2)\,\bar{x} + \frac{\bar{x}}{(1+\alpha\bar{x})^3} + r\mu(\alpha r\mu + 1) = 0$.

Part (1) of Proposition 1 tells us that when the complementary effect is sufficiently large, no finite equilibrium exists. The reason is that in such settings the complementary effect creates a 'snowballing' effect on both party's investment efforts and hence any finite equilibrium is not stable since an incremental increase in effort levels is always beneficial. While this setting is unrealistic, it does show that in the limit the optimal wholesale price converges to $r/2$ such that the supplier and the manufacturer equally split the supply chain profit. This demonstrates our earlier observation that even though the first mover is afforded with complete pricing power, such a power is curbed by the complementary nature of the sourcing relationship and hence the optimal wholesale price tends to be fairer than one might have expected. Furthermore, the above setting is not an artifact of our model, since for any reasonable convex cost function there always exists a sufficiently large complementary effect α such that no finite equilibrium can exist. We note that once market risk is considered then the above phenomenon no longer exists.

Part (2) of Proposition 1 presents the interior case where a finite equilibrium exists. Notice that the optimal wholesale price is always lower than $r/2$, meaning that the manufacturer earns a higher unit margin than the supplier does. This is somewhat as expected since it is the manufacturer that sets the wholesale price to maximize its own profit. Nevertheless, as we analytically show in the following corollary below, the optimal wholesale price w^M increases in the complementary parameter α, especially when α is relatively large. This reflects on the fact that the complementary effect limits the manufacturer's ability to lower the wholesale price, especially when α is relatively large. Specifically, we have:

Corollary 1 (Complementary Effect) *Suppose* $\alpha r\mu < \sqrt{2}$ *so that* $x^M = \bar{x}$ *and* $w^M = \bar{w}$*, where* $\bar{x}$ *and* $\bar{w}$ *are defined in part (2) of Proposition 1. Then: 1. If* $0 \leq \alpha r\mu < 0.75$*, then* $\bar{x} < 1/\alpha$*, and* $\bar{w}$ *decreases in* $\bar{x}$*. If* $\alpha r\mu \geq 0.75$*, then* $\bar{x} \geq 1/\alpha$*, and* $\bar{w}$ *increases in* $\bar{x}$*. 2. If* $0.75 \leq \alpha r\mu \leq 1.10$*,* x_m^M, w^M *and* x_s^M *increase in* α*.*

Part (1) of Corollary 1 suggests that when the manufacturer increases its optimal investment effort level (i.e., as $\bar{x}$ increases), all else being equal, the manufacturer can afford to lower its optimal wholesale price $\bar{w}$ only when the complementary effect α is relatively small. Specifically, when the complementary effect α is relatively large (so that the supposition in part (2) of the corollary holds), the manufacturer has to offer a higher wholesale price and exerts a higher effort to entice a higher investment effort from the supplier. As a result, we conjecture that the manufacturer may benefit from the endogenous pricing power and potentially reverse the first-mover disadvantage result established in Lemma 1 *only* when the complementary effect is relatively small. We shall formally explore this conjecture after we present the model where the supplier moves first by making the advanced investment and pricing decisions, as follows.

Model (S): Supplier Moves First. Here the supplier invests first by setting the investment effort x_s and wholesale price w, and then the manufacturer decides its effort level $x^*_m(x_s, w)$ for given (x_s, w). It is immediate to realize that Model (S) is identical to Model (M) if the wholesale price is alternatively defined as $w' = r - w$. One can then solve for the optimal (x_s, w', x_m) using the same approach in Model (M). Specifically, denote (x^S_s, w^S) as the supplier's optimal investment and pricing decisions in Model (S), and x^S_m as the manufacturer's corresponding optimal investment decision. The following identities must hold: $x^S_s = x^M_m$, $w^S = r - w^M$ and $x^S_m = x^M_s$.

Denote (π^{M*}_m, π^{M*}_s) and (π^{S*}_m, π^{S*}_s) as the optimal profits for the manufacturer and the supplier in Model (M) and Model (S), respectively. Then we must have: $\pi^{M*}_m = \pi^{S*}_s$, and $\pi^{M*}_s = \pi^{S*}_m$. Consequently, the total supplier chain profits remain the same in the two models; that is, $\pi^{M*}_m + \pi^{M*}_s = \pi^{S*}_m + \pi^{S*}_s$. Based on the above observations, the following theorem characterizes some sufficient conditions regarding the effect of endogenous wholesale price on the first-mover disadvantage.

Theorem 1 (First Mover Disadvantage: No Market Risk) *Comparing Model (M) with Model (S), the following results hold:*

1. *If $\alpha r\mu \le 0.46$, then first-mover disadvantage is reversed: $\pi^{M*}_m - \pi^{S*}_m = \pi^{S*}_s - \pi^{M*}_s > 0$.*
2. *If $1 \le \alpha r\mu \le 1.08$, then first-mover disadvantage persists: $\pi^{M*}_m - \pi^{S*}_m = \pi^{S*}_s - \pi^{M*}_s < 0$.*
3. *If $\alpha r\mu \ge \sqrt{2}$, then first-mover disadvantage approaches to zero: $\pi^{M*}_m - \pi^{S*}_m = \pi^{S*}_s - \pi^{M*}_s = 0$.*

Part (1) of the above theorem shows that endogenous pricing power causes the first-mover disadvantage in the classical model to shift to a strict advantage when the complementary effect is small. In this setting, the substitution effect of the margin decision that affords first-mover advantage more than offsets the complementary effect of the effort decisions that affords second-mover advantage. The following corollary clarifies this point by showing decisions and profits for the special case where there is no complementary effect.

Corollary 2 (Non-complementary Sourcing) *If $\alpha = 0$, then $x^M_m = x^S_s = r\mu, w^M = r - w^S = 0$ and $x^M_s = x^S_m = 0$. Furthermore, $\pi^{M*}_m = \pi^{S*}_s = (r\mu)^2/2 > \pi^{S*}_m = \pi^{M*}_s = 0$.*

Next, when the complementary effect (i.e., α) is moderately high, part (2) of Theorem 1 says that the endogenous pricing power is unable to overcome the first-mover disadvantage due to the downside of the complementary effect caused by the free-riding behavior of the supplier under complementary sourcing. This confirms our conjecture following Corollary 1 and suggests that even if making advance investment allows strategic wholesale pricing decision, such a power is insufficient to overcome the first-mover disadvantage. Finally, when the complementary effect is sufficiently high so that $\alpha r\mu \geq \sqrt{2}$, the optimal wholesale price converges to $r/2$ (Proposition 1, part (1)), and the supplier and the manufacturer equally split the supply chain profit. Therefore, the two models are essentially the same, as suggested by part (3) of Theorem 1.

To sum up, in the benchmark case setting without market risk, the endogenous wholesale price offers limited benefit to the first mover, and, as the complementary effect becomes stronger, the first-mover disadvantage persists. A key reason that the endogenous price offers less value than expected is because the complementary effect is an intrinsic safeguard that limits the first mover's ability to fully exploit its pricing power. For example, after Cannon and Nikon dropped out of EUV development, ASML becomes a virtual monopoly in the EUV market. While it is possible to charge very high prices for its EUV scanners, ASML refrains from significant price hikes because of tight complementary nature of EUV equipment and chip making. Therefore, in a complementary sourcing relationship where the product performance has inter-dependency on both supplier and manufacturer efforts, first-mover disadvantage is unlikely to be reversed with endogenous pricing power. Next, we consider the case where investment decisions are made under market risk.

3.2. With Market Risk

With market risk, the first mover must decide the optimal investment effort and wholesale price before observing realized market risk ϵ but the second mover decides its investment effort conditional on the realized market risk. Consequently, this uncertain market risk may put further downward pressure on the first mover disadvantage discussed in the benchmark case with no market risk. We next investigate whether this intuition is true, and, for expositional clarity, we present the special case where ϵ follows a Bernoulli distribution with $\epsilon_1 = \epsilon_0 + \sigma, \epsilon_2 = \epsilon_0 - \sigma, 0 \leq \sigma \leq \epsilon_0$ and $p_1 = p_2 = 0.5$. Notice in this case, $\bar{\epsilon} = \mathsf{E}(\epsilon) = \epsilon_0$.[3] The analysis of ϵ following a general discrete distribution is presented in the Appendix §A1.

Model (M): Manufacturer Moves First For any given manufacturer's effort investment and pricing decisions (x_m, w), the supplier's optimal investment effort (conditional on realized market risk ϵ) are presented in the following lemma.

[3] The no market risk case studied in §3.1 can be recovered by setting $\sigma = 0$ and letting $\epsilon_0 \to \infty$. Thus, market risk exerts an uncertain bound on market demand.

Lemma 2 (Conditional Supplier Effort) *For any given* (x_m, w) *and realized market risk* $\epsilon = \epsilon_i$, $i = 1, 2$, *the supplier's optimal investment effort is given by:*

$$x_s^*(x_m, w|\epsilon = \epsilon_i) = \begin{cases} 0 & \text{if } x_m \geq \epsilon_i; \\ \min\left(x_s^0(x_m, w), \frac{\epsilon_i - x_m}{1+\alpha x_m}\right) & \text{if } x_m \leq \epsilon_i, \end{cases} \tag{4}$$

where $x_s^0(x_m, w) = \mu w(1 + \alpha x_m)$.

The determination of the supplier's optimal investment effort therefore depends on a specific market risk realization. Anticipating the market risk and the supplier's optimal response characterized in the above lemma, the manufacturer makes the optimal investment effort and pricing decisions to maximize its expected profit: $\pi_m(x_m, w) = (r - w)\sum_{i=1}^{2} p_i d_i(x_m, x_s^*(x_m, w|\epsilon = \epsilon_i), \epsilon_i) - \frac{1}{2}x_m^2$, where $d_i(x_m, x_s^*(x_m, w|\epsilon = \epsilon_i), \epsilon_i) = \mu \min\{x_m + x_s^*(x_m, w|\epsilon = \epsilon_i) + \alpha x_m x_s^*(x_m, w|\epsilon = \epsilon_i), \epsilon_i\}$ is the market demand given $\epsilon = \epsilon_i$.

It follows from Lemma 2 that the manufacturer faces three possible regions of its investment effort x_m relative to the potential market risk ϵ: $x_m \geq \epsilon_1$, $\epsilon_1 \geq x_m \geq \epsilon_2$, and $x_m \leq \epsilon_2$. In the following result, we define and rank possible candidates for the manufacturer's optimal investment in Model (M), denoted as x_m^M.

Lemma 3 (Effort Bound) *Let* x_1 *be the unique value in* $[0, \epsilon_1]$ *that satisfies* $\frac{1+\alpha(2\epsilon_1 - x_1)}{(1+\alpha x_1)^3}\epsilon_0 = x_1$, *and* x_2 *be the unique value in* $[0, \epsilon_2]$ *that satisfies* $\frac{1+\alpha(2\epsilon_2 - x_2)}{(1+\alpha x_2)^3}\epsilon_2 = x_2$. *Suppose* $r\mu \geq \epsilon_1 + 2\epsilon_0$. *Then we have:* $x_i \leq \epsilon_i$, *for* $i = 1, 2$, *and* $x_1 \geq x_2$.

Proposition 2 (Optimal Manufacturer Effort) *Define* $\pi_1 = \left(r - \frac{\epsilon_1 - x_1}{\mu(1+\alpha x_1)^2}\right)\mu\epsilon_0 - \frac{1}{2}x_1^2$, *and* $\pi_2 = \left(r - \frac{\epsilon_2 - x_2}{\mu(1+\alpha x_2)^2}\right)\mu\epsilon_2 - \frac{1}{2}x_2^2$. *Let* k *denote the smallest index in* $\{1, 2\}$ *such that* $\pi_k = \max\{\pi_1, \pi_2\}$. *Suppose* $r\mu \geq 3\epsilon_0 + \sigma$. *Then the manufacturer's optimal decisions can be determined as:* $(x_m^M, w^M) = \left(x_k, \frac{\epsilon_k - x_k}{\mu(1+\alpha x_k)^2}\right)$. *Furthermore, we have:* $x_m^M \leq \epsilon_0$, *and the manufacturer's optimal expected profit is:* $\pi_m^{M*} = \pi_k = \max\{\pi_1, \pi_2\}$.

Proposition 2 shows that the manufacturer's optimal investment level x_m^M never exceeds the expected market risk ϵ_o, and thus the manufacturer can potentially benefit from such a lower effort by leading the investment effort. Next, the supplier's optimal investment effort depends on the realized market risk, and as a result, the corresponding market demand (conditional on the realized market risk $\epsilon = \epsilon_i$) may be higher than the expected market demand. Therefore, while uncertain market risk poses an additional hurdle for the manufacturer to overcome the free-riding behavior of the supplier under complementary sourcing, it also creates an opportunity for more efficient investment efforts subsequently. Thus, the first-mover disadvantage result may or may not persist under market risk. We shall re-examine this issue later.

Model (S): Supplier Moves First In Model (S), the supplier moves first by setting the effort x_s and price w, and the manufacturer decides his effort level $x_m^*(x_s, w|\epsilon = \epsilon_i)$ after observing the market risk $\epsilon = \epsilon_i$. Observe that Model (S) can be transformed to Model (M) if one redefine $w' = r - w$, and solve for the optimal (x_s, w', x_m) in Model (S). Specifically, define (x_s^S, w^S) as the supplier's optimal decisions, and $x_m^S(x_s^S, w^S|\epsilon = \epsilon_i)$ as the manufacturer's corresponding optimal decision (conditional on $\epsilon = \epsilon_i$), then we must have: $x_s^S = x_m^M$, $w^S = r - w^M$, and $x_m^S(x_s^S, w^S|\epsilon = \epsilon_i) = x_s^M(x_m^M, w^M|\epsilon = \epsilon_i)$. Hence, the following proposition ensues.

Proposition 3 (Optimal Supplier Effort) *Suppose* $r\mu \geq \epsilon_1 + 2\epsilon_0$. *Then:* $(x_s^S, w^S) = \left(x_k, r - \frac{\epsilon_k - x_k}{\mu(1+\alpha x_k)^2}\right)$, *where* $\pi_k = \max\{\pi_1, \pi_2\}$. *Furthermore, for realized market risk* $\epsilon = \epsilon_i$, $i = 1, 2$, *the manufacturer's optimal effort can be determined as:* $x_m^S(x_s^S, w^S|\epsilon = \epsilon_i) = 0$ *if* $x_s^S \geq \epsilon_i$; *and* $x_m^S(x_s^S, w^S|\epsilon = \epsilon_i) = \min\left(\mu(r - w^S)(1 + \alpha x_s^S), \frac{\epsilon_i - x_s^S}{1+\alpha x_s^S}\right)$ *if* $x_s^S \leq \epsilon_i$.

Having characterized the optimal decisions in Model (M) and Model (S), now we are ready to compare the profit performances in these two models to examine the first mover disadvantage/advantage under market risk. Recall that (π_m^{M*}, π_s^{M*}) and (π_m^{S*}, π_s^{S*}) denote the optimal expected profits for the manufacturer and the supplier in Model (M) and Model (S), respectively. The following result follows from Propositions 2 and 3.

Corollary 3 (Optimal Profit Comparison) *1.* $\pi_m^{M*} = \pi_s^{S*}$, $\pi_s^{M*} = \pi_m^{S*}$; *2.* $\pi_m^{M*} + \pi_s^{M*} = \pi_m^{S*} + \pi_s^{S*}$.

The expected total supply chain profit remains the same in the two models, regardless of whether the manufacturer or the supplier makes advance investment. Next, we compare the manufacturer's expected profits in Model (M) and Model (S), and identify conditions under which the first-mover disadvantage is reversed; that is, $\pi_m^{M*} > \pi_m^{S*}$.

Theorem 2 (Reversal of First Mover Disadvantage: With Market Risk) *Suppose* $r\mu \geq 3\epsilon_0 + \sigma$ *and* $\sigma/\epsilon_0 \leq 3 - 2\sqrt{2}$. *Then* $\pi_m^{M*} > \pi_m^{S*}$, *and* $\pi_s^{S*} > \pi_s^{M*}$.

The left-hand side of the condition in Theorem 2 can be interpreted as the revenue potential of the market (r is the selling price while μ is the market size scalar). The right-hand side of the condition is a function of the highest possible market realizations. Hence, the sufficient condition roughly represents situations where the market revenue potential is much higher than the weighted market risks. In such settings, Theorem 2 suggests that the revenue potential is impacted by market risks and the manufacturer is better off making advance investment to capture as much revenue potential as possible, as opposed to leaning on supplier's investment effort by delaying its own investment.

It is worth pointing out that the condition in Theorem 2 is a conservative sufficient condition. First-mover disadvantage can be reversed even if the conditions identified in Theorem 2 fail to hold. As an illustration, Figure 1 shows that first-mover disadvantage is reversed for the Bernoulli distribution case although the parameter values are such that $r\mu = 1 < 2\epsilon_1 + (\epsilon_0 - p_1\epsilon_1)/p_1 = 180$. [4]

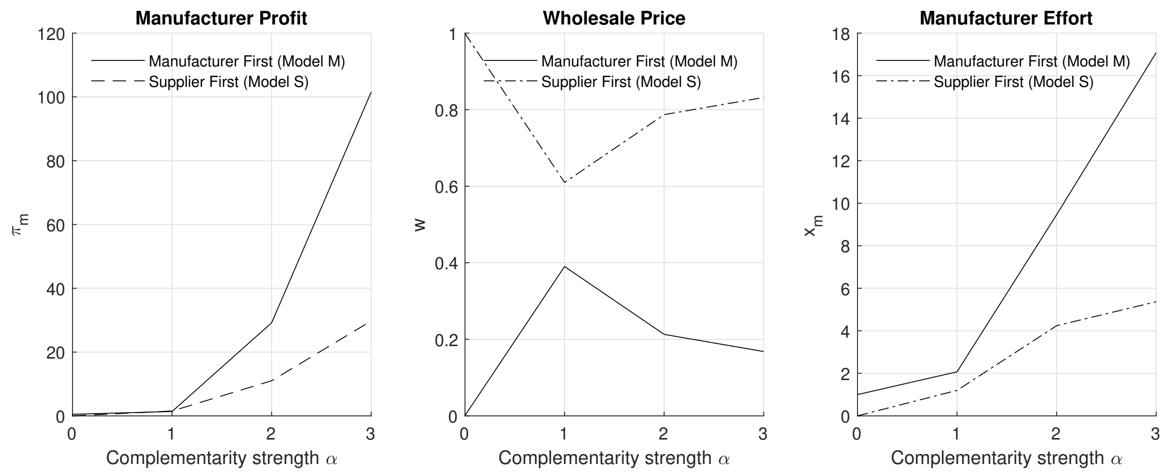

Figure 1 **The manufacturer profit, wholesale price, and effort in Model (M) versus Model (S). Market risk follows Bernoulli distribution with $\epsilon = \epsilon_0 \pm \delta$ with equal probability, $\epsilon_0 = 50$, and $\delta = 30$.**

Figure 1 illustrates that the manufacturer is strictly better off by investing first for almost all ranges of complementary effect α, even when α exceeds the theoretical bounds of $\sqrt{2}$ (beyond which no equilibrium exists for the no market risk case). This suggests that when there is a strong complementary effect in the sourcing relationship, it is increasingly more attractive to invest effort first than wait to see realized market risk and then make effort investment. This is somewhat unexpected, given the fact that first-mover disadvantage originates from complementary effect, and the existence of market risk uncertainty shall dampen the benefit of advance investment and worsen the first-mover disadvantage result. Part of the intuition is related to the fact that the supplier, acting as a second mover, may not exert investment effort if market demand turns out to be low but can exert high efforts if market demand turns out to be high. Anticipating this fact, the manufacturer, acting as a first mover, sets a lower wholesale price to extract the complementary (spillover) value from supplier's subsequent investments. This observation can be verified in Figure 1 by noting that the wholesale price eventually declines as complementary effect increases. Note that, while not apparent from the figure, the manufacturer's investment effort eventually plateaus as the complementary effect strengthens, since the manufacturer can leverage the supplier's investments

[4] Figure 1 and all subsequent figures (unless otherwise noted) are plotted with Bernoulli market risk where $\mathsf{E}[\epsilon] = \epsilon_0$ and $\epsilon_0 = 50$.

as opposed to keep increasing its own effort level. The above observations also hold under more general market risk distributions (see Appendix §A1).

3.3. Market Risk Volatility

As hinted in the conditions in Theorem 2, the first mover advantage is closely related to the market volatility. In what follows, we analytically and numerically evaluate the impact of market risk volatility on the optimal investment efforts, wholesale prices, and expected profits of the two parties, as well as the performance difference of the manufacturer in Model (M) (as the first mover) and Model (S) (as the second mover). The following result ensues.

Proposition 4 (Market Risk) *Suppose $r\mu \geq 3\epsilon_0 + \sigma$. Then:*

1. *For $0 \leq \sigma \leq \epsilon_0$, x_1 increases in σ, and x_2 decreases in σ. Therefore $x_2 \leq x_0 \leq x_1 \leq \epsilon_0$, where x_0 is the optimal investment effort for the first mover in the case when $\sigma = 0$.*
2. *For $0 \leq \sigma \leq \epsilon_0$, both π_1 and π_2 decrease in σ. Therefore $\pi_m^{M*} = \max\{\pi_1, \pi_2\}$ decreases in σ, and $\pi_m^{M*} \leq \pi_0$, where $\pi_0 = \left(r - \frac{\epsilon_0 - x_0}{\mu(1+\alpha x_0)^2}\right)\mu\epsilon_0 - \frac{1}{2}x_0^2$ is optimal profit for the first mover when $\sigma = 0$.*

Recall x_1 and x_2 are the only two possible candidates for the optimal investment effort of the first mover, with corresponding expected profits π_1 and π_2, respectively. Part (1) of Proposition 4 suggests that depending on whether x_1 or x_2 is the "dominating" candidate (in terms of profit comparison), the optimal investment effort for the first mover may be increasing or decreasing in the market risk volatility σ. Nevertheless, part (2) of the proposition says that the optimal expected profit of the first mover always decreases in σ, confirming our intuition that that expected profit suffers from the presence of market risk uncertainty. Thus, compared to the case with no market risk uncertainty; that is, the case when $\sigma = 0$, the manufacturer (as the first mover) will exert a lower effort and obtain a lower expected profit: $x_m^M \leq x_0$ and $\pi_m^{M*} \leq \pi_0$, especially in the case when $\pi_2 > \pi_1$ so that $x_m^M = x_2$.

