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Improving reliability of a shared supplier with competition and spillovers

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ABSTRACT

Supplier reliability is a key determinant of a manufacturer's competitiveness. It reflects a supplier's capability of order fulfillment, which can be measured by the percentage of order quantity delivered in a given time window. A perfectly reliable supplier delivers an amount equal to the order placed by its customer, while an unreliable supplier may deliver an amount less than the amount ordered. Therefore, when suppliers are unreliable, manufacturers often have incentives to help suppliers improve delivery reliability. Suppliers, however, often work with multiple manufacturers and the benefit of enhanced reliability may spill over to competing manufacturers. In this study, we explore how potential spillover influences manufacturers' incentives to improve supplier's reliability. We consider two manufacturers that compete with imperfectly substitutable products on Type I service level (i.e., in-stock probability). The manufacturers share a common supplier who, due to variations in production quality or yield, is unreliable. Manufacturers may exert efforts to improve the supplier's reliability in the sense that the delivered quantity is stochastically larger after improvement. We develop a two-stage model that encompasses supplier improvement, uncertain supply and random demand in a competitive setting. In this complex model, we characterize the manufacturers' equilibrium in-stock probability. Moreover, we characterize sufficient conditions for the existence of the equilibrium of the manufacturers' improvement efforts. Finally, we numerically test the impact of market characteristics on the manufacturers' equilibrium improvement efforts. We find that a manufacturer's equilibrium improvement effort usually declines in market competition, market uncertainty or spillover effect, although its expected equilibrium profit typically increases in spillover effect.

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1. Introduction

Supplier reliability is increasingly being recognized as a key determinant of manufacturers' competitiveness. It reflects a supplier's capability of order fulfillment, which can be measured by the percentage of order quantity delivered in a given time window. A recent survey by Accenture finds that "supplier reliability is seen across the industry as significantly more important than cost" (Erhardt, Langlinais, & Ratta, 2010, p. 10). Manufacturers therefore often help to improve delivery reliability when suppliers are unreliable. Suppliers, however, often work with multiple manufacturers (Markoff, 2001), and hence a manufacturer's effort to improve supplier reliability may benefit its direct competitors. Empirical evidence suggests that manufacturers are often aware of, and also wary of, the potential spillover effect, but different manufacturers seem to take the issue differently.

Farney (2000) describes supplier improvement effort by UTC's Pratt & Whitney Aircraft unit (P&W) with Dynamic Gunver Technologies (DGT) (now a unit of Britain's Smiths Group). UTC initiates improvement effort with DGT despite the fact that (a) DGT has close relationship with a P&W's competitor, Rolls Royce, and (b) "by leveraging its expertise and knowledge gained from working with UTC, Dynamic successfully won bids from Allied Signal, Rolls Royce, and General Electric." (p. 5). Although being aware of the competitive concerns above, "UTC had attempted to bring process improvements to DGT operations. DGT had received substantial assistance from P&W in the form of workshops in Kaizen process improvement, lean manufacturing, and UTC's ACE program for quality improvement." (p. 5). UTC were, however, wary of the spillover effect: "Their goal did not include the scenario where [DGT] competed with UTC for other business and partnered with UTC's competitors." (p. 8). In this case, UTC seems to reluctantly accept the existence of spillover effect.

Toyota, on the other hand, seems to have a more open mind towards the spillover effect: "Production processes are simply not viewed as proprietary and Toyota accepts that some valuable

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knowledge will spill over to benefit competitors." (Dyer & Nobeoka, 2000, p. 358).

Yet in Honda's case, its supplier improvement program implicitly encourages suppliers to work with its competitors: Honda espouses suppliers' self-reliance, i.e., "balancing responsiveness to Honda's needs with a sufficiently diversified customer base." (Sako, 2004, p. 296). In fact, encouraging suppliers to work with multiple manufacturers is often a policy of many firms to avoid the "captive supplier issue." (Lascelles & Dale, 1990, p. 53).

Given the different attitudes exhibited by different firms toward the spillover effect, we explore in this research how potential spillover effect influences manufacturers' reliability improvement efforts and the resulting expected profits. We consider the scenario where two manufacturers share a common supplier, which has a production process that is subject to random output due to variations in quality or production yield. Both manufacturers may exert effort to improve the reliability (e.g., expected yield) of the supplier's production process. We develop a two-stage model to investigate the impact of spillover upon the manufacturers' improvement efforts in a competitive setting. In the first stage, each manufacturer decides its improvement effort and incurs the corresponding improvement cost. In the second stage, as a result of the manufacturers' improvement efforts, the supplier has a new, more reliable production process. The manufacturers then place orders from the supplier, and compete on service levels in the consumer market.

In this model, we show the existence of the equilibrium in the service level competition, and characterize the manufacturers' equilibrium service levels and corresponding inventory decisions in the second stage. Moreover, we characterize sufficient conditions for the existence of the equilibrium of the manufacturers' improvement efforts in the first stage. Finally, we