In Figure 2, we further examine the impact of the market risk volatility (i.e., σ) on the performance of the manufacturer (as the first mover). The figure corroborates our findings in Proposition 4 that the manufacturer's expected profit consistently decreases in the market risk volatility σ, but the optimal investment effort can be increasing or decreasing in σ. Furthermore, the impact of the market risk volatility on the behavior of the optimal investment effort and the optimal wholesale price depends on the degree of the complementary effect α. When the complementary effect is strong ($\alpha = 3$), the optimal effort decreases while the wholesale price increases with the market risk volatility. This means that the manufacturer (as the first mover) exerts a lower investment effort but offers a higher wholesale price to reduce the negative impact of market volatility on the supplier's incentive to exert effort. In contrast, when the complementary effect is relatively

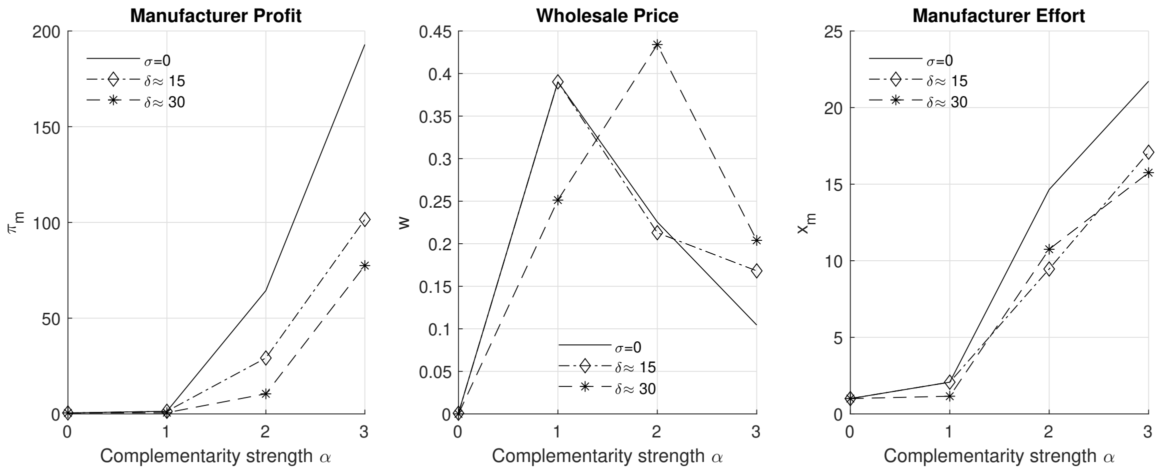

Figure 2 **The manufacturer profit, wholesale price, and effort as a first mover under market risk.**

low ($\alpha = 1$), the manufacturer can afford to exert a lower effort and set a lower wholesale price, especially when the market risk volatility is low to moderate.

In sum, we demonstrate that the first-mover disadvantage can be reversed, not despite of the market risk, but because market risk allows the first mover to reduce wholesale price and investment effort and yet increases the potential profit when market demand turns out to be high. This effect is especially strengthened when the complementary effect is high. Interestingly, while market risk is a critical factor that reverses the commonly accepted notion of first-mover disadvantage under complementary effect, increased market risk volatility typically reduces the magnitude of such a reversal. That is, being the first mover by investing first is advantageous when there is market risk and wholesale price can be endogenously set, however, as market volatility increases, such advantages are typically weakened (but not eliminated). This result contrasts starkly with the received wisdom that first mover disadvantage worsens with complementary relationship and that market risk exerts further downward pressure on the first mover's profit. Our results therefore refine the current understanding of the nature of collaborative sourcing under more realistic settings where market is risky and wholesale price can be influenced by the party that invests early.

The above analysis rests on three assumptions: (a) the first mover can strategically set the wholesale price to influence the second mover's investment levels, (b) the second mover can observe market risk before making investment decisions, and (c) the market selling price is fixed. While these assumptions are valid for many settings, there are situations where each of these assumptions may not hold. Thus, it is both practically relevant and theoretically interesting to analyze the alternative setting the above assumptions are relaxed. This is the focus of the next section.

4. Model Extension

4.1. Fixed (Exogenous) Wholesale Price

In this section, we consider the setting where the wholesale price is fixed (exogenous) regardless of who invests first. A fixed wholesale price, potentially asymmetric to the manufacturer and the supplier, approximates the setting where the wholesale price is based on negotiation cost (e.g., market power) that does not depend on which party invests first (Rubinstein 1982). This helps to isolate the effect of wholesale price on first-mover disadvantages. We adopt the same model as analyzed in §3.2, except that the wholesale price w is fixed but can take any value on $[0, r]$.

For expositional clarity, in what follows we focus on the maximum volatility case of $\sigma = \epsilon_0$, that is, $\epsilon_1 = 2\epsilon_0$ and $\epsilon_2 = 0$. This approximates an upper bound on the first mover disadvantage - see Proposition 4. A special case of the Bernoulli distribution is when $\sigma = 0$ so that $\epsilon_1 = \epsilon_2 = \epsilon_0$. This case of minimum variance in market risk (equivalently, when ϵ is constant, and $\epsilon \equiv \epsilon_0$) is analyzed in the Appendix §A4. Further, the analysis of the optimal investment efforts is similar to the base model, and hence the details are relegated to the Appendix §A5. The following theorem gives sufficient conditions for our key findings under the fixed wholesale price setting.

Theorem 3 (First Mover Disadvantage: Fixed Wholesale Price) *When ϵ follows a Bernoulli distribution with sample space $\{0, \epsilon_1 = 2\epsilon_0\}$ and success probability p_1; i.e., Prob$(\epsilon = \epsilon_1) = p_1$, we have:*

1. *Suppose $\epsilon_1 \leq r\mu/2$, and $\epsilon_1/\mu \leq w \leq r - \epsilon_1/\mu$, then the first-mover disadvantage is reversed.*
2. *Suppose $\epsilon_1 > r\mu/2$ and $w = r/2$. Then we have:*
   (a) *If $\alpha r\mu\sqrt{p_1} \geq 2$, the first-mover disadvantage is reversed.*
   (b) *If $\sqrt{2} \leq \alpha r\mu\sqrt{p_1} < 2$ and $\epsilon_1 < \frac{r\mu(2+2\sqrt{p_1}-\alpha r\mu p_1)}{(2-\alpha r\mu\sqrt{p_1})^2}$, the first-mover disadvantage is reversed.*
   (c) *If $\sqrt{2} \leq \alpha r\mu\sqrt{p_1} < 2$ and $\epsilon_1 \geq \frac{r\mu(2+2\sqrt{p_1}-\alpha r\mu p_1)}{(2-\alpha r\mu\sqrt{p_1})^2}$, the first-mover disadvantage is preserved.*

Theorem 3 suggests that even if the manufacturer does not accrue pricing power as the first mover and the wholesale price is fixed, it can still be better off by leading the effort investment. Notice that the suppositions in part (1) of Theorem 3 are the same as that in Theorem 2 when $\sigma = \epsilon_0$, except that an additional condition on the range of the fixed wholesale price w is required. This additional condition suggests that the first mover disadvantage is reversed when the power relationship between the supplier and the manufacturer is relatively balanced but can persist otherwise.

Part of the intuition for the reversal of first-mover disadvantage result even in the absence of pricing power is that market risk carries both downside cost (low market taste realization negates early investment) and upside reward (high market taste realization encourages large subsequent investments by the second mover). With complementary effect on investment efforts, the upside reward can offset the downsize cost associated with market risk, resulting in the first mover being better off by leading investment efforts. In essence, market risk makes it possible for the first mover to exert lower investment efforts while the second mover cannot resist high investment efforts when market turns out to better than expected. To further clarify the effect of endogenous wholesale price on the first mover disadvantage, below we numerically illustrate the difference between endogenous wholesale price and fixed wholesale price on first mover disadvantages.

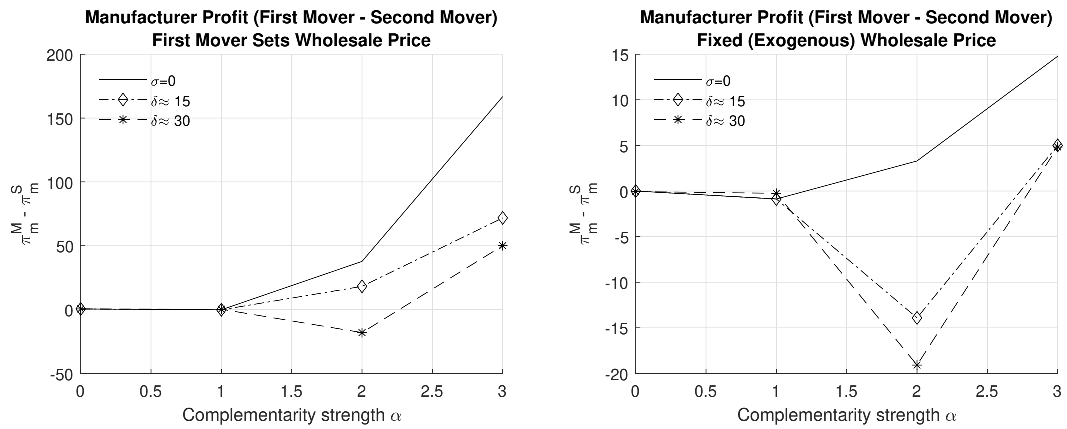

Figure 3 **The manufacturer profit difference as a first mover versus as a second mover. In the left panel, the wholesale price is set by the first mover. In the right panel, the wholesale price is fixed at $r/2$ such that the manufacturer and the supplier have equal margins.**

Figure 3 shows that the first mover disadvantage is reversed more profoundly under endogenous wholesale price (left panel) than that under fixed wholesale price (right panel). This is as expected because the ability to set wholesale price affords the manufacturer another lever to incentivize the supplier to make desired investment efforts. Nevertheless, the right panel of Figure 3 shows that the first mover disadvantage can still be reversed as the complementary effect strengthens - even if the first mover does not possess pricing power. Additionally, the figure shows that regardless of whether the wholesale price is set by the first mover, volatility in market risk hurts the first mover as the first mover faces greater risk in its investment efforts. This is consistent with the endogenous price case as discussed in Proposition 4.

In summary, we show that the key result under §3.2 continues to hold when the first mover cannot dictate the wholesale price. Nevertheless, the wholesale price must be such that the margins are relatively equitable for either the supplier or the manufacturer to lead the investment effort. Not being able to set wholesale price in general hurts the first mover, but such a pricing power is not necessary for firms to lead investment efforts as a first mover. As long as there exists sufficient complementary effect and market is somewhat risky, then leading investment efforts can be advantageous. So far, our analyses assume that the second mover can observe realized market risk before making investment decisions. We next study the alternative setting where the second mover cannot observe realized market risk before making investment decisions.

4.2. Persistent Market Risk

In this section, we consider the case where the second mover faces the same (persistent) market risk as the first mover, that is, the second mover cannot observe realized market demand before making investment decisions. In such a setting, the second mover cannot enjoy the benefit of improved market clarity. Intuition suggests that this setting should favor the first mover since the second mover is less likely to free ride on the first mover's investment conditioning on the market risk realizations. We next explore whether this intuition holds true in general. To isolate the effect of persistent market risk (from pricing effects), we consider a similar setting as that in §4.1, where the wholesale price is fixed. Additionally, to fully expose the effect of persistent market risk, we consider the setting where the manufacturer and the supplier face maximum variance in market risk, that is, $\sigma = \epsilon_0$ such that $\epsilon_1 = 2\epsilon_0$ and $\epsilon_2 = 0$.

Without loss of generality, we consider the case where the manufacturer is the first mover and the supplier must decide its investment effort facing the same market risk. First, for any given x_m, the supplier's expected profit is $\pi_s(x_s|x_m) = p_1 w\mu \min\{x_m + x_s + \alpha x_m x_s, \epsilon_1\} - \frac{1}{2}x_s^2$ where $p_1 = \text{Prob}(\epsilon = \epsilon_1)$. Next, anticipating the supplier's optimal effort $x_s^*(x_m)$ for any given manufacturer's effort x_m, the manufacturer determines its optimal effort, denoted as x_m^M, to maximize its expected profit: $\pi_m(x_m) = p_1(r-w)\mu \min\{x_m + x_s^*(x_m) + \alpha x_m x_s^*(x_m), \epsilon_1\} - \frac{1}{2}x_m^2$. Finally, the corresponding supplier's optimal effort is: $x_s^M = x_s^*(x_m^M)$.

We investigate whether the manufacturer and the supplier are better or worse off by leading investment efforts. For clarity, we consider a special case under diffuse market risk (i.e., $p_1 = 0.5$) with identical margins for the manufacturer and supplier (i.e., $w = r - w = r/2$). In this symmetric margin case, the party that invests less effort in equilibrium is better off. Thus, the first mover disadvantage (advantage) can be indirectly verified by examining whether the first mover exerts higher or lower efforts than the second mover in equilibrium. For notational simplicity, we normalize $r = 2$ (i.e., $w = 1$) without loss of generality.

Theorem 4 (First-Mover Disadvantage: Persistent Market Risk, Symmetric Margins) *Suppose the second mover faces the same persistent market risk as the first mover. When ϵ follows a Bernoulli distribution with sample space $\{0, \epsilon_1 = 2\epsilon_0\}$ and success probability 0.5; i.e., Prob$(\epsilon = \epsilon_1) = 0.5$, we have:*

1. *If $\epsilon_1 \leq \frac{1}{2}\mu$, then the first-mover disadvantage is reversed.*
2. *If $\epsilon_1 > \frac{1}{2}\mu$ and $\alpha\mu \geq 2$, then then the first-mover disadvantage is reversed.*

3. *If $\epsilon_1 > \frac{1}{2}\mu$ and $\sqrt{2} \leq \alpha\mu < 2$, then then the first-mover disadvantage is reversed if $\frac{1}{2}\mu < \epsilon_1 < \frac{\mu(4-\alpha\mu)}{(2-\alpha\mu)^2}$; and the first-mover disadvantage is preserved if $\epsilon_1 \geq \frac{\mu(4-\alpha\mu)}{(2-\alpha\mu)^2}$.*

Theorem 4 suggests that, under persistent market risk the first mover disadvantage can again be reversed, that is, the manufacturer can be better off by leading investment efforts. The intuition is consistent with the case where the second mover observes the realized market risk before investment (see discussions under Theorem 3). Only here the second mover appears to be worse off due to persistent market risk before making investment decisions. To further pursue this question, we next examine whether the first mover is hurt when the second mover can observe market risk (as compared with the case where the second mover cannot observe market risk). Surprisingly, the following proposition shows that delaying the second mover's investment decisions after realized market risk can benefit both the manufacturer as a first mover and the supplier as a second mover.

Proposition 5 *Suppose the manufacturer is the first mover. For any given x_m, we have:*

1. *The supplier's expected profit is higher if it can observe realized market risk than that under persistent market risk.*
2. *If the supplier can observe realized market risk before investment and that the realized ϵ turns out to be higher (i.e., $\epsilon = \epsilon_1$), the supplier's optimal investment effort level is higher than that under persistent market risk.*
3. *The manufacturer as a first mover benefits from the supplier observing realized market risk before making investment decisions.*

Part of the intuition for the above proposition is that the benefit of the supplier observing realized market risk improves the investment efficiency such that the supplier's *expected* investment level could be higher than that under persistent market risk. Such a higher investment level not only benefits the supplier but also benefits the manufacturer due to the complementary effect. In contrast, when the supplier faces persistent market risk, its investment efforts are in general lower and thus reduces the marginal value of the manufacturer's advance investment efforts. In essence, the option value afforded to the second mover under realized market risk can spill over to the first mover, resulting in the first mover being better off by leading investment efforts. The following figure numerically illustrates that the manufacturer benefits from the supplier observing realized market risk before making investment decisions.

Figure 4 illustrates that the manufacturer is worse off when the supplier does not observe realized market taste (all values are negative). This is somewhat unexpected, as it suggests that the first mover should encourage the second mover to reap the benefit of postponing its investment depending on realized market taste. As discussed above, seeing realized market taste by the second

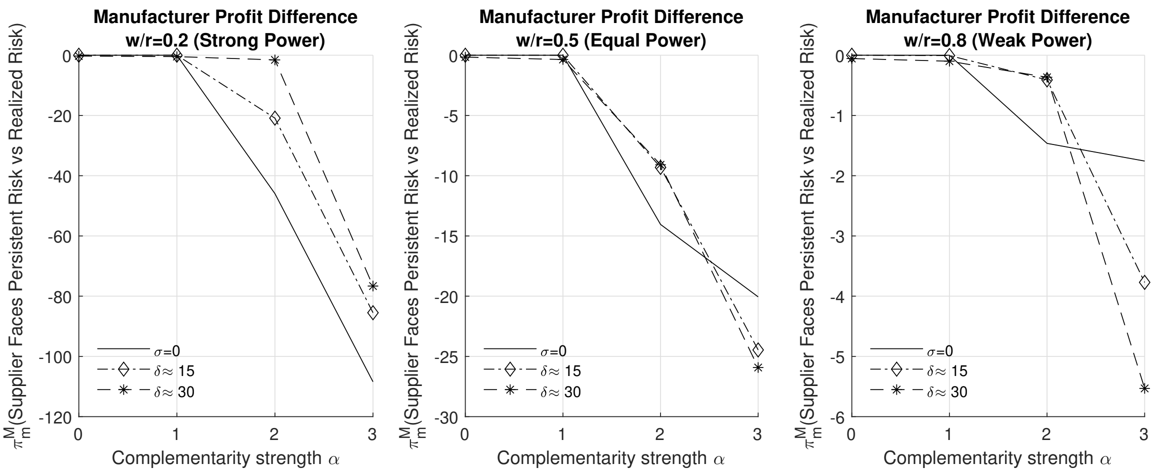

Figure 4 The manufacturer profit difference as a first mover when the supplier faces persistent market risk versus realized risk.

mover allows it to tailor its investment decisions more efficiently, which creates a reverse spillover effect where the manufacturer also benefits due to the complementary effect.

It is worth pointing out that, while the supplier's investment level is higher when market risk turns out to be better ($\epsilon = \epsilon_1$), in general its expected investment level could be higher or lower than that under persistent market risk. Furthermore, while the supplier benefits from observing market taste for any given x_m, in equilibrium the supplier could be better or worse off. The reason is that the manufacturer will adjust its investment level, depending on whether the supplier observes the market risk before making investment decisions. Specifically, when the manufacturer substantially reduces its investment effort anticipating the supplier would observe market taste, then the supplier could be worse off by observing market uncertainty. Nevertheless, our numerical study indicates that the supplier is typically still better off by observing market risk even accounting for manufacturer's reduced effort levels.

4.3. Endogenous Market Selling Price

In practice, the selling price can often be set by the downstream manufacturer upon observing realized market risk, although investment decisions for both the manufacturer and the supplier are often made before market risk is realized. This occurs when investments have long lead times, but the selling price can be adjusted more easily to reflect the realized market conditions. In such a setting, it is not immediately clear how endogenous selling price may influence the inherent first mover disadvantage. We thus examine in this section how endogenous price affects the manufacturer's incentive to invest as a first mover.

We adopt the same model setup as that studied in §4.2 with two extensions. First, we allow the selling price to be set by the manufacturer after market risk is realized. Second, we allow the wholesale price to be dependent on the endogenous market selling price. Specifically, we assume that the wholesale price is set for any given power structure $0 \leq \eta \leq 1$ such that the manufacturer pays the supplier η fraction of the unit market selling price. Specifically, for the unit market selling price r, the wholesale price paid to the supplier is ηr. This means that the manufacturer and the supplier share the gain or loss (in margins) depending on the realized market risk.

The sequence of events unfolds as follows. (1) Both the manufacturer and the supplier make investment decisions before market risk is realized, regardless of which party invests first. (2) The manufacturer sets selling price based on the realized market risk as well as the first stage investment decisions. Such a setting is also known as operational investment with recourse pricing. For the market selling price r, we adopt the commonly used linear demand function: $D(r|x_m, x_s, \epsilon) = d(x_m, x_s, \epsilon) - br$, where $d(x_m, x_s, \epsilon) = \mu \min\{x_m + x_s + \alpha x_m x_s, \epsilon\}$, and b is the slope of the linear demand function. The analysis of the manufacturer and supplier optimal investment efforts follow a similar approach to the base mode, and the details are thus relegated to the Appendix §A6.

A direct comparison of the manufacturer and supplier profits is challenging, because with endogenous pricing the profit function is a high-order polynomial that stymies analytical treatment. Nevertheless, we can indirectly evaluate whether the manufacturer is better off to lead investment efforts by examining a symmetric margin special case, that is, profit margins are equal with $\eta = 0.5$.

Theorem 5 (Reversal of First-Mover Disadvantage: Endogenous Selling Price) *Suppose the manufacturer moves first (in effort investment) and sets the optimal market selling price after the market risk uncertainty is resolved. Then we have:*

1. *If $\mu > 2\sqrt{2b}$, then the first-mover disadvantage is reversed.*
2. *Suppose $\eta = 0.5$, $\mu_0 \leq \mu < 2\sqrt{2b}$, where μ_0 is the unique value in $[0, 2\sqrt{2b}]$ that satisfies: $\mu_0^2 + 2b\mu_0 - 8b = 0$. Furthermore, suppose $(1+\alpha\epsilon_1)^2 < 8b/\mu^2 < \frac{\alpha\epsilon_1(1+\alpha\epsilon_1)}{(1+\alpha\epsilon_1)-\sqrt{1+\alpha\epsilon_1}}$. Then the first-mover disadvantage is reversed.*

The sufficient conditions in Theorem 5 are more likely to be satisfied when market demand is sensitive to price ($\sqrt{2b}$ is large), market is broad (μ is large), and complementary effect and market risk is moderately strong ($\alpha\epsilon_1$ is moderate). Recall that if market price is exogenous with no market risk, the first mover disadvantage persists. This suggests that endogenous market price under risky market condition can reverse the inherent first mover disadvantage with complementary sourcing.

Figure 5 illustrates more general settings where the profits margins can be asymmetric and market risk volatility takes a broader set of values. Notice that the power structure η significantly influences the magnitude of first mover advantage but not the general trend in reversing first mover disadvantage. In contrast, volatility in market risk amplifies the reversal of the first mover disadvantage, that is, the manufacturer is more likely to be better off by leading investment efforts

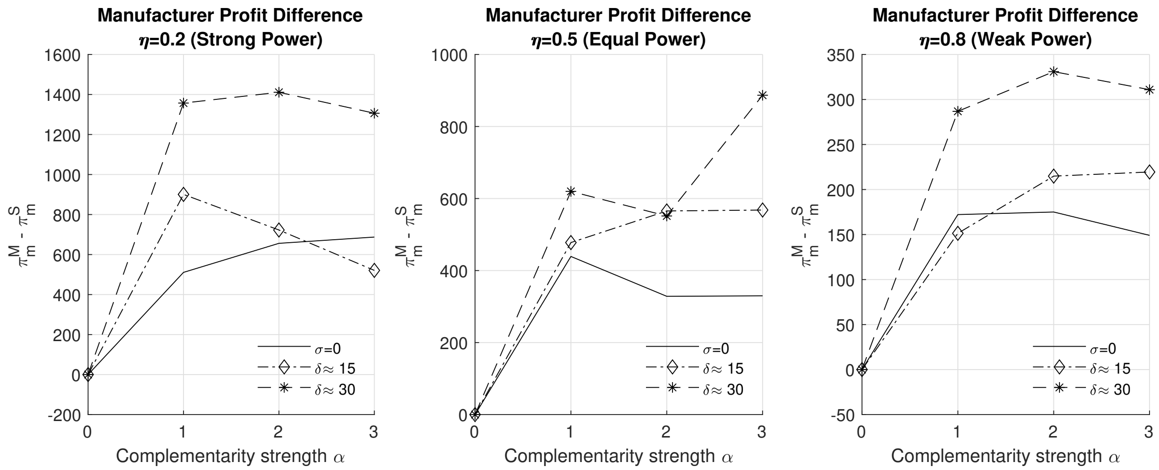

Figure 5 **The manufacturer profit difference as a first mover when the market selling price is endogenous and price sensitivity parameter** $b = 0.5$.

under high market volatility. This contrasts with the case where the manufacturer can set wholesale price (but not the market selling price), see Figure 6.

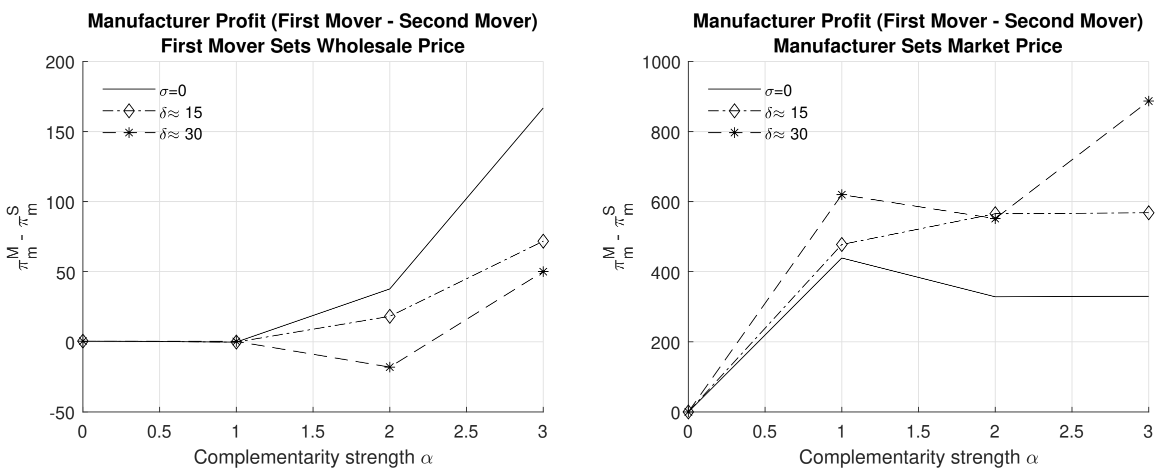

Figure 6 **The manufacturer profit difference as a first mover versus second mover. Left panel shows endogenous wholesale price, and right panel shows endogenous market price.**

While the ability to set wholesale price w or the market selling price r can both strongly reverse the first mover disadvantage, the underlying reason is somewhat different. In presence of market risk, the manufacturer as a lead investor will lower the wholesale price as market risk volatility increases to mitigate its impact on profit, but will increase the market selling price when market conditions turns out to be better than expected. Such an upside gain can more than offset the downside loss, resulting in the manufacturer raising expected market selling price as market volatility increases. As a result, this leads to the manufacturer benefit more from market volatility by moving first in investment efforts. This suggests that the ability to set market price is more effective to improve first mover's performance than the ability to set wholesale price under volatile market risk.

5. Discussion and Conclusions

Leveraging collaborative sourcing to improve product attractiveness and hence market demand often calls for supply chain partners to make advance investment in efforts facing market risk. It is therefore important to understand under what conditions a manufacturer (or supplier) is more likely to make advance investment effort. A key obstacle to effective collaboration is the first-mover disadvantage identified in the literature (Gal-Or 1985). Expanding that literature to allow for market risk and a two-dimensional decision space where investment efforts are complementary, but pricing decision is not, we demonstrate that such operational considerations allow a manufacturer to achieve better performance by leading investment efforts, even if such investment is made under significant market risk. Raising the awareness of *first-mover advantage* in complementary sourcing is an important contribution to both academic researchers and industry practitioners. Our key insight is that the commonly accepted first-mover disadvantage under complementary sourcing is often reversed under market risk (with or without endogenous pricing), which are present in more practical sourcing relationships. In fact, we demonstrate that as the complementary effect strengthens, the first-mover disadvantage is more likely to be reversed, that is, the manufacturer is increasingly better off by leading investment efforts.

A closely related benchmark setting is when the manufacturer and the supplier wait until market risk is realized and then exert investment effort simultaneously, each anticipating the other's investment effort. The detailed analysis contrasting this alternative benchmark case can be found in an unabridged version of the paper (details available upon request). Here we briefly highlight the key insights. First, it is straightforward to show that, all else being equal, sequential move dominates simultaneous move because the latter can be replicated by the former. However, we find that this dominance often fails to hold under market risk due to informational advantage associated with simultaneous move. Nevertheless, with simultaneous move, the wholesale price is less likely to reside with the manufacturer (as compared when it invests first). As such, the manufacturer can be still better off with advance investment than that under simultaneous investment. In fact, when the complementary effect is strong, the second mover (under sequential investment) is worse off under simultaneous investment (when the manufacturer sets wholesale price). This suggests that, with complementary sourcing, acting first by the manufacturer can be a win-win decision for both supply chain partners.

This paper also identifies opportunities for future research on supplier collaboration. One valuable area for future research is a scenario where a supplier is risk averse and has limited resources. In this case, there often exists a bound on the supplier's investment effort, making it less effective for the manufacturer to motivate the supplier to exert sufficient investment efforts. Another future research opportunity is to consider weakest-link effect, i.e., user experience heavily depends on the lowest performance attribute. For example, customers may not be attracted by a hardware system with inferior software. Investigating such cases will help to enrich our understanding of effective strategy choices for different types of sourcing relationships.

Acknowledgement

We would like to thank the Department Editor, the Associate Editor, and two anonymous referees for their valuable inputs that significantly improved and enriched the paper.

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Supplements for "*Investment Efforts Under Complementary Sourcing: The Role of Market Risk and Endogenous Pricing*"

This document contains additional results and proofs. Note that some of these results partially rely on auxiliary technical analyses from an unabridged version of the manuscript. Details are available upon request.

A1. General Discrete Market Risk

In this section, we consider the case when the market risk ϵ is stochastic where ϵ following a general discrete distribution such that $\epsilon = \epsilon_i$ with probability p_i, where $i \in \{1, 2, \cdots, n\}$, and, without loss of generality, assume $\epsilon_1 \geq \epsilon_2 \geq \cdots \geq \epsilon_n$. Denote the expected market risk as $\epsilon_0 = \epsilon_0 = \sum_i p_i \epsilon_i$.

A1.1. Model (M): Manufacturer Moves First

For any given manufacturer's effort investment and pricing decisions (x_m, w), the supplier's optimal investment effort (conditional on realized market risk $\epsilon = \epsilon_i$, $i = 1, 2, \cdots, n$) can be determined by the following lemma.

Lemma A1 *For any given (x_m, w) and realized market risk $\epsilon = \epsilon_i$, $i = 1, 2, \cdots, n$, the supplier's optimal investment effort is given by:*

$$x_s^*(x_m, w | \epsilon = \epsilon_i) = \begin{cases} 0 & \text{if } x_m \geq \epsilon_i; \\ \min\left(x_s^0(x_m, w), \frac{\epsilon_i - x_m}{1 + \alpha x_m}\right) & \text{if } x_m \leq \epsilon_i, \end{cases} \tag{A1}$$

where $x_s^0(x_m, w) = \mu w(1 + \alpha x_m)$.

Proof of Lemma A1: The proof is identical to that of Lemma A3, by replacing the realized market risk ϵ_0 by ϵ_i, for $i = 1, 2, \cdots, n$. We omit the details. $\square$

Anticipating the market risk and the supplier's optimal response characterized in the above lemma, the manufacturer makes the optimal investment effort and pricing decisions to maximize its expected profit: $\pi_m(x_m, w) = (r - w)\sum_{i=1}^n p_i d_i(x_m, x_s^*(x_m, w | \epsilon = \epsilon_i), \epsilon_i) - \frac{1}{2}x_m^2$, where $d_i(x_m, x_s^*(x_m, w | \epsilon = \epsilon_i), \epsilon_i) = \mu \min\left(x_m + x_s^*(x_m, w | \epsilon = \epsilon_i) + \alpha x_m x_s^*(x_m, w | \epsilon = \epsilon_i), \epsilon_i\right)$ is the market demand given $\epsilon = \epsilon_i$. It follows from Lemma A1 that the manufacturer faces $n + 1$ possible regions of its investment effort x_m relative to the potential market risk ϵ: $x_m \geq \epsilon_1, \epsilon_1 \geq x_m \geq \epsilon_2, \cdots, \epsilon_{n-1} \geq x_m \geq \epsilon_n$, and $x_m \leq \epsilon_n$. The following terms and results facilitate the determination of (x_m^M, w^M), which represent the optimal investment effort and wholesale price for the manufacturer in Model (M). For $i = 1, 2, \cdots, n$, define: $A_i = \left(\sum_{j=1}^i p_j\right)\epsilon_i + \sum_{j=i+1}^n p_j \epsilon_j$, and $g_i(x) = \frac{1 + \alpha(2\epsilon_i - x)}{(1 + \alpha x)^3} A_i - x$. Let x_i denote the (unique) solution of $g_i(x) = 0$ in $x \in [0, \epsilon_i]$; that is, $g_i(x_i) = 0$. Then the following lemma ranks $x_i, i = 1, 2, \cdots, n$.

Lemma A2 *Suppose $r\mu \geq \epsilon_1 + \epsilon_0/p_1$. For $i = 1, 2, \cdots, n$, x_i defined above satisfies: $x_i \leq \epsilon_i$. Furthermore, $x_1 \geq x_2 \geq \cdots \geq x_n$.*

Proof of Lemma A2: To show the first statement, notice $A_i \leq \epsilon_i$, and $g_i(x = \epsilon_i) = \epsilon_i/(1+\alpha\epsilon_i)^3 - \epsilon_i \leq 0$. As $g_i(x)$ is decreasing in $x \in [0, \epsilon_i]$, and $g_i(x_i) = 0$, we must have: $x_i \leq \epsilon_i$. The second statement also follows from the facts that $g_i(x)$ is decreasing in $x \in [0, \epsilon_i]$, and $g_i(x_i) = 0$. This completes the proof. $\square$

To characterize the manufacturer's optimal investment effort, we first define: $\pi_i = \left(r - \frac{\epsilon_i - x_i}{\mu(1+\alpha x_i)^2}\right)\mu A_i - \frac{1}{2}x_i^2$, for $i = 1, 2, \ldots, n$. Then let k denote the smallest index in $\{1, 2, \cdots, n\}$ such that $\pi_k = \max\{\pi_1, \pi_2, \cdots, \pi_n\}$. In addition, let $\hat{n} \in \{1, 2, \cdots, n\}$ satisfy: $\epsilon_{\hat{n}+1} < x_k \leq \epsilon_{\hat{n}}$ so that $x_k \leq \epsilon_i$ for $1 \leq i \leq \hat{n}$, and $x_k > \epsilon_i$ for $\hat{n}+1 \leq i \leq n$. It follows from Lemma A2 that $\hat{n} \geq k$.

Proposition A1 *Suppose $r\mu \geq \epsilon_1 + \epsilon_0/p_1$. Then the manufacturer's optimal decisions can be determined as: $(x_m^M, w^M) = \left(x_k, \frac{\epsilon_k - x_k}{\mu(1+\alpha x_k)^2}\right)$. Furthermore, for realized market risk $\epsilon = \epsilon_i$, $i = 1, 2, \cdots, n$, the supplier's optimal effort can be determined as:*

$$x_s^M(x_m^M, w^M | \epsilon = \epsilon_i) = \begin{cases} 0, & i \geq \hat{n}+1; \\ (\epsilon_i - x_k)/(1+\alpha x_k), & k+1 \leq i \leq \hat{n}; \\ (\epsilon_k - x_k)/(1+\alpha x_k), & i \leq k, \end{cases}$$

and the corresponding optimal market demand (conditional on $\epsilon = \epsilon_i$) is:

$$d_i^M := d(x_m^M, x_s^M(x_m^M, w^M | \epsilon = \epsilon_i), \epsilon_i) = \begin{cases} \mu\epsilon_i, & k+1 \leq i \leq n; \\ \mu\epsilon_k, & i \leq k. \end{cases}$$

Finally, the manufacturer's optimal expected profit is: $\pi_m^{M*} = \pi_k = \max\{\pi_1, \pi_2, \cdots, \pi_n\}$.

Proof of Proposition A1: First, for any given (x_m, w), the supplier's optimal decision associated with realized market risk $\epsilon = \epsilon_i$, denoted as $x_s^*(x_m, w, \epsilon_i)$, can be determined as:

$$x_s^*(x_m, w, \epsilon_i) = \begin{cases} 0 & \text{if } x_m \geq \epsilon_i \\ \frac{\epsilon_i - x_m}{1+\alpha x_m} & \text{if } x_m \leq \epsilon_i \text{ and } w \geq \frac{\epsilon_i - x_m}{\mu(1+\alpha x_m)^2} \\ \mu w(1+\alpha x_m) & \text{if } x_m \leq \epsilon_i \text{ and } w \leq \frac{\epsilon_i - x_m}{\mu(1+\alpha x_m)^2} \end{cases} \tag{A2}$$

Define $d_i(x_m, w) = \min\{x_m + x_s^*(x_m, w) + \alpha x_m x_s^*(x_m, w), \epsilon_i\}$. Then we have:

$$d_i(x_m, w) = \begin{cases} \epsilon_i & \text{if } x_m \geq \epsilon_i \\ \epsilon_i & \text{if } x_m \leq \epsilon_i \text{ and } w \geq \frac{\epsilon_i - x_m}{\mu(1+\alpha x_m)^2} \\ \mu w(1+\alpha x_m)^2 + x_m & \text{if } x_m \leq \epsilon_i \text{ and } w \leq \frac{\epsilon_i - x_m}{\mu(1+\alpha x_m)^2} \end{cases} \tag{A3}$$

Next, to solve the manufacturer's optimal decisions (x_m^M, w^M), divide the range of $x_m \geq 0$ into $n+1$ intervals with breakpoints $\epsilon_n \leq \epsilon_{n-1} \leq \cdots \leq \epsilon_2 \leq \epsilon_1$, where in region (i), $i = 1, 2, \cdots, n+1$, we have: $\epsilon_i \leq x_m \leq \epsilon_{i-1}$, where we define: $\epsilon_0 = \infty$ and $\epsilon_{n+1} = 0$.

Region (1): When $x_m \geq \epsilon_1$. It follows from (A3) that the manufacturer's expected profit is: $\pi_m(x_m, w) = (r-w)\mu \sum_{i=1}^n p_i\epsilon_i - \frac{1}{2}x_m^2$. It is easy to check that the optimal payment price in region 1, denoted as $w^{(1)}$, is: $w^{(1)} = 0$, and the manufacturer's optimal effort in this region, denoted as $x_m^{(1)}$, is: $x_m^{(1)} = \epsilon_1$, and the corresponding optimal expected profit for the manufacturer is: $\pi_m^{(1)} = r\mu\epsilon_0 - \frac{1}{2}\epsilon_1^2$.

Now for $i = 2, 3, \cdots, n+1$, consider Region (i), where $\epsilon_i \leq x_m \leq \epsilon_{i-1}$, with $\epsilon_{n+1} = 0$. It follows from (A3) that for $j = i, \cdots, n$, $d_j(x_m, w) = \epsilon_j$. However, for $j = 1, 2, \cdots, i-1$, because $x_m \leq \epsilon_j$, it follows from (A3) that one must further consider the range of w, specifically whether $w \geq \frac{\epsilon_j - x_m}{\mu(1+\alpha x_m)^2}$ holds or not. Overall there are $i-1$ breakpoints for w, defined as $w_j(x_m) = \frac{\epsilon_j - x_m}{\mu(1+\alpha x_m)^2}$, for $j = 1, 2, \cdots, i-1$, yielding i regions of w. Specifically, for given $i = 2, 3, \cdots, n+1$, and $j = 1, 2, \cdots, i-1$, define region (i, j) as the region of (x_m, w) where $\epsilon_i \leq x_m \leq \epsilon_{i-1}$ and $w_j(x_m) \leq w \leq w_{j-1}(x_m)$, with $w_0(x_m) \equiv \infty$. Furthermore, define region (i, i) is as the region of (x_m, w) where $\epsilon_i \leq x_m \leq \epsilon_{i-1}$ and $w \leq w_{i-1}(x_m)$. In the following, for given i, we will consider these i regions of (x_m, w), and derive the optimal effort and wholesale price of the manufacturer in each of these i regions, denoted as $(x_m^{(ij)}, w^{(ij)})$, for $j = 1, 2, \cdots, i$, respectively.

For $i = 2, 3, \cdots, n+1$, consider region $(i, 1)$; i.e., when $\epsilon_i \leq x_m \leq \epsilon_{i-1}$ and $w \geq w_1(x_m)$. Because $w_1(x_m) \geq w_2(x_m) \geq \cdots \geq w_{i-1}(x_m)$, if follows that $w \geq w_j(x_m)$ for all $j = 1, 2, \cdots, i-1$. Further, it follows from (A3) that: $d_j(x_m, w) = \epsilon_j$ for $j = 1, 2, \cdots, i-1$. Therefore the manufacturer's expected profit in this region is: $\pi_m(x_m, w) = (r-\mu)\mu\epsilon_0 \sum_{j=1}^n p_j\epsilon_j - \frac{1}{2}x_m^2 = (r-\mu)\mu\epsilon_0 - \frac{1}{2}x_m^2$. The optimal wholesale price in this region must satisfy: $w^*(x_m) = w_1(x_m)$. Correspondingly, the manufacturer's expected profit is: $\pi_m(x_m) = (r - w_1(x_m))\mu\epsilon_0 - \frac{1}{2}x_m^2$. Under the assumption that $x_m \leq \epsilon_{i-1} \leq \epsilon_1$, it can be verified that $\pi_m(x_m)$ is a concave function of x_m, and the first-order solution that satisfies $\pi_m'(x_m) = 0$ is: $x_m = x_1$, where x_1 is the unique solution of $g_1(x) = 0$ in $x \in [0, \epsilon_1]$, with function g_1 defined in the paragraph before Lemma A2. Specifically, $g_1(x) = \frac{1+\alpha(2\epsilon_1 - x)}{(1+\alpha x)^3}\epsilon_0 - x$. Now considering the constraint of x_m in this region $(i, 1)$; that is, $\epsilon_i \leq x_m \leq \epsilon_{i-1}$, the optimal effort in this region, denoted as $x_m^{(i1)}$, can be determined as: if $\epsilon_i \leq x_1 \leq \epsilon_{i-1}$, then $x_m^{(i1)} = x_1$; if $x_1 \leq \epsilon_i$, then $x_m^{(i1)} = \epsilon_i$; and if $x_1 \geq \epsilon_{i-1}$, then $x_m^{(i1)} = \epsilon_{i-1}$. Consequently, the optimal wholesale price in this region, denoted as $w^{(i1)}$, is: $w^{(i1)} = w_1(x_m^{(i1)})$, and the corresponding optimal expected profit for the manufacturer, denoted as $\pi_m^{(i1)}$, is given by the following: if $\epsilon_i \leq x_1 \leq \epsilon_{i-1}$, then $\pi_m^{(i1)} = \pi_1$; if $x_1 \leq \epsilon_i$, then $\pi_m^{(i1)} = (r - w_1(\epsilon_i))\mu\epsilon_0 - \frac{1}{2}\epsilon_i^2$; and if $x_1 \geq \epsilon_{i-1}$, then $\pi_m^{(i1)} = (r - w_1(\epsilon_{i-1}))\mu\epsilon_0 - \frac{1}{2}\epsilon_{i-1}^2$.

Now we consider region (i, j), for $j = 2, 3, \cdots, i-1$, where $\epsilon_i \leq x_m \leq \epsilon_{i-1}$ and $w_j(x_m) \leq w \leq w_{j-1}(x_m)$. Then for $k = 1, 2, \cdots, j-1$, we have: $w \leq w_k(x_m)$, and $d_k(x_m, w) = \mu w(1+\alpha x_m)^2 + x_m$; and for $k = j, j+1, \cdots, i-1$, we have: $w \geq w_k(x_m, w)$ and $d_k(x_m, w) = \epsilon_k$. Therefore the manufacturer's expected profit is: $\pi_m(x_m, w) = (r-w)\mu\{\sum_{k=1}^{j-1} p_k[\mu w(1+\alpha x_m)^2 + x_m] + \sum_{k=j}^n p_k\epsilon_k\} - \frac{1}{2}x_m^2$. This is concave in w, and solving the first-order condition (i.e., $\partial\pi_m/\partial w = 0$) yields: $w^0 =$

$\frac{r}{2} - \frac{\sum_{k=1}^{j} p_k x_m + \sum_{k=j}^{n} p_k \epsilon_k}{2\sum_{k=1}^{j-1} p_k \mu (1+\alpha x_m)^2}$. Observe that under the assumption that $r\mu \geq \epsilon_1 + \frac{\epsilon_0}{p_1}$, we must have: $w_0 \geq w_{j-1}(x_m)$. Thus the optimal w in this region must satisfy: $w^*(x_m) = w_{j-1}(x_m)$. Substituting $w = w^*(x_m)$ into $\pi_m(x_m, w)$, we get: $\pi_m(x_m) = \pi_m(x_m, w^*(x_m)) = (r - w_{j-1}(x_m))\mu A_{j-1} - \frac{1}{2}x_m^2$, where $A_{j-1} = \sum_{k=1}^{j-1} p_k \epsilon_{j-1} + \sum_{k=j}^{n} p_k \epsilon_k$. Under the assumption that $x_m \leq \epsilon_{i-1} \leq \epsilon_{j-1}$, it is straightforward to note that $\pi_m(x_m)$ is concave in x_m, and solving $\pi'_m(x_m) = 0$ yields: $x_m = x_{j-1}$, where x_{j-1} is the unique solution of $g_{j-1}(x) = 0$ in $x \in [0, \epsilon_{j-1}]$. Specifically, x_{j-1} satisfies $\frac{1+\alpha(2\epsilon_{j-1} - x_{j-1})}{(1+\alpha x_{j-1})^3} - x_{j-1} = 0$. Finally, considering the range of x_m; that is, $\epsilon_i \leq x_m \leq \epsilon_{i-1}$, the optimal effort in this region, $x_m^{(ij)}$, can be determined as: if $\epsilon_i \leq x_{j-1} \leq \epsilon_{i-1}$, then $x_m^{(ij)} = x_{j-1}$; if $x_{j-1} \leq \epsilon_i$, then $x_m^{(ij)} = \epsilon_i$; and if $x_{j-1} \geq \epsilon_{i-1}$, then $x_m^{(ij)} = \epsilon_{i-1}$. Consequently, the optimal payment price is: $w^{(ij)} = w_{j-1}(x_m^{(ij)})$, and the optimal expected profit for the manufacturer, denoted as $\pi_m^{(ij)}$, can be determined as: if $\epsilon_i \leq x_{j-1} \leq \epsilon_{i-1}$, then $\pi_m^{(ij)} = \pi_{j-1}$; if $x_{j-1} \leq \epsilon_i$, then $\pi_m^{(ij)} = (r - w_{j-1}(\epsilon_i))\mu A_{j-1} - \frac{1}{2}\epsilon_i^2$; and if $x_{j-1} \geq \epsilon_{i-1}$, then $\pi_m^{(ij)} = (r - w_{j-1}(\epsilon_{i-1}))\mu A_{j-1} - \frac{1}{2}\epsilon_{i-1}^2$.

Next, similar procedure can be applied to determine the optimal solution in region (i,i), where $\epsilon_i \leq x_m \leq \epsilon_{i-1}$ and $w \leq w_{i-1}(x_m)$. Specifically, the manufacturer's expected profit is: $\pi_m(x_m, w) = (r-w)\mu\{\sum_{k=1}^{i-1} p_k[\mu w(1+\alpha x_m)^2 + x_m] + \sum_{k=i}^{n} p_k \epsilon_k\} - \frac{1}{2}x_m^2$. Under the assumption $r\mu \geq \epsilon_1 + \frac{\epsilon_0}{p_1}$, the optimal wholesale price must satisfy: $w^*(x_m) = w_{i-1}(x_m)$. Substituting $w = w^*(x_m)$ into $\pi_m(x_m, w)$, we get: $\pi_m(x_m) = \pi_m(x_m, w^*(x_m)) = (r - w_{i-1}(x_m))\mu A_{i-1} - \frac{1}{2}x_m^2$. Solving $\pi'_m(x_m) = 0$ yields: $x_m = x_{i-1}$. Considering the range of x_m; i.e., $x_m \leq \epsilon_{i-1}$, and the fact that $x_{i-1} \leq \epsilon_{i-1}$, then the optimal effort in region (i,i), denoted as $x_m^{(ii)}$, can be determined as: if $x_{i-1} \geq \epsilon_i$, then $x^{(ii)} = x_{i-1}$; and if $x_{i-1} \leq \epsilon_i$, then $x^{(ii)} = \epsilon_i$. Consequently, the optimal wholesale price is: $w^{(ii)} = w_{i-1}(x_m^{(ii)})$, and the corresponding optimal expected profit for the manufacturer can be determined as: if $x_{i-1} \geq \epsilon_i$, then $\pi_m^{(ii)} = \pi_{i-1}$; and if $x_{i-1} \leq \epsilon_i$, then $\pi_m^{(ii)} = (r - w_{i-1}(\epsilon_i))\mu A_{i-1} - \frac{1}{2}\epsilon_i^2$.

Finally, for given $i = 2, 3, \cdots, n+1$, after solving the optimal solutions $(x_m^{(ij)}, w^{(ij)})$ in all the i regions (i,j) for $j = 1, 2, \cdots, i$, it is necessary to compare the optimal expected profits for the manufacturer in these i regions, that is, $\pi_m^{(ij)}$. Denote $\pi_m^i = \max\{\pi_m^{(i1)}, \pi_m^{(i2)}, \cdots, \pi_m^{(ii)}\}$, then π_m^i is the optimal expected profit for the manufacturer in region (i) of x_m when $\epsilon_i \leq x_m \leq \epsilon_{i-1}$. Next, it is necessary to compare all the π_m^i, for $i = 1, 2, \cdots, n+1$ to determine the maximum value, which is the optimal expected profit for the manufacturer in Model (M); that is, $\pi_m^M = \max\{\pi_m^{(1)}, \pi_m^{(2)}, \cdots, \pi_m^{(n+1)}\}$. This will also yield the corresponding optimal decisions for the manufacturer in Model (M); that is, (x_m^M, w^M). The supplier's optimal effort can be traced back accordingly, as $x_s^M(x_m^M, w^M, \epsilon_i)$ for any realized market risk $\epsilon = \epsilon_i$ in period 2, for $i = 1, 2, \cdots, n$. Toward this end, it follows from the solution procedure in region (i) of x_m above that there are at most $n + n(n+1)/2 = n(n+3)/2$ candidates for the manufacturer's optimal decisions (x_m^m, w^M) in Model (M), and they are: $(x_i, w_i(x_i))$ for $i = 1, 2, \cdots, n$; and $(\epsilon_i, w_j(\epsilon_i))$, for $i = 1, 2, \cdots, n$ and

$j=1,2,\cdots,i$. The corresponding expected profits associated with these $n(n+3)/2$ candidates are: π_i for $i=1,2,\cdots,n$, and $(r-w_j(\epsilon_i))\mu A_j - \frac{1}{2}\epsilon_i^2$, for $i=1,2,\cdots,n$ and $j=1,2,\cdots,i$. Furthermore, for $j=1,2,\cdots,n$, recall x_j are the optimal solution that maximizes $(r-w_j(x))\mu A_j - \frac{1}{2}x^2$. It follows immediately that: $\pi_j = (r-w_j(x_j))\mu A_j - \frac{1}{2}x_j^2 \geq (r-w_j(\epsilon_i))\mu A_j - \frac{1}{2}\epsilon_i^2$, for $i=1,2,\cdots n$. Therefore for profit comparisons, the $n(n+1)/2$ candidates in the forms of $(\epsilon_i, w_j(\epsilon_i))$ will be dominated by the other n candidates in the forms of $(x_i, w_i(x_i))$, and we have shown that $(x_i, w_i(x_i))$ are the only n possible candidates for the optimal solutions for the manufacturer in Model (M) with corresponding expected profits π_i for the manufacturer. The rest of the results in Proposition A1 follow immediately, and we omit the details. This completes the proof of Proposition A1. □

Proposition A1 shows that in general the manufacturer's optimal investment level x_m^M can lie in any of the n regions partitioned by the market risk realizations, i.e., $[\epsilon_{i+1}, \epsilon_i]$, $i \in \{1, 2\ldots, n\}$ (define $\epsilon_{n+1}=0$), and it is upper bounded by the highest possible market risk realization, i.e., $x_m^M \leq \epsilon_1$.

A1.2. Model (S): Supplier Moves First

In Model (S), the supplier moves first by setting the effort x_s and price w, and the manufacturer decides his effort level $x_m^*(x_s, w|\epsilon=\epsilon_i)$ after observing the market risk $\epsilon=\epsilon_i$. Observe that Model (S) can be transformed to Model (M) if one redefine $w' = r-w$, and solve for the optimal (x_s, w', x_m) in Model (S). Specifically, define (x_s^S, w^S) as the supplier's optimal decisions, and $x_m^S(x_s^S, w^S|\epsilon = \epsilon_i)$ as the manufacturer's corresponding optimal decision (conditional on $\epsilon=\epsilon_i$), then we must have: $x_s^S = x_m^M$, $w^S = r - w^M$, and $x_m^S(x_s^S, w^S|\epsilon=\epsilon_i) = x_s^M(x_m^M, w^M|\epsilon=\epsilon_i)$. Hence, the following proposition ensues.

Proposition A2 *Suppose* $r\mu \geq \epsilon_1 + \epsilon_0/p_1$. *Then:* $(x_s^S, w^S) = \left(x_k, r - \frac{\epsilon_k - x_k}{\mu(1+\alpha x_k)^2}\right)$. *Furthermore, for realized market risk* $\epsilon=\epsilon_i$, $i=1,2,\cdots,n$, *the manufacturer's optimal effort can be determined as:* $x_m^S(x_s^S, w^S|\epsilon=\epsilon_i)=0$ *for* $i \geq \hat{n}+1$; $x_m^S(x_s^S, w^S|\epsilon=\epsilon_i) = (\epsilon_i - x_k)/(1+\alpha x_k)$ *for* $k+1 \leq i \leq \hat{n}$; *and* $x_m^S(x_s^S, w^S|\epsilon=\epsilon_i) = (\epsilon_k - x_k)/(1+\alpha x_k)$ *for* $i \leq k$.

Proof of Proposition A2. The proof follows analogously from that for Proposition A1. □

Recall that (π_m^{M*}, π_s^{M*}) and (π_m^{S*}, π_s^{S*}) denote the optimal expected profits for the manufacturer and the supplier in Model (M) and Model (S), respectively. Specifically, we have:

$$\pi_m^{M*} = \pi_k = (r-w^M)\mu A_k - \frac{1}{2}x_k^2, \tag{A4}$$

$$\pi_m^{S*} = w^M \mu A_k - \frac{1}{2}\sum_{i=1}^{k} p_i \left(\frac{\epsilon_k - x_k}{1+\alpha x_k}\right)^2 - \frac{1}{2}\sum_{i=k+1}^{\hat{n}} p_i \left(\frac{\epsilon_i - x_k}{1+\alpha x_k}\right)^2. \tag{A5}$$

Next, we identify sufficient conditions under which the first-mover disadvantage is reversed.

Theorem A1 *Suppose* $r\mu \geq 2\epsilon_1 + \max\{(\epsilon_0 - p_1\epsilon_1)/p_1, \epsilon_1^2/(2\epsilon_n)\}$. *Then* $\pi_m^{M*} > \pi_m^{S*}$.

Proof of Theorem A1: Considering the expressions of π_m^M and π_m^S given in (A4) and (A5), it suffices to find a condition under which $(r-w^M)\mu A_k - \frac{1}{2}x_k^2 \geq w^M \mu A_k$, where $w^M = (\epsilon_k - x_k)/(\mu(1+\alpha x_k)^2)$. This is equivalent to: $r\mu \geq 2(\epsilon_k - x_k)/(1+\alpha x_k)^2 + x_k^2/(2A_k)$. This holds if $r\mu \geq 2\epsilon_k + x_k^2/(2A_k)$. Because $x_k \leq \epsilon_k \leq \epsilon_1$, and $A_k \geq A_n = \epsilon_n$, we have: $2\epsilon_k + x_k^2/(2A_k) \leq 2\epsilon_1 + \epsilon_1^2/(2\epsilon_n)$. Therefore if $r\mu \geq 2\epsilon_1 + \epsilon_1^2/(2\epsilon_n) = \epsilon_1(\epsilon_1/(2\epsilon_n)+2)$, then we are done. This is the sufficient condition that is given in the theorem. □

The interpretations and implications of Theorem A1 are similar to those discussed under Theorem 2 and hence we refer interested reader to §3.2 for more details. To further explore the impacts of market risk volatility, effort complementarity, as well as their interaction effect on the first-mover disadvantage/advantage result, we present the following numerical findings when the market risk follows a Normal distribution.

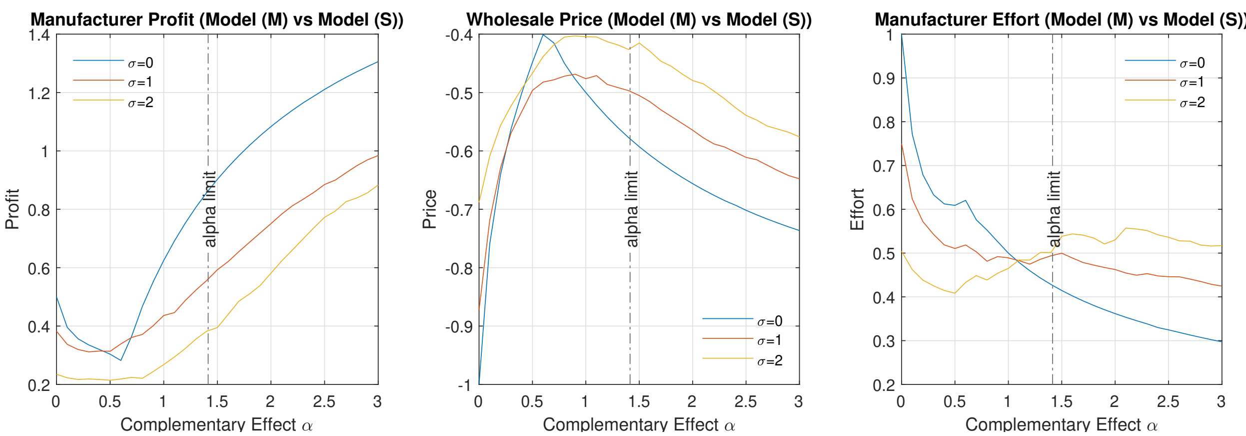

Figure 7 **Impact of market risk volatility on manufacturer (first mover) performance. Figure plotted by scaling $r=1$, $\mu=1$, and setting $\epsilon \sim N(m,\sigma)$ with mean $m=2$ and standard deviation $\sigma=0,1,2$.**

Figure 7 corroborates Proposition 4 and our observations in Figure 2: the manufacturer is typically worse off as market risk volatility increases.

A2. Proofs

Proof of Lemma 1. First, consider Model (M). Observe that in absence of market risk (i.e., when $\epsilon \equiv \infty$), and for a fixed w, the supplier's profit is: $\pi_s(x_s|x_m) = \mu_s(x_m + x_s + \alpha x_m x_s) - \frac{1}{2}x_s^2$, for any given x_m, and the supplier's optimal effort is: $x_s^*(x_m) = \mu_s(1+\alpha x_m)$, where $\mu_s = w\mu$. Anticipating $x_s^*(x_m)$, the manufacturer's profit is: $\pi_m(x_m) = \mu_m[\mu_s(1+\alpha x_m)^2 + x_m] - \frac{1}{2}x_m^2$, where $\mu_m = (r-w)\mu$. We can check that the optimal manufacturer's effort, denoted as x_m^M, is given by:

$$x_m^M = \begin{cases} \frac{\mu_m(1+2\alpha\mu_s)}{1-2\alpha^2\mu_m\mu_s} := x_m^0 & \text{if } 1-2\alpha^2\mu_m\mu_s > 0 \\ \infty & \text{if } 1-2\alpha^2\mu_m\mu_s \leq 0; \end{cases} \tag{A6}$$

and consequently, the corresponding supplier's optimal effort, denoted as x_s^M, is given by:

$$x_s^M = \begin{cases} \frac{\mu_s(1+\alpha\mu_m)}{1-2\alpha^2\mu_m\mu_s} & \text{if } 1-2\alpha^2\mu_m\mu_s > 0 \\ \infty & \text{if } 1-2\alpha^2\mu_m\mu_s \le 0. \end{cases} \tag{A7}$$

Next, in Model (S) when the supplier moves the first, similar analysis yields the following optimal efforts (x_m^S, x_s^S):

$$x_s^S = \begin{cases} \frac{\mu_s(1+2\alpha\mu_m)}{1-2\alpha^2\mu_m\mu_s} := x_s^0 & \text{if } 1-2\alpha^2\mu_m\mu_s > 0 \\ \infty & \text{if } 1-2\alpha^2\mu_m\mu_s \le 0; \end{cases} \tag{A8}$$

and

$$x_m^S = \begin{cases} \frac{\mu_m(1+\alpha\mu_s)}{1-2\alpha^2\mu_m\mu_s} & \text{if } 1-2\alpha^2\mu_m\mu_s > 0 \\ \infty & \text{if } 1-2\alpha^2\mu_m\mu_s \le 0. \end{cases} \tag{A9}$$

Furthermore, it is easy to show that: (1) $x_m^M \ge x_m^S$, $x_s^S \ge x_s^M$; and (2) $d(x_m^M, x_s^M) \ge d(x_m^S, x_s^S)$ if and only if $w \ge r/2$, where $d(x_m, x_s) = x_m + x_s + \alpha x_m x_s$. Finally, denote (x_m^{M*}, x_s^{M*}) and (x_m^{S*}, x_s^{S*}) as the optimal profits for the manufacturer and the supplier in the two models. Then we can check that when $1-2\alpha^2\mu_m\mu_s > 0$, we have: $\pi_m^{M*} - \pi_m^{S*} \le 0$, and $\pi_s^{S*} - \pi_s^{M*} \le 0$; and when $1-2\alpha^2\mu_m\mu_s \le 0$, we have: $\pi_m^{M*} = \pi_m^{S*}$, and $\pi_s^{S*} = \pi_s^{M*}$. Therefore the first-mover disadvantage persists. $\square$

Proof of Proposition 1: First, taking the first and second derivatives of $\pi_m(x_m, w)$ given in (3) with respective to w and x_m yields:

$$\frac{\partial \pi_m}{\partial w} = \mu[(r-2w)\mu(1+\alpha x_m)^2 - x_m], \qquad \frac{\partial^2 \pi_m}{\partial w^2} = -2\mu^2(1+\alpha x_m)^2 < 0,$$
$$\frac{\partial \pi_m}{\partial x_m} = (r-w)\mu(2\alpha\mu w+1) + [2\alpha^2\mu^2 w(r-w)-1]x_m, \qquad \frac{\partial^2 \pi_m}{\partial x_m^2} = 2\alpha^2\mu^2 w(r-w) - 1.$$

As $\pi_m(x_m, w)$ is concave in w, for any given $x_m \ge 0$, the optimal price in $[0, r]$ is: $w^*(x_m) = \max\{w^0(x_m), 0\}$, where $w^0(x_m) = \frac{r}{2} - \frac{x_m}{2\mu(1+\alpha x_m)^2}$. Furthermore, $w^0(x_m) \ge 0$ is equivalent to: $h(x_m) := \alpha^2 r\mu x_m^2 + (2\alpha r\mu - 1)x_m + r\mu \ge 0$. Note that as long as $\alpha r\mu \ge \frac{1}{4}$, $h(x_m) \ge 0$ for all x_m. In this case, $w^*(x_m) = w^0(x_m)$, and $\pi_m(x_m) := \pi_m(x_m, w = w^0(x_m)) = \frac{[r\mu(1+\alpha x_m)^2 + x_m]^2}{4(1+\alpha x_m)^2} - \frac{1}{2}x_m^2$. We can check that:

$$\pi_m'(x_m) = \frac{(\alpha r\mu)^2 - 2}{2}x_m + \frac{x_m}{2(1+\alpha x_m)^3} + \frac{r\mu(\alpha r\mu + 1)}{2}, \tag{A10}$$

$$\pi_m''(x_m) = \frac{(\alpha r\mu)^2 - 2}{2} + \frac{1 - 2\alpha x_m}{2(1+\alpha x_m)^4}. \tag{A11}$$

It follows from (A10) that: if $\alpha r\mu \ge \sqrt{2}$, then $\pi_m'(x_m) > 0$ for all $x_m \ge 0$, therefore the optimal manufacturer's effort is: $x_m^M = +\infty$, the optimal price $w^M = w^0(x_m^M) = \frac{r}{2}$, and the optimal supplier's effort is: $x_s^S = +\infty$. This proves the first statement. In the remainder of the proof, we assume $\alpha r\mu < \sqrt{2}$.

Second, suppose $\frac{1}{4} \le \alpha r\mu < \sqrt{2}$. It is easy to check that π_m'' given in (A11) is decreasing in $x_m \in [0, \infty)$. In addition, $\pi_m''(x_m = 0) = \frac{(\alpha r\mu)^2 - 1}{2}$, and $\pi_m''(x_m = 0) \ge 0$ for $\alpha r\mu \ge 1$ and $\pi_m''(x_m = 0) < 0$

for $\alpha r\mu < 1$. If $\frac{1}{4} \leq \alpha r\mu < 1$, then $\pi''_m(x_m) < 0$ for all $x_m \in [0, \infty)$, implying $\pi_m(x_m)$ is concave in $x_m \in [0, \infty)$. In this case, as $\pi'_m(x_m = 0) > 0$ and $\pi'_m(x_m = +\infty) = -\infty$, we know there must exist a unique value of $x_m \in (0, \infty)$, denoted as $\bar{x}$, that satisfies the first-order condition; that is, $\pi'_m(x_m = \bar{x}) = 0$. Furthermore, $x_m^M = \bar{x}$, $w^M = w^0(x_m = \bar{x}) := \bar{w}$ and $x_s^M = \mu\bar{w}(1 + \alpha\bar{x})$.

If $1 \leq \alpha r\mu < \sqrt{2}$, then $\pi''_m(x_m) \geq 0$ for $x_m \in [0, \tilde{x}]$, and $\pi''_m(x_m) < 0$ for $x_m \in (\tilde{x}, \infty)$, where $\tilde{x}$ satisfies $\pi''_m(x_m = \tilde{x}) = 0$, implying $\pi_m(x_m)$ is a convex-concave function of $x_m \in [0, \infty)$. As $\pi'_m(x_m = 0) > 0$, we must have: $\pi'_m(x_m) > 0$ for $x_m \in [0, \tilde{x}]$, so $\pi_m(x_m)$ is increasing in $x_m \in [0, \tilde{x}]$. Furthermore, as $\pi'_m(x_m = \tilde{x}) > 0$ and $\pi'_m(x_m = +\infty) < 0$, the concavity of $\pi_m(x_m)$ on $x_m \in (\tilde{x}, \infty)$ implies that there must exist a unique value of $x_m \in (\tilde{x}, \infty)$ that satisfies the first-order condition, which is $\bar{x}$. Furthermore, we must have: $x_m^M = \bar{x}$ in this case.

Next, suppose $0 < \alpha r\mu < \frac{1}{4}$. Then it is easy to check that $w^0(x_m) \geq 0$, or equivalently, $h(x_m) \geq 0$ if and only if $x_m \leq x_1$ or $x_m \geq x_2$; and $w^0(x_m) < 0$, or equivalently $h(x_m) < 0$ if and only if $x_1 < x_m < x_2$, where $x_1 = \frac{1-2\alpha r\mu - \sqrt{1-4\alpha r\mu}}{2\alpha^2 r\mu}$, and $x_2 = \frac{1-2\alpha r\mu + \sqrt{1-4\alpha r\mu}}{2\alpha^2 r\mu}$. We can show that: $x_2 > \frac{1}{\alpha}$, and $x_1 < \frac{1}{\alpha}$. Furthermore, if $\alpha r\mu \leq \frac{2}{9}$, we have: $x_1 \leq \frac{1}{2\alpha}$; and if $\frac{2}{9} < \alpha r\mu < \frac{1}{4}$, we have: $\frac{1}{2\alpha} < x_1 < \frac{1}{\alpha}$.

We first consider the region when for $x_m \geq x_2$. Because $\pi''_m(x_m = \frac{1}{2\alpha}) < 0$ and $\pi''_m(x_m)$ is decreasing in x_m, we must have: $\pi''_m(x_m) < 0$ for all $x_m > \frac{1}{2\alpha}$, implying $\pi_m(x_m)$ is concave in x_m for $x_m > \frac{1}{2\alpha}$. Furthermore, we can check that: $\pi'_m(x_m = \frac{1}{2\alpha}) = \frac{1}{108\alpha}(81(\alpha r\mu)^2 + 54\alpha r\mu - 46) = \frac{1}{108\alpha}(\alpha r\mu - 0.491)(\alpha r\mu + 1.157)$. Thus $\pi'_m(x_m = \frac{1}{2\alpha}) < 0$, for $\alpha r\mu < \frac{1}{4}$. Combining this with the fact that $\pi_m(x_m)$ is concave in $x_m > \frac{1}{2\alpha}$, we have $\pi'_m(x_m) < 0$ for $x_m \geq \frac{1}{2\alpha}$. Finally, recall that $x_2 > \frac{1}{\alpha} > \frac{1}{2\alpha}$, we must have: $\arg\max_{x_m \geq x_2} \pi_m(x_m) = x_2$.

Now we consider the region when $x_m \leq x_1$. Once again, because $\pi''(x_m = 0) < 0$ and $\pi''(x_m)$ is decreasing in $x_m \geq 0$, we have $\pi''(x_m) < 0$ for all $x_m \geq 0$. If $\frac{2}{9} < \alpha r\mu < \frac{1}{4}$, then $x_1 \geq \frac{1}{2\alpha}$. Furthermore, because $\pi'(x_m = \frac{1}{2\alpha}) < 0$, we have: $\pi'(x_m = x_1) < 0$. Considering $\pi'(x_m = 0) > 0$, we know the first-order solution $\bar{x} \in (0, x_1)$, and $\arg\max_{x_m \leq x_1} = \bar{x}$. If $\alpha r\mu \leq \frac{2}{9}$, then $x_1 \leq \frac{1}{2\alpha}$, and $\arg\max_{x_m \leq x_1} = \min\{\bar{x}, x_1\}$. To compare x_0 with x_1 for this case when $\alpha r\mu \leq \frac{2}{9}$, we can check that $\frac{\partial x_1}{\partial \alpha} > 0$, implying x_1 is increasing in $\alpha > 0$. When $\alpha = 0$, it follows from the expression of $h(x_m) = -x_m + r\mu$ that $x_1 = x_2 = r\mu$. Thus for all $\alpha > 0$, we must have: $x_1 > r\mu$. Furthermore, we can check that: $\pi'_m(x_m = r\mu) = \frac{1}{2}r\mu\left((\alpha r\mu)^2 + \alpha r\mu + \frac{1}{(1+\alpha r\mu)^3)} - 1\right) < 0$ for $\alpha r\mu \leq \frac{2}{9}$. It follows from the concavity of $\pi_m(x_m)$ and $x_1 > r\mu$ that: $\pi'(x_m = x_1) < \pi'(x_m = r\mu) < 0$. Therefore we must have: $\bar{x} < x_1$, and $\arg\max_{x_m \leq x_1} = x_0$. Overall, we have shown that for $0 < \alpha r\mu < \frac{1}{4}$, $\arg\max_{x_m \leq x_1} \pi_m(x_m) = \bar{x}$.

Finally, we consider the region when $x_1 < x_m < x_2$. In this region, we have: $w^*(x_m) = 0, x_s^*(x_m, w^*(x_m)) = 0$; Thus $\pi_m(x_m) := \pi_m(x_m, w = w^*(x_m) = 0) = r\mu x_m - \frac{1}{2}x_m^2$. This is a concave function of x_m, and the first-order solution is $x_m^* = r\mu$. To determine the profit-maximizer in the range $x_m \in (x_1, x_2)$, we can check that for $\alpha r\mu < \frac{1}{4}$, we must have: $r\mu \leq \frac{1}{4\alpha} < \frac{1}{2\alpha} < x_2$. Next, if $\alpha r\mu \leq \frac{2}{9}$, we have shown in the previous paragraph that: $x_1 > r\mu$; and if $\frac{2}{9} < \alpha r\mu < \frac{1}{4}$, we have: $x_1 >$

$\frac{1}{2\alpha} > r\mu$. Therefore we must have: $\arg\max_{x_1<x_m<x_2} \pi_m(x_m) = x_1$. Putting all these three regions together, we have shown that for $0 < \alpha r\mu < \frac{1}{4}$, $x_m^M = \arg\max_{x_m \geq 0} \pi_m(x_m) = \bar{x}$. The case with $\alpha = 0$ can be solved easily and we omit the details. Therefore we have proved statement 2, and this completes the proof of Proposition 1. □

Proof of Corollary 1: It follows from Proposition 1 that when $\alpha r\mu < \sqrt{2}$, $x^M = \bar{x}$, $w^M = \bar{w}$, and $x_s^M = \mu\bar{w}(1+\alpha\bar{x})$, where $\bar{x}$ and $\bar{w}$ are given in Statement 2 of Proposition 1. The proof of the first statement is straightforward and omitted. To show the comparative statistics results of x_m^M, w^M and x_s^S with respective to α, under the supposition $0.75 \leq \alpha r\mu \leq 1.1013$ in statement 2 of the corollary, it suffices to prove that $\bar{x}$ increases in α. To do this, recall from the Proof of Proposition 1 that $\bar{x}$ satisfies $\pi_m'(\bar{x}) = 0$, where $\pi_m'(x_m)$ is given by (A10). Taking derivative of both sides of $\pi_m'(\bar{x}) = 0$ with respective to α, we obtain:

$$\pi_m''(\bar{x})\frac{\partial \bar{x}}{\partial \alpha} + \frac{(r\mu)^2}{2(1+\alpha\bar{x})^4}\left[(2\alpha\bar{x}+1)(1+\alpha\bar{x})^4 - \frac{3\bar{x}^2}{(r\mu)^2}\right] = 0 \tag{A12}$$

Under the assumption that $0.75 \leq \alpha r\mu \leq 1.1013$, one can prove that: $1/\alpha < \bar{x} < 3/\alpha$. This can be verified by showing that $\pi_m'(x_m = 1/\alpha) > 0$ and $\pi_m'(x_m = 3/\alpha) < 0$, where $\pi_m'(x_m)$ given by (A10). Then we have: $(2\alpha\bar{x}+1)(1+\alpha\bar{x})^4 - \frac{3\bar{x}^2}{(r\mu)^2} > 3 \cdot 16 - 3 \cdot 9/(\alpha r\mu)^2 = 3[16 - 9/(\alpha r\mu)^2] \geq 0$. The last inequality holds because $\alpha r\mu \geq 3/4$. Furthermore, it follows from the Proof of Proposition 1 that when $1/4 \leq \alpha r\mu \leq \sqrt{2}$, $\pi_m''(\bar{x}) < 0$. Therefore it follows from (A19) that: $\partial\bar{x}/\partial\alpha > 0$. This completes the proof of Corollary 1. □

Proof of Theorem 1: We first consider the case when $0 \leq \alpha r\mu < \sqrt{2}$. It follows from Proposition 1 that: $x_m^M = \bar{x}$, $w^M = \bar{w}$ and $x_s^M = \mu\bar{w}(1+\alpha\bar{x})$, where $\bar{x}$ and $\bar{w}$ are defined in Proposition 1. Therefore we have the following expressions for the profit functions of the manufacturer in Model (M) and Model (S):

$$\begin{aligned}
\pi_m^M &= (r-\bar{w})\mu(\bar{x} + \mu\bar{w}(1+\alpha\bar{x}) + \alpha\bar{x}\mu\bar{w}(1+\alpha\bar{x})) - \frac{1}{2}\bar{x}^2, \\
\pi_m^S &= \bar{w}\mu(\bar{x} + \mu\bar{w}(1+\alpha\bar{x}) + \alpha\bar{x}\mu\bar{w}(1+\alpha\bar{x})) - \frac{1}{2}(\mu\bar{w}(1+\alpha\bar{x}))^2.
\end{aligned}$$

It follows that:

$$\pi_m^M - \pi_m^S = \frac{1}{8(1+\alpha\bar{x})^2}\left\{5\bar{x}^2 + (1+\alpha\bar{x})^2\left[2r\mu\bar{x} + r^2\mu^2(1+\alpha\bar{x})^2 - 4\bar{x}^2\right]\right\}. \tag{A13}$$

Define $h(t) = 5t^2 + (1+\alpha t)^2[2r\mu t + r^2\mu^2(1+\alpha t)^2 - 4t^2]$ for $t \geq 0$. Then $h(t)$ is a polynomial function of t with order 4. It can be verified that: $h(t=0) = (r\mu)^2 > 0$, and $h(t = r\mu) = (r\mu)^2\{[(1+\alpha r\mu)^2 + 1]^2 + 4\} > 0$. Furthermore, we have: $h'(t) = 10t + (1+\alpha t)[4\alpha r^2\mu^2(1+\alpha t)^2 + 6\alpha r\mu t + 2r\mu - 16\alpha t^2 - 8t]$. Thus $h'(t=0) = 4\alpha r^2\mu^2 + 2r\mu > 0$, and $h'(t = r\mu) = 2r\mu[2 - 6\alpha r\mu + (\alpha r\mu)^2 + 6(\alpha r\mu)^3 + 2(\alpha r\mu)^4]$. Next, it follows from (A10) that: $\pi'(x_m = r\mu) = \frac{\alpha(r\mu)^2}{2(1+\alpha r\mu)^3}(\alpha r\mu + 2)\left[(\alpha r\mu)^3 + 2(\alpha r\mu)^2 + \alpha r\mu - 1\right]$. It is straightforward to note that when $0 \le \alpha r\mu \le 0.4655$, $\pi_m'(x_m = r\mu) < 0$. Furthermore, recall from the Proof of Proposition 1 that when $\alpha r\mu \le 1$, $\pi_m(x_m)$ is concave in $x_m \in [0, \infty)$ (because $\pi''(x_m)$ is decreasing in $x_m \in [0, \infty)$, and $\pi''(x_m = 0) \le 0$ when $\alpha r\mu \le 1$). Combining the definition of $\bar{x}$; i.e., $\pi_m'(x_m = \bar{x}) = 0$ and $\pi_m'(x_m = r\mu) < 0$ yields the conclusion that $\bar{x} < r\mu$ when $0 \le \alpha r\mu \le 0.4655$. In addition, observe that $h'(t = r\mu)$ is decreasing in $\alpha r\mu$ for $0 \le \alpha r\mu \le 0.4655$, and when $\alpha r\mu = 0$, $h'(t = r\mu) > 0$; when $\alpha r\mu = 0.4655$, $h'(t = r\mu) > 0$. Therefore for all $0 \le \alpha r\mu \le 0.4655$, it must be true that $h'(t = r\mu) > 0$.

To sum up, when $0 \le \alpha r\mu \le 0.4655$, $h(t = 0) > 0, h'(t = 0) > 0, h(t = r\mu) > 0$, and $h'(t = r\mu) > 0$. Because $h(t)$ is a 4th-order polynomial function of t, it follows that $h(t) > 0$ for all $0 \le t \le r\mu$, which clearly holds for $\bar{x} \in [0, r\mu)$. That is, $h(t = \bar{x}) > 0$ when $0 \le \alpha r\mu \le 0.4655$. It follows from (A13) that $\pi_m^M - \pi_m^S > 0$ when $0 \le \alpha r\mu \le 0.4655$. This completes the proof of the first statement in the Proposition.

Secondly, suppose $1 \le \alpha r\mu < \sqrt{2}$. Because $\pi_m''(x_m)$ given in (A11) is decreasing in x_m, and $\pi_m''(x_m = 0) \ge 0$ for $1 \le \alpha r\mu < \sqrt{2}$, hence $\pi_m(x_m)$ is convex-concave in $x_m \in [0, \infty)$. Furthermore, because $\pi_m'(x_m = 0) > 0$, $\pi_m(x_m)$ is increasing in x_m in the region when $\pi_m(x_m)$ is convex in x_m, and it follows from the Proof of Proposition 1 that $\bar{x}$ that satisfies $\pi_m'(x_m = \bar{x}) = 0$ must lie in the region of x_m when $\pi_m(x_m)$ is concave in x_m. Specifically, $\bar{x}$ satisfies:

$$\left[(\alpha r\mu)^2 - 2\right]\bar{x} + \frac{\bar{x}}{(1 + \alpha\bar{x})^3} + r\mu(\alpha r\mu + 1) = 0.$$

Notice $x/(1 + \alpha r\mu)^3$ is a concave function with maximum value of $4/(27\alpha)$ (when $x = 1/(2\alpha)$). Thus we must have: $0 \le \bar{x}/(1 + \alpha\bar{x})^3 \le 4/(27\alpha)$, and

$$\left[2 - (\alpha r\mu)^2\right]\bar{x} = \frac{\bar{x}}{(1 + \alpha\bar{x})^3} + r\mu(\alpha r\mu + 1) \in \left[r\mu(\alpha r\mu + 1), r\mu(\alpha r\mu + 1) + \frac{4}{27\alpha}\right].$$

Consequently,

$$\bar{x} \in \left[\frac{r\mu(\alpha r\mu + 1)}{2 - (\alpha r\mu)^2}, \frac{r\mu(\alpha r\mu + 1) + \frac{4}{27\alpha}}{2 - (\alpha r\mu)^2}\right].$$

Furthermore, as $r\mu(\alpha r\mu + 1)/(2 - (\alpha r\mu)^2)$ is increasing in $\alpha r\mu$ for $\alpha r\mu < \sqrt{2}$, and $r\mu(\alpha r\mu + 1)/(2 - (\alpha r\mu)^2)|_{\alpha r\mu = 1} = 2r\mu$, we must have: $\bar{x} \ge 2r\mu$ when $1 \le \alpha r\mu < \sqrt{2}$. Define $h(t = 2r\mu) = (r\mu)^2[9 - 40\alpha r\mu - 24(\alpha r\mu)^2 + 32(\alpha r\mu)^3 + 16(\alpha r\mu)^4]$, it can be verified that $h(t = 2r\mu) < 0$ for $0 \le \alpha r\mu \le 1.0811$, and $h(t = 2r\mu) > 0$ for $1.0811 < \alpha r\mu < \sqrt{2}$. Next, because $(r\mu(\alpha r\mu + 1) + 4/(27\alpha))/(2 - (\alpha r\mu)^2) = (27\alpha r\mu(\alpha r\mu + 1) + 4)/(27\alpha(2 - (\alpha r\mu)^2))$ is increasing in $\alpha r\mu$ for $1 \le \alpha r\mu \le 1.0811$, we have that: $(r\mu(\alpha r\mu + 1) + 4/(27\alpha))/(2 - (\alpha r\mu)^2) \le (27(1.0811)(1.0811 + 1) + 4)/(27\alpha(2 - (1.0811)^2)) = 2.84/\alpha$, for $1 \le \alpha r\mu \le 1.0811$. Furthermore, observe that: $h(t = 2.84/\alpha) = 1/\alpha^2[217.43(\alpha r\mu)^2 + 83.76(\alpha r\mu) - 435.4]$, and $h(t = 2.84/\alpha) < 0$ for $1 \le \alpha r\mu \le 1.0811$. In summary, when $1 \le \alpha r\mu \le$

1.0811, considering the facts that: $h(t=0)>0$, $h'(t=0)>0$, $h(t=r\mu)>0$, $h(t=2r\mu)<0$ and $h(t=2.84/\alpha)<0$, as well as the range of $\bar{x}$: $2r\mu \le \bar{x} \le 2.84/\alpha$, we can conclude that: $h(\bar{x})<0$, implying $\pi_m^M - \pi_m^S < 0$, for $1 \le \alpha r\mu \le 1.0811$. This completes the proof of statement 2 of Theorem 1.

Finally, when $\alpha r\mu \ge \sqrt{2}$, it follows from Proposition 1 that $x_m^M = x_s^S = \infty$, $w^M = w^S = r/2$, and $x_m^S = x_s^M = \infty$. Thus the two models are essentially identical, and $\pi_m^M - \pi_m^S = 0$. This completes the proof. □

Proof of Corollary 2. The corollary statement follows from Proposition 1 and Theorem 1 by setting $\alpha = 0$. □

Proof of Lemma 2: The proof is identical to that of Lemma A3, by replacing the realized market risk ϵ_0 by ϵ_i for $i=1,2$. We omit the details. □

Proof of Lemma 3: The proof follows from that of Lemma A2 in the general discrete distribution case, when $n=2$. We omit the details. □

Proof of Proposition 2: The proof follows from that of Proposition A1 in the general discrete distribution case, when $n=2$. We omit the details. □

Proof of Proposition 3: The proof is analogous to that of Proposition 2. We omit the details. □

Proof of Corollary 3: The Corollary statements follows directly from Propositions 2 and 3. □

Proof of Theorem 2: The proof follows from that of Theorem A1, when $n=2$, $\epsilon_1 = \epsilon_0 + \sigma, \epsilon_2 = \epsilon_0 - \sigma$, and $p_1 = p_2 = 0.5$. We omit the details. □

Proof of Proposition 4: The first statement follows from the definitions of x_1 and x_2, the fact that the function $\frac{1+\alpha(\epsilon-x)}{(1+\alpha x)^3}\epsilon - x$ decreases in $x \in [0,\epsilon]$, and $x_1 = x_2 = x_0$ when $\sigma = 0$. Next, to show the second statement, it follows from the definitions of π_1 and π_2, as well as the facts that $\pi_1'(x_1)=0$ and $\pi_2'(x_2)=0$ that: $\frac{\partial \pi_1}{\partial \sigma} = -\frac{\epsilon_0}{(1+\alpha x_1)^2} < 0$, and $\frac{\partial \pi_2}{\partial \sigma} = -\frac{r\mu(1+\alpha x_2)^2 - 2(\epsilon_0-\sigma)+x_2}{(1+\alpha x_2)^2} < 0$. The last inequality follows from the assumption that $r\mu \ge 2\epsilon_1 \ge 2\epsilon_2 = 2(\epsilon_0 - \sigma)$. Finally, as $\pi_m^{M*} = \max\{\pi_1, \pi_2\}$, it is easy to verify that π_m^{M*} also decreases in σ. Furthermore, as $\pi_1 = \pi_2 = \pi_0$ when $\sigma = 0$, we must have: $\pi_m^{M*} = \max\{\pi_1, \pi_s\} \le \pi_0$. This completes the proof. □

Proof of Theorem 3: Part (1): Under the suppositions that $\epsilon_1 \le r\mu/2$, and $\epsilon_1/\mu \le w \le r - \epsilon_1/\mu$, the following results follows: $x_m^M = 0$, $\pi_m^M = p_1(r-w)\mu\epsilon_1$; $x_m^S(\epsilon=0)=0$, $x_m^S(\epsilon=\epsilon_1)=\epsilon_1$, and the manufacturer's expected profit in Model (S) is: $\pi_m^S = p_1[(r-w)\mu\epsilon_1 - \frac{1}{2}\epsilon_1]$. Thus $\pi_m^M > \pi_m^S$, and the first-mover disadvantage is reversed for the manufacturer. Similar proof holds for the supplier.

Part (2): Now suppose $\epsilon_1 > r\mu/2$ and $w = r/2$. Furthermore, suppose $\sqrt{p_1}\alpha r\mu \ge \sqrt{2}$. Then it follows from Proposition A6 that: $x_m^M = \bar{x}$, where $\bar{x}$ satisfies: $\bar{x} + \frac{r\mu}{2}(1+\alpha\bar{x}_m)^2 = \epsilon_1$, and $\pi_m^M = \frac{p_1 r\mu}{2}\epsilon_1 - \frac{1}{2}\bar{x}^2$. Furthermore, we have: $x_m^S(\epsilon=0)=0$, and $x_m^S(\epsilon=\epsilon_1) = \frac{r\mu}{2}(1+\alpha\bar{x})$, and the manufacturer's expected profit in Model (S) is: $\pi_m^S = p_1\{\frac{r\mu}{2}\epsilon_1 - \frac{1}{2}[\frac{r\mu}{2}(1+\alpha\bar{x})]^2\}$. Notice that $\pi_m^M > \pi_m^S$ if and only if $\sqrt{p_1} r\mu > (2-\sqrt{p_1}\alpha r\mu)\bar{x}$. This condition clearly holds when $\sqrt{p_1}\alpha r\mu \ge 2$. This proves Part

2(a). Next, suppose $\sqrt{2} \le \sqrt{p_1}\alpha r\mu < 2$. Then $\pi_m^M > \pi_m^S$ if and only if: $\bar{x} < \frac{\sqrt{p_1}r\mu}{2-\sqrt{p_1}\alpha r\mu)}$. As $\bar{x}$ satisfies $\bar{x} + \frac{r\mu}{2}(1+\alpha\bar{x})^2 = \epsilon_1$, it follows that $\bar{x} < \frac{\sqrt{p_1}r\mu}{2-\sqrt{p_1}\alpha r\mu)}$ if and only if $\frac{\sqrt{p_1}r\mu}{2-\sqrt{p_1}\alpha r\mu)} + \frac{r\mu}{2}\left(1+\alpha\frac{\sqrt{p_1}r\mu}{2-\sqrt{p_1}\alpha r\mu)}\right)^2 > \epsilon_1$. The preceding condition is further equivalent to $\epsilon_1 < \frac{r\mu(2+2\sqrt{p_1}-p_1\alpha r\mu)}{(2-\sqrt{p_1}\alpha r\mu)^2}$. This proves Part 2(b) and Part 2(c). □

Proof of Theorem 4. As we discussed in §4.2, in this symmetric margin case with $w = r/2$, the comparison of the manufacturer's (or the supplier's) optimal expected profit in Model (M) and Model (S) is equivalent to the comparison of the manufacturer's (or the supplier's) optimal efforts in the two models, which is further equivalent to the comparison of the optimal efforts for the manufacturer and the supplier in Model (M). Specifically, first-mover disadvantage is reversed if and only if $x_m^M < x_s^M$. Therefore, Part (1) of Theorem 4 follows from the following proposition on optimal efforts.

Proposition A3 (Optimal Efforts) *Suppose the second-mover faces the same persistent market risk as the first mover. When ϵ follows a Bernoulli distribution with sample space $\{0, \epsilon_1 = 2\epsilon_0\}$ and success probability 0.5; i.e., Prob$(\epsilon = \epsilon_1) = 0.5$, the optimal efforts for the manufacturer and the supplier, denoted as (x_m^M, x_s^M), can be determined as follows:*

1. *If $\epsilon_1 \le \frac{1}{2}\mu$, then $x_m^M = 0$, and $x_s^M = \epsilon_1$.*
2. *If $\epsilon_1 > \frac{1}{2}\mu$, then we have:*

   (a) *If $\alpha\mu \ge \sqrt{2}$, then $x_m^M = \bar{x}_m$ and $x_s^M = \frac{\mu}{2}(1+\alpha\bar{x}_m) = \frac{\epsilon_1 - \bar{x}_m}{1+\alpha\bar{x}_m}$, where $\bar{x}_m$ is the unique value in $[0, \epsilon_1]$ that satisfies $\bar{x}_m + \frac{1}{2}\mu(1+\alpha\bar{x}_m)^2 = \epsilon_1$.*

   (b) *If $\alpha\mu < \sqrt{2}$, then $x_m^M = \min\{\bar{x}_m, x_m^0\} \le \bar{x}_m$, and $x_s^M = \frac{\mu}{2}(1+\alpha x_m^M) \le \frac{\epsilon_1 - x_m^M}{1+\alpha x_m^M}$, where $\bar{x}_m$ is defined in Statement 2(a) above, and x_m^0 is the "unconstrained" solution in the unbounded case when $\epsilon \equiv \infty$; specifically, $x_m^0 = \frac{\mu(1+\alpha\mu)}{2-\alpha^2\mu^2}$.*

Proof of Proposition A3: Notice the profit functions for the supplier and the manufacturer are identical to those in the case with constant market risk and fixed wholesale price (as presented in §A4), if we re-define the constant risk therein as $\epsilon_0 = \epsilon_1$, and the terms μ_m and μ_s therein as: $\mu_m = p_1(r-w)\mu$, and $\mu_s = p_1 w\mu$. Proposition A3 thus follows from Lemma A4 immediately, after substituting $r = 2$ (and $w = 1$), and $p_1 = 0.5$. □

We now turn our attention to proving Part (2) of Theorem 4. Suppose $\epsilon_1 > \frac{1}{2}\mu$ and $\alpha\mu \ge \sqrt{2}$, it follows from Part 2(a) in Proposition A3 that $x_m^M = \bar{x}_m$, and $x_s^M = \frac{\mu}{2}(1+\alpha\bar{x}_m)$. Thus $x_m^M < x_s^M$ if and only if $\bar{x}_m < \frac{\mu}{2}(1+\alpha\bar{x}_m)$, which is further equivalent to: $(2-\alpha\mu)\bar{x}_m < \mu$. Because $x_m^M > 0$, this condition obviously holds if $\alpha\mu > 2$. Therefore Part (2) follows immediately.

Now suppose $\epsilon_1 > \frac{1}{2}\mu$ and $\sqrt{2} \le \alpha\mu < 2$. Then $x_m^M < x_s^M$ if and only if $\bar{x}_m < \frac{\mu}{2-\alpha\mu}$. Given $\bar{x}_m$ is the unique value in $[0, \epsilon_1]$ that satisfies $\bar{x}_m + \frac{1}{2}\mu(1+\alpha\bar{x}_m)^2 = \epsilon_1$, it is easy to check that $\bar{x}_m < \frac{\mu}{2-\alpha\mu}$

if and only if $\frac{\mu}{2-\alpha\mu}+\frac{1}{2}\mu(1+\alpha\frac{\mu}{2-\alpha\mu})^2>\epsilon_1$, which is equivalent to: $\epsilon_1<\frac{\mu(4-\alpha\mu)}{(2-\alpha\mu)^2}$. Furthermore, when $\sqrt{2}\le\alpha\mu<2$, we can show that: $\frac{\mu(4-\alpha\mu)}{(2-\alpha\mu)^2}>\frac{1}{2}\mu$ always holds. Therefore Part (3) follows. □

Proof of Proposition 5. For any given x_m, the supplier's expected profit is $\pi_s(x_s|x_m)=\frac{\mu}{2}\min(x_m+x_s+\alpha x_m x_s,\epsilon_1)-\frac{1}{2}x_s^2$ if the supplier does not observe realized market risk, while otherwise it is $\pi_s(x_s|x_m)=\frac{1}{2}\left(\mu\min(x_m+x_s+\alpha x_m x_s,\epsilon_1)-\frac{1}{2}x_s^2\right)$. Part (1) then follows directly because for any given x_m, the supplier cannot be worse off by observing market risk.

For part (2), it is clear from the above expressions that, when market risk turns out to be ϵ_1, the optimal x_s^* is higher than the optimal investment effort made under persistent market risk. For part (3), note that the manufacturer is better off with the supplier observing risk because, when the market risk turns out to be low ($\epsilon=\epsilon_2$), the supplier's investment effort is irrelevant; whereas when the market risk turns out to be high ($\epsilon=\epsilon_2$), the supplier's investment is higher. Thus, the manufacturer strictly benefits from the supplier observing market taste. □

The following corollary is useful for subsequent proofs.

Corollary A1 (Regions of Optimal Supplier Effort: Endogenous Selling Price) *The following properties hold for the optimal supplier effort.*

1. *If $\eta\mu^2\ge 4b$, then :*

$$x_s^*(x_m)=\begin{cases}0 & \text{if } x_m>\epsilon_1;\\ \frac{\epsilon_1-x_m}{1+\alpha x_m} & \text{if } x_m\le\epsilon_1.\end{cases}$$

2. *If $\eta\mu^2<4b$ and $\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1>\alpha\epsilon_1$, then :*

$$x_s^*(x_m)=\begin{cases}0 & \text{if } x_m>\epsilon_1;\\ \frac{\epsilon_1-x_m}{1+\alpha x_m} & \text{if } x_m^0\le x_m\le\epsilon_1;\\ x_s^0(x_m) & \text{if } 0\le x_m\le x_m^0,\end{cases}\tag{A14}$$

3. *Suppose $\eta\mu^2<4b$, and $\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1\le\alpha\epsilon_1$, then we have:*

$$x_s^*(x_m)=\begin{cases}0 & \text{if } x_m>\epsilon_1;\\ \frac{\epsilon_1-x_m}{1+\alpha x_m} & \text{if } \min\left\{\frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha},x_m^0\right\}\le x_m\le\epsilon_1;\\ x_s^0(x_m) & \text{if } 0\le x_m\le\min\left\{\frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha},x_m^0\right\},\end{cases}\tag{A15}$$

Proof of Corollary A1. First observe that x_m^0 is the unique value in $[0,\epsilon_1]$ that satisfies: $\alpha^2\eta\mu^2\epsilon_1(x_m^0)^2+(2\alpha\eta\mu^2\epsilon_1+4b)x_m^0+(\eta\mu^2-4b)\epsilon_1=0$. Part (1). When the corollary condition holds; that is, when $\eta\mu^2\ge 4b$, we have: $d(x_m,x^*(x_m),\epsilon_1)=\epsilon_1$ for all $x_m\ge 0$. Thus for given x_m, the manufacturer's expected profit is: $\pi_m(x_m)=\frac{1}{8b}\eta(1-\eta)\mu^2\epsilon_1^2-\frac{1}{2}x_m^2$. Therefore the optimal manufacturer's effort must be: $x_m^M = 0$. Part (2). When the corollary conditions hold; that is, when $\eta\mu^2 < 4b$, and $\frac{2}{\mu}\sqrt{\frac{b}{\eta}} - 1 > \alpha\epsilon_1$, it is easy to check that for any given x_m, the manufacturer's expected profit is:

$$\pi_m(x_m) = \begin{cases} \frac{1}{8}\eta(1-\eta)\mu^2\epsilon_1^2 - \frac{1}{2}x_m^2 & \text{if } x_m \geq x_m^0; \\ \frac{1}{8}\eta(1-\eta)\mu^2\left[\frac{x_m}{1-\frac{\eta\mu^2}{4b}(1+\alpha x_m)^2}\right]^2 - \frac{1}{2}x_m^2 & \text{if } 0 \leq x_m \leq x_m^0. \end{cases} \tag{A16}$$

To determine the optimal effort level for the manufacturer, x_m^M, it follows from (A16) that we only need to focus on the region when $0 \leq x_m \leq x_m^0$; that is, $x_m^M = \arg\max_{0 \leq x_m \leq x_m^0} \pi_m(x_m)$. In other words, we must have: $x_m^M \leq x_m^0$. Part (3). When the corollary conditions hold; that is, when $\eta\mu^2 < 4b$, and $\frac{2}{\mu}\sqrt{\frac{b}{\eta}} - 1 \leq \alpha\epsilon_1$, the manufacturer's expected profit for any given x_m is:

$$\pi_m(x_m) = \begin{cases} \frac{1}{8}\eta(1-\eta)\mu^2\epsilon_1^2 - \frac{1}{2}x_m^2 & \text{if } x_m \geq \min\left\{\frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}, x_m^0\right\}; \\ \frac{1}{8}\eta(1-\eta)\mu^2\left[\frac{x_m}{1-\frac{\eta\mu^2}{4b}(1+\alpha x_m)^2}\right]^2 - \frac{1}{2}x_m^2 & \text{if } 0 \leq x_m \leq \min\left\{\frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}, x_m^0\right\}. \end{cases} \tag{A17}$$

Therefore we must have: $x_m^M = \arg\max_{0 \leq x_m \leq \min\left\{\frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}, x_m^0\right\}} \pi_m(x_m) \leq x_m^0$. $\square$

Proof of Theorem 5. Part (1) follows from Proposition A7(1), and Corollary A1(1) that: $x_m^M = 0$, $x_s^M = \epsilon_1$, and $d(x_m^M, x_s^M, \epsilon_1) = \epsilon_1$. Next, consider the symmetric margin case in Part (2); that is, when $\eta = 0.5$. Note that the first-mover disadvantage is reversed if and only if $x_m^M < x_s^M$. Under the suppositions that $\mu_0 \leq \mu < 2\sqrt{2b}$ and $1 + \alpha\epsilon_1 < 2\sqrt{2b}/\mu$, Proposition A7(2) implies that: $x_m^M = x_m^0$. It then follows from Corollary A1(2) and the definition of x_m^0 that $x_s^M = x_s^*(x_m^M) = \frac{\epsilon_1 - x_m^M}{1+\alpha x_m^M}$; that is, we have: $x_m^M + x_s^M + \alpha x_m^M x_s^M = \epsilon_1$. Observe that $x_m^M < x_s^M$ if $x_m^M < \tilde{x}$, where $\tilde{x}$ is the unique value in $[0, \epsilon_1]$ that satisfies: $2\tilde{x} + \alpha\tilde{x}^2 = \epsilon_1$. Specifically, $\tilde{x} = \frac{-1+\sqrt{1+\alpha\epsilon_1}}{\alpha}$. Finally, in order to have $x_m^M = x_m^0 < \tilde{x}$, it follows from the definition of x_m^0 that we need: $\alpha^2(0.5)\mu^2\epsilon_1(\tilde{x})^2 + (2\alpha(0.5)\mu^2\epsilon_1 + 4b)\tilde{x} + (0.5\mu^2 - 4b)\epsilon_1 > 0$. This condition is equivalent to: $8b/\mu^2 < \frac{\alpha\epsilon_1(1+\alpha\epsilon_1)}{(1+\alpha\epsilon_1)-\sqrt{1+\alpha\epsilon_1}}$. Therefore, under the suppositions of Theorem 5(2), we must have: $x_m^M < x_s^M$, and the first-mover disadvantage is reversed. $\square$

A3. Constant Market Risk, Endogenous Wholesale Price

In this section, we consider the case when the market risk ϵ is known to the manufacturer and the supplier a priori: $\epsilon \equiv \epsilon_0$, where ϵ_0 represents the expected market taste/appetite. This serves as building block for analyzing the general case with stochastic market risk.

A3.1. Manufacturer Moves First: Model (M)

In Model (M), the manufacturer moves first by making the advance effort investment and pricing decisions. Given $\epsilon \equiv \epsilon_0$, $d(x_m, x_s, \epsilon_0) = \mu \min\{u(x_m, x_s), \epsilon_0\} = \mu \min\{x_m + x_s + \alpha x_m x_s, \epsilon_0\}$. As a result, the presence of the market risk limits the supplier and the manufacturer's appetites for anticipative effort investment, and hence in contrast to the result in the base model when there is no market risk, a bounded equilibrium effort level always exists even if there is a strong complementary effect. Specifically, for any given manufacturer's investment and pricing decisions (x_m, w), the supplier's optimal investment effort (given $\epsilon \equiv \epsilon_0$) can be determined by the following lemma.

Lemma A3 *For any given (x_m, w) and $\epsilon \equiv \epsilon_0$, the supplier's optimal investment effort is given as:*

$$x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = \begin{cases} 0 & \text{if } x_m \geq \epsilon_0; \\ \min\left(x_s^0(x_m, w), \frac{\epsilon_0 - x_m}{1+\alpha x_m}\right) & \text{if } x_m \leq \epsilon_0, \end{cases} \tag{A18}$$

where $x_s^0(x_m, w) = \mu w(1 + \alpha x_m)$.

Proof of Lemma A3: We prove the lemma statement by considering the following all possible cases/ranges of x_m: Case 1: If $x_m \geq \epsilon_0$, then for all $x_s \geq 0$, we have $x_s + x_m + \alpha x_s x_m > \epsilon_0$. Therefore $\pi_s(x_s|x_m, w) = w\mu\epsilon_0 - \frac{1}{2}x_s^2$, and $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = 0$. Case 2: If $x_m \leq \epsilon_0$, then there are two sub-cases to consider: Case 2-1: For $x_s \geq \frac{\epsilon_0 - x_m}{1+\alpha x_m}$, $\pi_s(x_s|x_m, w) = w\mu\epsilon_0 - \frac{1}{2}x_s^2$, and $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = \frac{\epsilon_0 - x_m}{1+\alpha x_m}$. Case 2-2: For $0 \leq x_s \leq \frac{\epsilon_0 - x_m}{1+\alpha x_m}$, $\pi_s(x_s|x_m, w) = w\mu(x_s + x_m + \alpha x_s x_m) - \frac{1}{2}x_s^2$. This is a concave function of x_s, and $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = \min(x_s^0(x_m, w), \frac{\epsilon_0 - x_m}{1+\alpha x_m})$, where $x_s^0(x_m, w) = \mu w(1 + \alpha x_m)$. Overall, in Case 2 the optimal solution $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = \min(x_s^0(x_m, w), \frac{\epsilon_0 - x_m}{1+\alpha x_m})$. Combining the above cases yields the lemma statement. □

The supplier's effort depends on the relative magnitude of the manufacturer's investment level as well as the expected market appetite ϵ_0: if the expected market appetite for the product is low, then the supplier does not exert any investment effort and simply free rides on the manufacturer's effort investment. On the other hand, if the expected market appetite is high, then the supplier exerts a positive investment effort, bounded either by the interior optimal investment level $x_s^0(x_m, w)$ or by the highest level the market will bear, i.e., $(\epsilon_0 - x_m)/(1 + \alpha x_m)$.

The manufacturer's problem is to determine the optimal effort investment and pricing decisions, denoted as (x_m^M, w^M), to maximize its profit: $\pi_m(x_m, w) = (r - w)d(x_m, x_s^*(x_m, w|\epsilon \equiv \epsilon_0), \epsilon_0) - \frac{1}{2}x_m^2$. When ϵ_0 approaches to infinity, the manufacturer's optimal effort level and wholesale price should converge to those interior solutions as presented in §3.1. Therefore, we next focus on the case when ϵ_0 is relatively low.

Proposition A4 *Suppose $r\mu \geq 2\epsilon_0$. Then the manufacturer's optimal decisions can be determined as: $(x_m^M, w^M) = (x_0, w_0)$, where x_0 is the unique value in $(0, \epsilon_0]$ that satisfies $\frac{1+\alpha(2\epsilon_0 - x_0)}{(1+\alpha x_0)^3}\epsilon_0 - x_0 = 0$ and $w_0 = \frac{\epsilon_0 - x_0}{\mu(1+\alpha x_0)^2}$. The supplier's optimal investment effort is: $x_s^M = \mu w^0(1+\alpha x_0) = \frac{\epsilon_0 - x_0}{1+\alpha x_0}$, and the optimal market demand is: $d(x_m^M, x_s^M, \epsilon_0) = \mu\epsilon_0$.*

Proof of Proposition A4: Anticipating the supplier's optimal response $x_s^*(x_m, w|\epsilon \equiv \epsilon_0)$ for any given (x_m, w), the manufacturer's expected profit is: $\pi_m(x_m, w) = (r-w)d(x_m, x_s^*(x_m, w|\epsilon = \epsilon_0), \epsilon_0) - \frac{1}{2}x_m^2 = (r-w)\mu\min(x_s^*(x_m, w) + x_m + \alpha x_s^*(x_m, w)x_m, \epsilon) - \frac{1}{2}x_m^2$.

Region 1: When $x_m \geq \epsilon_0$, we have: $\pi_m(x_m, w) = (r-w)\mu\epsilon_0 - \frac{1}{2}x_m^2$. It is easy to check that the optimal solution must satisfy: $x_m^* = \epsilon_0$ and $w^* = 0$.

Region 2: When $x_m \leq \epsilon_0$. It follows from Lemma A3 that: $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = \min(x_s^0(x_m, w), \frac{\epsilon_0 - x_m}{1+\alpha x_m})$. Furthermore, we have: $x_s^0(x_m, w) \geq \frac{\epsilon_0 - x_m}{1+\alpha x_m}$ iff $w \geq \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$. Furthermore, we can verify that under the assumption that $r\mu \geq 2\epsilon_0$, we have: $\frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2} \leq r$ holds for all $x_m \geq 0$.

Region 2-1: When $x_m \leq \epsilon_0$ and $w \geq \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$. Then we have: $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = \frac{\epsilon_0 - x_m}{1+\alpha x_m}$, and $\pi_m(x_m, w) = (r-w)\mu\epsilon_0 - \frac{1}{2}x_m^2$. Notice that $\frac{\epsilon - x_m}{\mu(1+\alpha x_m)^2}$ is a decreasing function of x_m. Therefore although $\pi_m(x_m, w)$ is decreasing in x_m, we cannot set the optimal x_m^* as 0, because w will be the highest in this case, which may lead to a lower expected profit for the manufacturer. On the other hand, as π_m is decreasing in w, we must have: $w^*(x_m) = \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$. Therefore the manufacturer's optimization problem in this case is: $\max_{0 \leq x_m \leq \epsilon_0} \pi_m(x_m) = (r - \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2})\mu\epsilon_0 - \frac{1}{2}x_m^2$. Observe that: $\pi_m'(x_m) = \frac{1-\alpha x_m + 2\alpha\epsilon_0}{(1+\alpha x_m)^3}\epsilon_0 - x_m$, and $\pi_m''(x_m) = -\frac{\alpha(1+\alpha x_m) + 3\alpha(1+\alpha(2\epsilon_0 - x_m))}{(1+\alpha x_m)^4}\epsilon_0 - 1$. Furthermore, we have: $\pi_m''(x_m) < 0$ for $x_m \leq \epsilon_0$, implying $\pi_m(x_m)$ is concave in $x_m \in [0, \epsilon_0]$. To determine the optimal x_m^* in this region, notice $\pi_m'(x_m = 0) > 0$, and $\pi_m'(x_m = \epsilon_0) = \frac{\epsilon_0}{(1+\alpha\epsilon_0)^2} - \epsilon_0 \leq 0$. Thus there must exist an unique optimal value $x_0 \in (0, \epsilon_0]$ that satisfies: $\pi_m'(x_0) = 0$. Consequently, we can determine the optimal price $w^* = \frac{\epsilon_0 - x_0}{\mu(1+\alpha x_0)^2} = w_0$.

Region 2-2: When $x_m \leq \epsilon_0$ and $w \leq \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$. Then we have: $x_s^*(x_m, w|\epsilon \equiv \epsilon_0) = x_s^0(x_m, w) = \mu w(1+\alpha x_m)$ and $\pi_m(x_m, w) = (r-w)\mu[\mu w(1+\alpha x_m)^2 + x_m] - \frac{1}{2}x_m^2$. Furthermore, We have:

$$\frac{\partial \pi_m}{\partial w} = \mu[\mu(r-2w)(1+\alpha x_m)^2 - x_m], \quad \frac{\partial^2 \pi_m}{\partial w^2} = -2\mu^2(1+\alpha x_m)^2 < 0,$$
$$\frac{\partial \pi_m}{\partial x_m} = (r-w)\mu(2\alpha\mu w + 1) + [2\alpha^2\mu^2 w(r-w) - 1]x_m, \quad \frac{\partial^2 \pi_m}{\partial x_m^2} = 2\alpha^2\mu^2 w(r-w) - 1.$$

Note that for any given x_m, $\pi_m(x_m, w)$ is concave in w. Setting $\frac{\partial \pi_m}{\partial w} = 0$ yields: $w^0(x_m) = \frac{r\mu(1+\alpha x_m)^2 - x_m}{2\mu(1+\alpha x_m)^2}$. We can check that $w^0(x_m) \geq \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$ if and only if $h_1(x_m) := r\mu(1+\alpha x_m)^2 + x_m - 2\epsilon_0 \geq 0$. As $h_1(x_m)$ increases in x_m, we can check that under the assumption that $r\mu \geq 2\epsilon_0$, we have

$h_1(x_m) \geq 0$ for all $x_m \geq 0$, or equivalently, $w^0(x_m) \geq \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$. In this case, for any given $x_m \in [0, \epsilon_0]$, we must have: $w^*(x_m) = \frac{\epsilon_0 - x_m}{\mu(1+\alpha x_m)^2}$. Consequently, as $\pi_m(x_m, w^*(x_m)) = (r - w)\mu\epsilon_0 - \frac{1}{2}x_m^2$, we will have an identical problem to the one in Region 2-1 in determining the optimal x_m^*.

In summary, under the assumption that $r\mu \geq 2\epsilon$, the solutions to the Problems in Region 2-1 and Region 2-2 are identical, and they are given by $(x_m^*, w^*) = (x_0, w_0)$, where $x_0 \in (0, \epsilon_0]$ satisfies $x_0 = \frac{1-\alpha x_0 + 2\alpha\epsilon_0}{(1+\alpha x_0)^3}\epsilon_0$, and $w_0 = \frac{\epsilon_0 - x_0}{\mu(1+\alpha x_0)^2}$. Thus (x_0, w_0) is the optimal solution in Region 2. Next, considering that the optimal solution in Region 1; i.e., $(x^*, w^*) = (\epsilon_0, 0)$ is also a feasible solution in Region 2, therefore we can conclude that the optimal solution (x_0, w_0) in Region 2 must dominate the optimal solution in Region 1 (in terms of profit comparison). Finally, we conclude that under the assumption that $r\mu \geq 2\epsilon$, the manufacturer's optimal decision is: $(x_m^M, w^M) = (x_0, w_0)$. The supplier's optimal effort x_s^M and the optimal market demand $d(x_m^M, x_s^M, \epsilon_0)$ follow immediately. This completes the proof. □

Proposition A4 says that when the expected market appetite ϵ_0 is relatively low so that $r\mu \geq 2\epsilon_0$, the optimal effort investment and pricing decisions of the manufacturer and the supplier will be set so that the market demand reaches the highest value that the market can bear; that is, $d(x_m^M, x_s^M, \epsilon_0) = \mu\epsilon_0$. Specifically, the manufacturer's optimal effort level $x^M = x_0$, where x_0 is bounded above by ϵ_0 and it satisfies an implicit function as defined in Proposition A4, which depend on α and ϵ_0. Nevertheless, as $w_0 = \frac{\epsilon_0 - x_0}{\mu(1+\alpha x_0)^2}$, the optimal wholesale price w_0 always decreases in the optimal effort x_0, which contrasts the property of the optimal wholesale price $\bar{w}$ with respective to the optimal effort level $\bar{x}$ in the base model with no market risk, as given in part (1) of Corollary 1. The following corollary examines the impact of the complementary effect α on the manufacturer's optimal decisions in this model.

Corollary A2 *Suppose $r\mu \geq 2\epsilon_0$. The following properties hold for the optimal investment effort x_0 and wholesale price w_0 defined in Proposition A4.*

1. *If $\alpha\epsilon_0 \geq 2$, then $x_0 \geq 1/\alpha$; if $0.802 \leq \alpha\epsilon_0 < 2$, then $1/(2\alpha) \leq x_0 < 1/\alpha$; and if $\alpha\epsilon_0 < 0.802$, then $x_0 < 1/(2\alpha)$. Furthermore, $x_0 \geq \epsilon_0/2$ if and only if $\alpha\epsilon_0 \leq 2$.*
2. *x_0 decreases in α; and $w_0 < r/2$.*
3. *If $0.75 \leq \alpha r\mu \leq \sqrt{2}$, then $x_0 < \bar{x}$ and $w_0 < \bar{w}$, where $\bar{x}$ and $\bar{w}$ are the manufacturer's optimal investment effort and wholesale price in the base model, as defined in Proposition 1.*

Proof of Corollary A2: For $x \geq 0$, define: $\pi_m(x) = (r - \frac{\epsilon_0 - x}{\mu(1+\alpha x)^2})\mu\epsilon_0 - x^2/2$. Then we can show that $\pi''(x) \leq 0$ for $x \in [0, \epsilon_0]$, and x_0 satisfies $\pi_m'(x_0) = 0$. Next, $\pi_m'(x = \frac{1}{\alpha}) = (\alpha^2\epsilon_0^2 - 4)/(4\alpha) \geq 0$ iff $\alpha\epsilon_0 \geq 2$; and $\pi_m'(x = \frac{1}{2\alpha}) = (32\alpha^2\epsilon_0^2 + 8\alpha\epsilon_0 - 27)/(54\alpha) \geq 0$ iff $\alpha\epsilon_0 \geq 0.802$. Furthermore, we can check that $\pi_m'(x = \frac{\epsilon_0}{2}) \geq 0$ iff $(\alpha\epsilon_0)^3 + 6(\alpha\epsilon_0)^2 - 12(\alpha\epsilon_0) - 8 \leq 0$, which holds iff $0 \leq \alpha\epsilon_0 \leq 2$. Therefore the first statement follows from the concavity of $\pi_m(x)$ and the fact that $\pi_m'(x_0) = 0$.

To prove the second statement, we take the derivative with respective to α on both sides of $\pi'_m(x_0)=0$, getting:

$$\pi''_m(x_0)\frac{\partial x_0}{\partial \alpha}+\frac{(2\epsilon_0-x_0)(1-2\alpha x_0)-3x_0}{(1+\alpha x_0)^4}\epsilon_0=0 \tag{A19}$$

From the proof of the first statement above, we know if $\alpha\epsilon_0\geq 0.802$, then $x_0\geq\frac{1}{2\alpha}$, implying $(2\epsilon_0-x_0)(1-2\alpha x_0)-3x_0<0$ (because $x_0\leq\epsilon_0$). If $\alpha\epsilon_0<0.802$, then we have: $0<1-2\alpha x_0\leq 1$, and $(2\epsilon_0-x_0)(1-2\alpha x_0)-3x_0<2\epsilon_0-3x_0<0$. The last inequality holds because $x_0>\epsilon_0/2$ when $\alpha\epsilon_0<2$. Therefore we have shown that the second term in (A19) must be negative. Given $\pi''(x_0)<0$, it follows from (A19) that: $\frac{\partial x_0}{\partial\alpha}<0$.

Next, we can show when $r\mu\geq 2\epsilon_0$, $\frac{r}{2}-\frac{x}{2\mu(1+\alpha x)^2}\geq\frac{\epsilon_0-x}{\mu(1+\alpha x)^2}$ holds for any $x\geq 0$. Thus we must have: $w_0=\frac{\epsilon_0-x_0}{\mu(1+\alpha x_0)^2}\leq\frac{r}{2}-\frac{x_0}{2\mu(1+\alpha x_0)^2}<\frac{r}{2}$. This completes the proof of the second statement.

Finally, suppose $0.75\leq\alpha r\mu\leq\sqrt{2}$. It follows from Corollary 1 that: $\bar{x}\geq 1/\alpha$. Also, it follows from $r\mu\geq 2\epsilon_0$ that: $\alpha\epsilon_0\leq\sqrt{2}/2=0.707$, and the proof of the first statement above implies that: $x_0<\frac{1}{\alpha}$. Therefore we have shown: $\bar{x}>x_0$. Next, because $\bar{x}\geq 1/\alpha$ and $\frac{r}{2}-\frac{x}{2\mu(1+\alpha x)^2}$ increases in x on $x\geq 1/\alpha$, we have: $\bar{w}\geq\frac{r}{2}-\frac{1/\alpha}{2\mu(1+\alpha\cdot 1/\alpha)^2}=\frac{4\alpha r\mu-1}{8\alpha\mu}$. Because $x_0>\epsilon_0/2$ and $\frac{\epsilon_0-x}{\mu(1+\alpha x)^2}$ decreases in $x\in[0,\epsilon_0]$, we have: $w_0<\frac{\epsilon_0-\epsilon_0/2}{\mu(1+\alpha\cdot\epsilon_0/2)^2}=\frac{2\epsilon_0}{\mu(2+\alpha\epsilon_0)^2}$. Furthermore, when $\alpha r\mu\geq 3/4$, we can verify that: $\frac{2\epsilon_0}{\mu(2+\alpha\epsilon_0)^2}<\frac{4\alpha r\mu-1}{8\alpha\mu}$. Thus $\bar{w}>w_0$. This completes the proof of the corollary. □

Part (1) of Corollary A2 provides some useful bounds on the optimal investment effort x_0, and the conditions depend on both the complementary effect α and the expected market appetite ϵ_0. Part (2) suggests that, similar to the base model with no market risk, the endogenous pricing power enables the manufacturer (as the first mover) to earn a higher profit margin than the supplier does; that is, $w_0<r/2$. However, different from the base model with no market risk when the manufacturer has to increase its investment effort and pays a higher wholesale price to entice the supplier to exert a higher effort, especially when the complementary effect α is relatively strong (see part (2) of Corollary 1 and Figure 1), part (2) of Corollary A2 says that the manufacturer's optimal investment effort in the case with market risk actually decreases in the complementary effect α.

By comparing the optimal investment efforts and the optimal wholesale prices in the two cases with and without the market risk, especially when the complementary effect is relatively strong, part (3) of Corollary A2 suggests that $x_0<\bar{x}$ and $w_0<\bar{w}$. In other words, anticipating a constrained and lower supplier effort in the presence of market risk, the endogenous pricing power of the manufacturer (as the first mover) enables the manufacturer to exert a lower effort and pay a lower wholesale price compared to the case with no market risk, which curbs the supplier's ability to free ride on the manufacturer's advance investment effort. As a result, comparing with the case when there is no market risk so that the demand is unbounded above, we conjecture that the manufacturer has a higher chance to benefit from the endogenous pricing power as the first mover. This difference may potentially reverse the first-mover disadvantage for the manufacturer, especially when the complementary effect is high and the expected market appetite ϵ_0 is relatively low. Before we formally examine this conjecture, we first present the optimal decisions of the manufacturer and the supplier in Model (S) where the supplier moves first.

A3.2. Supplier Moves First: Model (S)

In this model, the supplier moves first by setting (x_s, w), and the manufacturer moves next by setting the corresponding $x_m^*(x_s, w|\epsilon \equiv \epsilon_0)$. By using the same arguments as in §3.1, this Model (S) can be transformed to Model (M) by defining $w' = r - w$ in Model (S). The optimal decisions for the supplier and the manufacturer are parallel to those in Proposition A4 and are presented in the following proposition for ease of reference.

Proposition A5 *Suppose $r\mu \geq 2\epsilon_0$. Then the supplier's optimal decisions can be determined as: $(x_s^S, w^S) = (x_m^M, r - w^M) = (x_0, r - w_0)$, where x_0 and w_0 are given in Proposition A4. Furthermore, the manufacturer's optimal investment effort is: $x_m^S = x_s^M = \mu w_0(1 + \alpha x_0) = \frac{\epsilon_0 - x_0}{1+\alpha x_0}$, and the optimal market demand is: $d(x_m^S, x_s^S, \epsilon_0) = \mu\epsilon_0$.*

Proof of Proposition A5: It follows from similar proof of Proposition A4, and the fact that Model (S) is identical to Model (M) if we define $w' = r - w$. We omit the details. $\square$

Now we are ready to compare the manufacturer's profits in Model (M) and Model (S) to examine if the first-mover disadvantage result persists under the model with both endogenous pricing and market risk with an expected market appetite $\epsilon \equiv \epsilon_0$. To proceed, the optimal profits of the manufacturer and the supplier in Models (M) and (S) are given by: $\pi_m^{M*} = (r - w^M)\mu\epsilon_0 - \frac{1}{2}{x_m^M}^2, \pi_m^{S*} = (r - w^S)\mu\epsilon_0 - \frac{1}{2}{x_m^S}^2$; and $\pi_s^{M*} = w^M\mu\epsilon_0 - \frac{1}{2}{x_s^M}^2, \pi_s^{S*} = w^S\mu\epsilon_0 - \frac{1}{2}{x_s^S}^2$.

Theorem A2 *Suppose $r\mu \geq 2\epsilon_0$. The first-mover disadvantage is reversed for both the manufacturer and the supplier: $\pi_m^{M*} > \pi_m^{S*}$ and $\pi_s^{S*} > \pi_s^{M*}$.*

Proof of Theorem A2: It follows from the facts that: $x_m^M = x_s^S, x_s^M = x_m^S$ and $w^M + w^S = r$ that: $\pi_m^{M*} > \pi_m^{S*}$ (or equivalently, $\pi_s^{S*} > \pi_s^{M*}$) if and only if $(r - w^M)\mu\epsilon_0 - \frac{1}{2}{x_m^M}^2 > w^M\mu\epsilon_0 - \frac{1}{2}{x_s^M}^2$, which is equivalent to: $(r - 2w^M)\mu\epsilon_0 > \frac{1}{2}{x_m^M}^2 - \frac{1}{2}{x_s^M}^2$. As $w^M = \frac{\epsilon_0 - x_m^M}{\mu(1+\alpha x_m^M)^2}$ and $x_s^M = \frac{\epsilon_0 - x_m^M}{1+\alpha x_m^M}$, we can show that the above condition is equivalent to: $2(r - 2\frac{\epsilon_0 - x_m^M}{\mu(1+\alpha x_m^M)^2})\mu\epsilon_0 > {x_m^M}^2 - (\frac{\epsilon_0 - x_m^M}{1+\alpha x_m^M})^2$, which is further equivalent to: $2r\mu\epsilon_0 + (2\alpha x_m^M + \alpha^2 {x_m^M}^2)(2r\mu\epsilon_0 - {x_m^M}^2) \geq 3\epsilon_0^2 - 2\epsilon_0 x_m^M$. This clearly holds especially under the assumption that $r\mu \geq 2\epsilon_0$ and the fact that $x_m^M = x_0 \leq \epsilon_0$. Therefore we have shown that the first-mover advantage strictly holds for both the manufacturer (in Model (M)) and the supplier (in Model (S)). This completes the proof. $\square$

Theorem A2 validates our conjecture following Corollary A2. It suggests that when the market appetite for the product is known a priori and it is relatively low; specifically, when $\epsilon_0 \leq r\mu/2$, then the manufacturer (or the supplier) is strictly better off by leading the investment and pricing decisions. The constrained market demand limits the ability of the second mover to free ride on the first mover's advance investment effort due to complementary sourcing. As a result, the first-mover disadvantage result is completely reversed in this model, regardless of the strength of the complementary effect parameter α. This contrasts our result in Theorem 1, which says that when there is no market risk, the endogenous pricing power of the first mover can only partially reverse the first-mover disadvantage, specifically when the complementary effect is relatively low. In conclusion, the existence of market risk makes endogenous pricing power related to advance investment more attractive to the manufacturer (or the supplier) and hence reverses the first-mover disadvantage observed in the base model with no market risk.

A4. Constant Market Risk, Fixed Wholesale Price

When $\epsilon \equiv \epsilon_0$, the analysis for the fixed wholesale price case is similar to that in Appendix §A3, except there is no wholesale price optimization for the first mover. Specifically, in Model (M) when the manufacturer is the first mover, the supplier's problem is to determine the optimal effort level $x_s^*(x_m)$ for any given manufacturer's effort x_m, in order to maximize its profit: $\pi_s(x_s|x_m) = w\mu \min\{x_m + x_s + \alpha x_m x_s, \epsilon_0\} - \frac{1}{2}x_s^2$. It follows from Lemma A3 that $x_s^*(x_m|\epsilon \equiv \epsilon_0)$ can be determined as: $x_s^*(x_m) = \min\left\{\mu w(1+\alpha x_m), \left(\frac{\epsilon_0 - x_m}{1+\alpha x_m}\right)^+\right\}$. Next, anticipating $x_s^*(x_m)$ for any x_m, the manufacturer's problem is to determine the optimal effort level, denoted as x_m^M, to maximize its profit: $\pi_m(x_m) = (r-w)\mu \min\{x_m + x_s^*(x_m) + \alpha x_m x_s^*(x_m), \epsilon_0\} - \frac{1}{2}x_m^2$. We summarize the optimal solutions in the following lemma. For simplicity of presentation, we define: $\mu_m = (r-w)\mu$, and $mu_s = w\mu$.

Lemma A4 *When $\epsilon \equiv \epsilon_0$, the optimal efforts (x_m^M, x_s^M), the corresponding optimal demand $d^M = d(x_m^M, x_s^M, \epsilon_0) = \min\{x_m^M + x_s^M + \alpha x_m^M x_s^M, \epsilon_0\}$, and the corresponding optimal profits for the manufacturer and the supplier; i.e., $\pi_m^M = \mu_m d^M - \frac{1}{2}{x_m^M}^2$, $\pi_s^M = \mu_s d^M - \frac{1}{2}{x_s^M}^2$, where $\mu_m = (r-w)\mu, \mu_s = w\mu$, are given as follows:*

1. *If $\mu_s = w\mu \geq \epsilon_0$, then $x_m^M = 0, x_s^M = \epsilon_0$; $d^M = \epsilon_0$; and $\pi_m^M = \mu_m\epsilon_0$, $\pi_s^M = \mu_s\epsilon_0 - \frac{1}{2}\epsilon_0^2$.*
2. *If $\mu_s = w\mu < \epsilon_0$, then we have:*

   (a) *If $1 - 2\alpha^2\mu_m\mu_s \leq 0$, then $x_m^M = \bar{x}_m, x_s^M = \mu_s(1+\alpha\bar{x}_m) = \frac{\epsilon_0 - \bar{x}_m}{1+\alpha\bar{x}_m}$; $d^M = \epsilon_0$; and $\pi_m^M = \mu_m\epsilon_0 - \frac{1}{2}\bar{x}_m^2$, $\pi_s^M = \mu_s\epsilon_0 - \frac{1}{2}\mu_s^2(1+\alpha\bar{x}_m)^2 = \frac{1}{2}\mu_s(\epsilon_0 + \bar{x}_m)$, where $\bar{x}_m \in [0, \epsilon_0]$ is unique, and it satisfies: $\bar{x}_m + \mu_s(1+\alpha\bar{x}_m)^2 = \epsilon_0$.*

(b) *If* $1-2\alpha^2\mu_m\mu_s>0$, *then* $x_m^M=\min\{\bar{x}_m,x_m^0\}$, $x_s^M=\mu_s(1+\alpha x_m^M)\le\frac{\epsilon_0-x_m^M}{1+\alpha x_m^M}$; $d^M=x_m^M+\mu_s(1+\alpha x_m^M)^2\le\epsilon_0$; *and* $\pi_m^M=\mu_m[x_m^M+\mu_s(1+\alpha x_m^M)^2]-\frac{1}{2}{x_m^M}^2$, $\pi_s^M=\mu_s[x_m^M+\mu_s(1+\alpha x_m^M)^2]-\frac{1}{2}\big[\mu_s(1+\alpha x_m^M)\big]^2=\mu_s[x_m^M+\frac{1}{2}\mu_s(1+\alpha x_m^M)^2]$, *where* $\bar{x}_m$ *is defined in Statement 2(a) above, and* x_m^0 *is the "unconstrained" solution in the unbounded case when* $\epsilon=\infty$; *specifically,* $x_m^0=\frac{\mu_m(1+2\alpha\mu_s)}{1-2\alpha^2\mu_m\mu_s}$.

Proof of Lemma A4: First, for any given x_m, the supplier's profit is:

$$\pi_s(x_s|x_m)=\begin{cases}\mu_s\epsilon_0-\frac{1}{2}x_s^2 & \text{if } x_m\ge\epsilon_0;\\ \mu_s\epsilon_0-\frac{1}{2}x_s^2 & \text{if } x_m\le\epsilon_0, \text{ and } x_s\ge\frac{\epsilon_0-x_m}{1+\alpha x_m},\\ \mu_s(x_m+x_s+\alpha x_m x_s)-\frac{1}{2}x_s^2 & \text{if } x_m\le\epsilon_0, \text{ and } x_s\le\frac{\epsilon_0-x_m}{1+\alpha x_m}.\end{cases}\tag{A20}$$

Therefore we can verify that: (1) if $x_m\ge\epsilon_0$, the optimal supplier's effort is: $x_s^*(x_m)=0$; and (2) if $x_m\le\epsilon_0$, then $x_s^*(x_m)=\arg\max_{x_s\le\frac{\epsilon_0-x_m}{1+\alpha x_m}}\pi_s(x_s)=\mu_s(x_m+x_s+\alpha x_m x_s)-\frac{1}{2}x_s^2=\min\{\mu_s(1+\alpha x_m),\frac{\epsilon_0-x_m}{1+\alpha x_m}\}$. The last equality follows from the fact that $\pi_s(x_s)$ is concave in x_s. Furthermore, we can show that: (1) if $\mu_s\ge\epsilon_0$, then $\mu_s(1+\alpha x_m)\ge\frac{\epsilon_0-x_m}{1+\alpha x_m}$ always holds for all $x_m\in[0,\epsilon_0]$; and (2) if $\mu_s<\epsilon_0$, then $\mu_s(1+\alpha x_m)\ge\frac{\epsilon_0-x_m}{1+\alpha x_m}$ for $x_m\in[\bar{x}_m,\epsilon_0]$, and $\mu_s(1+\alpha x_m)\le\frac{\epsilon_0-x_m}{1+\alpha x_m}$ for $x_m\in[0,\bar{x}_m]$, where $\bar{x}_m$ is the unique value in $[0,\epsilon_0]$ that satisfies: $\mu_s(1+\alpha\bar{x}_m)^2+\bar{x}_m=\epsilon_0$. Thus for any given $x_m\ge0$, the supplier's optimal effort, $x_s^*(x_m)$, is summarized as follows: (1) For $x_m\ge\epsilon_0$, $x_s^*(x_m)=0$; and (2) For $x_m\le\epsilon_0$, we have: (2a) If $\mu_s\ge\epsilon_0$, then $x_s^*(x_m)=\frac{\epsilon_0-x_m}{1+\alpha x_m}$; and (2b) If $\mu_s<\epsilon_0$, then $x_s^*(x_m)=\frac{\epsilon_0-x_m}{1+\alpha x_m}$ for $x_m\in[\bar{x}_m,\epsilon_0]$; and $x_s^*(x_m)=\mu_s(1+\alpha x_m)$ for $x_m\in[0,\bar{x}_m]$.

Next, anticipating the optimal supplier's effort $x_s^*(x_m)$ for any $x_m\ge0$, the manufacturer's problem is to determine the optimal effort, denoted as x_m^M, to maximize its profit $\pi_m(x_m)$. Specifically, (1) if $\mu_s\ge\epsilon_0$, we have: $\pi_m(x_m)=\mu_m\epsilon_0-\frac{1}{2}x_m^2$ for all $x_m\ge0$. Thus $x_m^M=0$. (2) If $\mu_s<\epsilon_0$, then we have: $\pi_m(x_m)=\mu_m\epsilon_0-\frac{1}{2}x_m^2$ for $x_m\ge\bar{x}_m$; and $\pi_m(x_m)=\mu_m(x_m+\mu_s(1+\alpha x_m)^2)-\frac{1}{2}x_m^2$ for $x_m\in[0,\bar{x}_m]$. Thus $x_m^M=\arg\max_{x_m\in[0,\bar{x}_m]}\pi_m(x_m)=\mu_m(x_m+\mu_s(1+\alpha x_m)^2)-\frac{1}{2}x_m^2$. Finally, we can show that: (2a) If $1-2\alpha^2\mu_s\mu_s\le0$, then $\pi_m(x_m)$ is convex and increasing in $x_m\ge0$, which implies that $x_m^M=\bar{x}_m$; and (2b) If $1-2\alpha^2\mu_s\mu_s>0$, then $\pi_m(x_m)$ is concave, and $x_m^M=\min\{\bar{x}_m,x_m^0\}$, where x_m^0 satisfies $\pi_m'(x_m)|_{x_m=x_m^0}=0$. Specifically, $x_m^0=\frac{\mu_m(1+2\alpha\mu_s)}{1-2\alpha^2\mu_m\mu_s}$. The rest of the results in Lemma A4 can be verified easily. We omit the details. □

It follows from Lemma A4 immediately that the optimal manufacturer's effort never exceeds $\bar{x}_m$, where recall $\bar{x}_m$ is the cutoff value of x_m at which the "unconstrained" (interior) solution $x_s^*(x_m)=\mu_s(1+\alpha x_m)$ coincides with the "constrained" (boundary) solution $x_s^*(x_m)=\frac{\epsilon_0-x_m}{1+\alpha x_m}$ (at which $x_m+x_s^*(x_m)+\alpha x_m x_s^*(x_m)=\epsilon_0$). Thus, we have $x_m^M\le\bar{x}_m\le\epsilon_0$. Next, in Model (S) where the supplier moves first, notice the effort optimization problems for the manufacturer and the supplier are identical to those in Model (M), if we swap μ_m and μ_s. Finally, by comparing the manufacturer's (or the supplier's) profits in Statements 1 of Lemma A4 and the equivalent supplier result, it is easy to check that when the suppositions in these two statements hold simultaneously, then we will have the reversal of first-mover disadvantage. Specifically, we have:

Theorem A3 *Suppose* $0 < \epsilon_0 \leq \frac{\mu r}{2}$ *and* $\frac{\epsilon_0}{\mu} \leq w \leq r - \frac{\epsilon_0}{\mu}$*. Then first-mover disadvantage is reversed for both the manufacturer and the supplier:* $\pi_m^M > \pi_m^S$ *and* $\pi_s^S > \pi_s^M$*.*

Proof of Theorem A3: When $\frac{\epsilon_0}{\mu} \leq w \leq r - \frac{\epsilon_0}{\mu}$, we have $\mu_s = w\mu \geq \epsilon_0$ and $\mu_m = (r-w)\mu \geq \epsilon_0$ so that the suppositions in Statements 1 of Lemma A4 (and equivalent statement for supplier) hold simultaneously. It follows immediately that: $\pi_m^M = \mu_m\epsilon_0 > \mu_m\epsilon_0 - \epsilon_0^2/2 = \pi_m^S$, and $\pi_s^S = \mu_s\epsilon_0 > \mu_s\epsilon_0 - \epsilon_0^2/2 = \pi_s^M$. This completes the proof. □

The reversal of first-mover disadvantage result in Theorem A3 is consistent with Theorem A2 in the case with constant market risk and endogenous wholesale price, which says that as long as ϵ_0 is small so that $\epsilon_0 \leq r\mu/2$ holds (the same condition as that in Theorem A3), then with wholesale price optimization we will always have the first-mover disadvantage reversal. When the manufacturer does not have the pricing power to choose the optimal wholesale price, then Theorem A3 requires an additional condition, which suggests that as long as the fixed wholesale price is relatively balanced, then the first-mover disadvantage will be reversed.

A5. Optimal Investment Efforts Under Fixed Wholesale Price

Model (M): Manufacturer Moves First. For any given manufacturer's effort investment x_m, the supplier's optimal investment effort (conditional on realized market risk ϵ) can be similarly determined by Lemma 2 in §3.2. Furthermore, when ϵ follows the Bernoulli distribution with sample space $\{0, \epsilon_1\}$ and success probability p_1 (i.e., $\text{Prob}(\epsilon = \epsilon_1) = p_1$), and when the supplier makes the effort investment decision after observing the market risk realization, note that the supplier's optimal (conditional) effort is independent of the success probability p_1, and it is identical to the corresponding optimal supplier's effort when the market risk is constant; that is, when $\epsilon \equiv 0$, or when $\epsilon \equiv \epsilon_1$, as presented in Appendix §A4. Specifically, we have: $x_s^*(x_m|\epsilon = 0) = 0$; and $x_s^*(x_m|\epsilon = \epsilon_1) = \min\left\{\mu w(1+\alpha x_m), \left(\frac{\epsilon_1 - x_m}{1+\alpha x_m}\right)^+\right\}$. Next, anticipating the market risk realization and the supplier's optimal response, the manufacturer sets the optimal investment effort to maximize its expected profit: $\pi_m(x_m) = (r-w)\sum_{i=1}^{2} p_i d(x_m, x_s^*(x_m|\epsilon = \epsilon_i), \epsilon_i) - \frac{1}{2}x_m^2$, where $d(x_m, x_s^*(x_m|\epsilon = \epsilon_i), \epsilon_i) = \mu \min\{x_m + x_s^*(x_m|\epsilon = \epsilon_i) + \alpha x_m x_s^*(x_m|\epsilon = \epsilon_i), \epsilon_i\}$ is the market demand given $\epsilon = \epsilon_i$. The following proposition characterizes the manufacturer's optimal investment effort and optimal expected profit.

Proposition A6 (Optimal Manufacturer Effort and Profit) *When* ϵ *follows a Bernoulli distribution with sample space* $\{0, \epsilon_1 = 2\epsilon_0\}$ *and success probability* p_1*; i.e., Prob*$(\epsilon = \epsilon_1) = p_1$*, the manufacturer's optimal effort in Model (M), denoted as* x_m^M*, and the optimal expected profit, denoted as* π_m^{M*}*, can be determined as follows:*

1. *If* $w\mu \geq \epsilon_1$*, then* $x_m^M = 0$*, and* $\pi_m^{M*} = p_1(r-w)\mu\epsilon_1$*.*

2. *If $w\mu < \epsilon_1$, then we have:*

(a) *If $1 - 2p_1\alpha^2 w(r-w)\mu^2 \leq 0$, then $x_m^M = \bar{x}_m$, and $\pi_m^{M*} = p_1(r-w)\mu\epsilon_1 - \frac{1}{2}\bar{x}_m^2$, where $\bar{x}_m$ is the unique value in $[0, \epsilon_1]$ that satisfies: $\bar{x}_m + w\mu(1+\alpha\bar{x}_m)^2 = \epsilon_1$.*

(b) *If $1 - 2p_1\alpha^2 w(r-w)\mu^2 > 0$, then $x_m^M = \min\{\bar{x}_m, x_m^0\}$, and $\pi_m^{M*} = p_1(r-w)\mu[x_m^M + w\mu(1+\alpha x_m^M)^2] - \frac{1}{2}{x_m^M}^2$, where $\bar{x}_m$ is defined in Statement 2(a) above, and x_m^0 is the "unconstrained" solution in the unbounded problem when $\epsilon = \infty$; specifically, $x_m^0 = \frac{p_1(r-w)\mu(1+2\alpha w\mu)}{1-2p_1\alpha^2 w(r-w)\mu^2]}$.*

Proof of Proposition A6: As $x_s^*(x_m|\epsilon = 0) = 0$, and $x_s^*(x_m|\epsilon = \epsilon_1)$ is identical to that in the constant market risk case when $\epsilon \equiv \epsilon_1$, the manufacturer's expected profit is given by: $\pi_m(x_m) = p_1(r-w)d(x_m, x_s^*(x_m|\epsilon = \epsilon_1), \epsilon_1) - \frac{1}{2}x_m^2$. This is identical to the manufacturer's effort optimization problem in the constant market risk case, when $\epsilon \equiv \epsilon_1$, and when we re-define $\mu_m = p_1(r-w)\mu$. Therefore Proposition A6 follows immediately from Lemma A4, when $\mu_m = p_1(r-w)\mu$, $\mu_s = w\mu$, with constant market risk ϵ_1. We omit the details. □

Similar to the results presented in Proposition 2 with endogenous wholesale price, the optimal effort for the manufacturer in the fixed wholesale price case can never exceed the highest possible market risk realization; i.e., $x_m^M \leq \epsilon_1 = 2\epsilon_0$.

Model (S): Supplier Moves First. In Model (S), the supplier moves first by setting the effort x_s, and the manufacturer decides its effort level $x_m^*(x_s|\epsilon = \epsilon_i)$ after observing the market risk realization $\epsilon = \epsilon_i$. Observe that the effort optimization problem in Model (S) (with given fixed wholesale price w) is identical to that in Model (M) (with given fixed wholesale price $r - w$). Therefore, the supplier's optimal effort and profit can be analogously determined by Proposition A6 by appropriate change of variables.

A6. Optimal Investment Efforts Under Endogenous Market Price

First, for any given effort levels (x_m, x_s), and the realized market taste ϵ, the manufacturer's revenue (given investment costs are already sunk) is $\pi_m(r|x_m, x_s, \epsilon) = (r - \eta r)\,[d(x_m, x_s, \epsilon) - br]$. Note that the manufacturer's market price decision does not depend on the relative power η, and the optimal market selling price is given by: $r^*(x_m, x_s, \epsilon) = \frac{1}{2b}d(x_m, x_s, \epsilon)$. The optimal market selling price, however, does depend on both party's investment efforts as well as the realized market risk, and it increases in both investment efforts and the realized market condition.

Next, we solve the effort determination problems for the two parties. Suppose the manufacturer is the first mover. For any given manufacturer's investment level x_m, and anticipating the optimal selling price: $r^*(x_m, x_s, \epsilon) = d(x_m, x_s, \epsilon)/(2b)$, the supplier's expected profit is given by:

$$\pi_s(x_s|x_m) = \mathsf{E}_\epsilon\left\{\eta r^*(x_m, x_s, \epsilon)\,[d(x_m, x_s, \epsilon) - br^*(x_m, x_s, \epsilon)]\right\} - \frac{1}{2}x_s^2 = \frac{\eta}{8b}d(x_m, x_s, \epsilon_1)^2 - \frac{1}{2}x_s^2.$$

The following lemma characterizes the supplier's optimal investment effort, denoted as $x_s^*(x_m)$, for any given manufacturer's effort x_m.

Lemma A5 (Optimal Supplier Effort) *For any given x_m, the optimal effort level by the supplier is given by:*

1. *If $x_m > \epsilon_1$, then $x_s^*(x_m) = 0$.*
2. *If $x_m \le \epsilon_1$, then:*
   (a) *If $x_m \ge \frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}$, then $x_s^*(x_m) = \frac{\epsilon_1 - x_m}{1+\alpha x_m}$;*
   (b) *If $x_m < \frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}$, then $x_s^*(x_m) = \min\{x_s^0(x_m), \frac{\epsilon_1 - x_m}{1+\alpha x_m}\}$, where $x_s^0(x_m)$ is the "unconstrained" (interior) solution when $\epsilon_1 = \infty$; specifically, $x_s^0(x_m) = \frac{x_m(1+\alpha x_m)}{4b/(\eta\mu^2)-(1+\alpha x_m)^2}$.*

Proof of Lemma A5. Recall $\pi_s(x_s) = \frac{1}{8b}\eta[\mu \min\{x_m + x_s + \alpha x_m x_s, \epsilon_1\}]^2 - \frac{1}{2}x_s^2$. Thus if $x_m > \epsilon_1$, we have: $\pi_s(x_s) = \frac{\eta}{8b}\mu^2\epsilon_1^2 - \frac{1}{2}x_s^2$. Thus $x_s^*(x_m) = 0$ and Part (1) follows. Now suppose $x_m \le \epsilon_1$. Then we have:

$$\pi_s(x_s) = \begin{cases} \frac{\eta}{8b}\mu^2\epsilon_1^2 - \frac{1}{2}x_s^2 & \text{if } x_s \ge \frac{\epsilon_1 - x_m}{1+\alpha x_m}; \\ \frac{\eta}{8b}\mu^2(x_m + x_s + \alpha x_m x_s)^2 - \frac{1}{2}x_s^2 & \text{if } x_s \le \frac{\epsilon_1 - x_m}{1+\alpha x_m}. \end{cases} \tag{A21}$$

It follows immediately that for $x_m \le \epsilon_1$, we must have:

$$x_s^*(x_m) = \arg\max_{x_s \le \frac{\epsilon_1 - x_m}{1+\alpha x_m}} \pi_s(x_s) := \frac{\eta}{8b}\mu^2(x_m + x_s + \alpha x_m x_s)^2 - \frac{1}{2}x_s^2.$$

It is easy to check that: $\pi_s'(x_s) = \frac{\eta}{4b}\mu^2 x_m(1+\alpha x_m) + [\frac{\eta}{4b}\mu^2(1+\alpha x_m)^2 - 1]x_s$. Therefore if $\frac{\eta}{4b}\mu^2(1+\alpha x_m)^2 - 1 \ge 0$, which is equivalent to: $x_m \ge \frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}$, then $\pi_s'(x_s) \ge 0$ for all $x_s \ge 0$, which implies that: $x_s^*(x_m) = \frac{\epsilon_1 - x_m}{1+\alpha x_m}$. This proves Part(2a). On the other hand, if $x_m < \frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}$ so that: $\frac{\eta}{4b}\mu^2(1+\alpha x_m)^2 - 1 < 0$ then $\pi_s(x_s)$ is concave in x_s, and it is easy to check that: $x_s^*(x_m) = \min\{x_s^0(x_m), \frac{\epsilon_1 - x_m}{1+\alpha x_m}\}$, where $x_s^0(x_m)$ satisfies: $\pi_s'(x_s)|_{x_s = x_s^0} = 0$. Specifically, $x_s^0(x_m) = \frac{x_m(1+\alpha x_m)}{4b/(\eta\mu^2)-(1+\alpha x_m)^2}$. Part (2b) thus follows. □

We next leverage Lemma A5 to characterize the manufacturer's optimal investment efforts. To facilitate the analysis, it is useful to define $x_m^0 \in [0, \epsilon_1]$ as the unique cut-off value of x_m at which the unconstrained (interior) solution $x_s^*(x_m) = x_s^0(x_m)$ coincides with the constrained (boundary) solution $x_s^*(x_m) = \frac{\epsilon_1 - x_m}{1+\alpha x_m}$. The following proposition characterizes the manufacturer's optimal effort, x_m^M.

Proposition A7 (Optimal Manufacturer Effort) *The following properties hold for the optimal manufacturer investment effort.*

1. *Suppose $\mu \ge 2\sqrt{\frac{b}{\eta}}$, then $x_m^M = 0$.*
2. *Suppose $\mu_0 \le \mu < 2\sqrt{\frac{b}{\eta}}$, where μ_0 is the unique value in $\left[0, 2\sqrt{\frac{b}{\eta}}\right]$ that satisfies: $\frac{\eta}{4b}\mu_0^2 + \frac{1}{2}\sqrt{\eta(1-\eta)}\mu_0 - 1 = 0$, then we have:*
   (a) *If $\frac{2}{\mu}\sqrt{\frac{b}{\eta}} - 1 > \alpha\epsilon_1$, then $x_m^M = x_m^0$.*
   (b) *If $\frac{2}{\mu}\sqrt{\frac{b}{\eta}} - 1 \le \alpha\epsilon_1$, then $x_m^M = \min\left\{\frac{\frac{2}{\mu}\sqrt{\frac{b}{\eta}}-1}{\alpha}, x_m^0\right\}$.*

Proof of Proposition A7. Part (1) follows from Corollary A1. Now suppose $\mu < 2\sqrt{\frac{b}{\eta}}$ as assumed in Part (2). We first prove Part (2a). Under the condition that $\frac{2}{\mu}\sqrt{\frac{b}{\eta}} - 1 > \alpha\epsilon_1$, it follows from part (2) of Corollary A1 that: $x_m^M = \arg\max_{0 \le x_m \le x_m^0} \pi_m(x_m)$, where $\pi_m(x_m) = \frac{1}{8}\eta(1-\eta)\mu^2\left[x_m/(1-\frac{\eta\mu^2}{4b}(1+\alpha x_m)^2)\right]^2 - \frac{1}{2}x_m^2$. Note that: $\pi_m'(x_m) = x_m f(x_m)$, where $f(x_m) = \frac{1}{4}\eta(1-\eta)\mu^2\frac{1-(\eta\mu^2)/(4b)(1+\alpha x_m)(1-\alpha x_m)}{[1-(\eta\mu^2)/(4b)(1+\alpha x_m)^2]^3} - 1$. Taking the derivative $f'(x_m)$ and observing that $1 - \frac{\eta\mu^2}{4b}(1+\alpha x_m)(1-\alpha x_m) > 1 - \frac{\eta\mu^2}{4b}(1+\alpha x_m)^2 > 0$, we have that: $f'(x_m) > 0$, which implies that $f(x_m)$ is increasing in x_m. Therefore if $f(x_m = 0) \ge 0$, we must have $f(x_m) \ge 0$ for all $x_m \ge 0$, which further implies that $\pi_m'(x_m) = x_m f(x_m) \ge 0$ for all $x_m \ge 0$. In addition, note that $f(x_m = 0) = \frac{\eta(1-\eta)\mu^2}{4[1-(\eta\mu^2)/(4b)]^2} - 1$. Thus $f(x_m = 0) > 0$ is equivalent to: $\frac{\eta}{4b}\mu^2 + \frac{1}{2}\sqrt{\eta(1-\eta)}\mu - 1 > 0$, which is further equivalent to: $\mu \ge \mu_0$, where μ_0 is the unique value in $[0, 2\sqrt{b/\eta}]$ that satisfies: $\frac{\eta}{4b}\mu_0^2 + \frac{1}{2}\sqrt{\eta(1-\eta)}\mu_0 - 1 = 0$. Therefore, under the suppositions in Part (2a), $\pi_m(x_m)$ is increasing in $x_m \in [0, x_m^0]$, and thus $x_m^M = x_m^0$. Part 2(b) can be analogously proved (details are omitted). □

It follows from Proposition A7 immediately that the optimal manufacturer's effort never exceeds x_m^0, that is, $x_m^M \le x_m^0$.

A7. Simultaneous Effort Investment

To isolate the contrast between advance investment and simultaneous investment, we assume that the manufacturer sets the wholesale price in both cases. For the simultaneous investment case, for any given wholesale price w, both the manufacturer and the supplier decide their investment efforts in response to each other's efforts. If the investment efforts are made before the market risk is realized, then it is straightforward to observe that advance investment dominates simultaneous investment. The reason is that for any optimal solutions to the simultaneous investment case, the manufacturer can always replicate such solutions through advance investment. In addition, with advance investment, the manufacturer can arbitrarily alter its investment decision, that is, not necessarily reacts to the supplier's investment decision as in the simultaneous investment case, and therefore advance investment is always more attractive than simultaneous investment. The following proposition ensues (proofs omitted).

Proposition A8 *Advance investment dominates simultaneous investment when investment decisions are made before market risk is realized.*

We next explore the alternative scenario where the investment decisions are made after the market risk is realized. This reflects an interesting tradeoff between investing early under market risk versus postponing investment after observing realized market risk. The relatively attractiveness of the advance versus simultaneous investment therefore hinges upon the market risk volatility. Note that while the manufacturer could set the wholesale price before market risk realizations, it can always adjust the price after market risk resolution and hence price commitment before market risk may not be credible.

With simultaneous investment, the equilibrium solutions for the optimal investment efforts can be found be solving the best response functions for the manufacturer and the supplier simultaneously. Next, after solving the best responses of the effort investments of the manufacturer and the supplier for any given wholesale price w and realized market risk $\epsilon = \epsilon_0$, the manufacturer will choose the best investment effort and set the optimal wholesale price to maximize its profit. For illustrative purposes, we present our main result for the deterministic market risk case where $\epsilon \equiv \epsilon_0$ and then conduct a comprehensive numerical study under stochastic market risk.

Proposition A9 *Suppose* $r\mu \geq 2\epsilon_0$*. The optimal wholesale price of the manufacturer is given by:* $w^* = w^0$*, where* w^0 *satisfies* $\frac{\tilde{x}(1+\alpha\tilde{x})^2}{2\alpha\mu w^0(1+\alpha\tilde{x})+1} = \epsilon_0$*, where* $\tilde{x} = \frac{-(2\alpha\mu w^0)+\sqrt{4\alpha^2\mu w^0\epsilon_0+4\alpha\mu w^0+1}}{2\alpha^2\mu w^0}$*. Furthermore, the optimal investment efforts of the manufacturer and the supplier are:* $x_m^* = \tilde{x}$ *and* $x_s^* = \frac{\epsilon_0 - x_m^*}{1+\alpha x_m^*}$*.*

Proof of Proposition A9: The proof is available upon request.

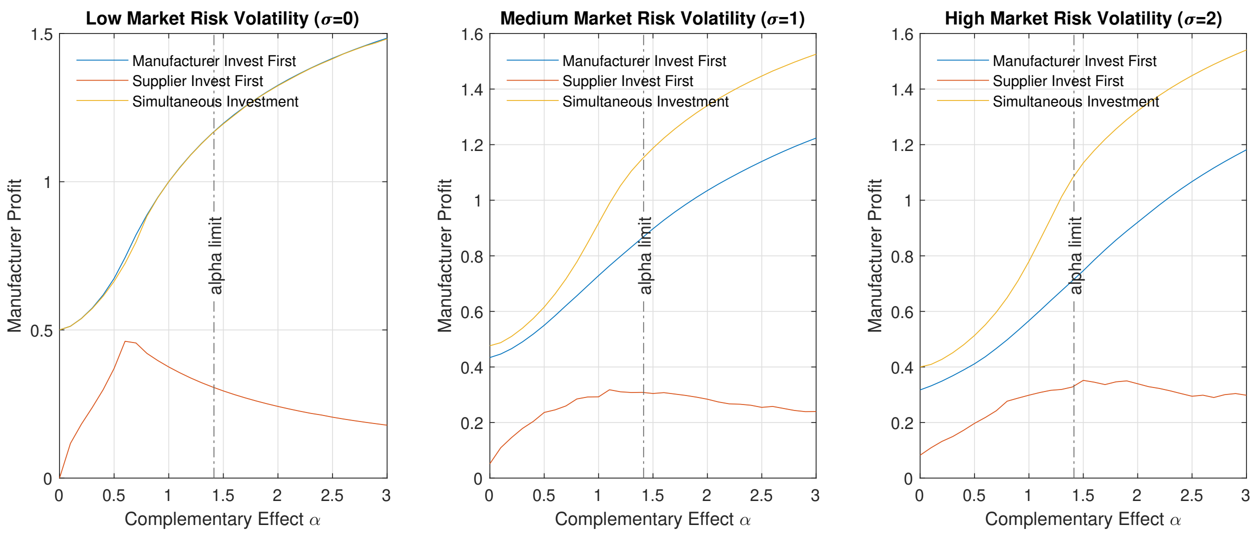

Figure 8 **Impact of market risk volatility on expected manufacturer profit (advance versus simultaneous investment). Figure plotted by scaling $r = 1$, $\mu = 1$, and setting $\epsilon \sim N(m, \sigma)$ with mean $m = 2$ and standard deviation $\sigma = 0, 1, 2$.**

When market risk volatility is low, the manufacturer's profit in advance investment weakly dominates that in simultaneous investment, as predicted by Proposition A8. This is because that in absence of risk in market taste, there is no informational advantage for simultaneous investment, and hence advance investment dominates. It is worth pointing out that advance investment can strictly dominate simultaneous investment under general parameter settings. As market risk volatility increases, as one might expect, the simultaneous investment case can dominate. This suggests that informational advantage associated with simultaneous investment can make the manufacturer strictly better off. Nevertheless, with simultaneous investment, it is unlikely that the manufacturer can dictate the wholesale price. As such, one should carefully interpret the comparison with the advance investment case. It is also of interest to examine how supplier's performance difference between the two cases. See Figure 9.

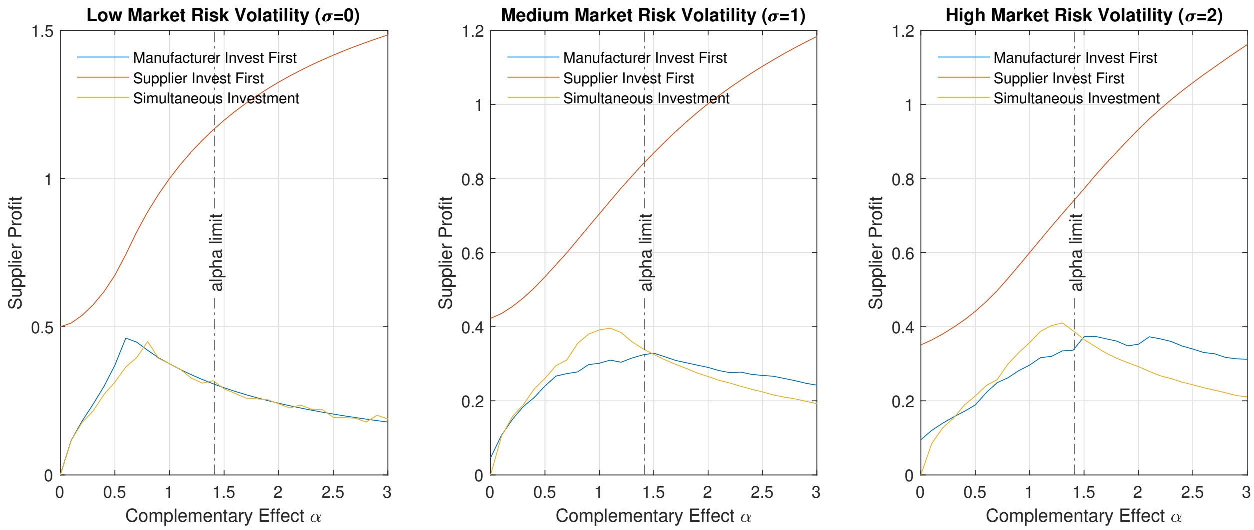

Figure 9 **Impact of market risk volatility on expected supplier profit (advance versus simultaneous investment). Figure plotted by scaling $r = 1$, $\mu = 1$, and setting $\epsilon \sim N(m, \sigma)$ with mean $m = 2$ and standard deviation $\sigma = 0, 1, 2$.**

Because of our assumption that the manufacturer sets the wholesale pricing decision, the supplier is typically worse off with simultaneous investment (if complementary effect is not too weak), as compared with the case where the manufacturer makes advance investment. An important managerial implication for the above implication is that advance investment by the manufacturer can be a win-win situation for both the manufacturer and the supplier as compared with the simultaneous investment case. This is especially true when market risk volatility is moderate, and the complementary effect is strong.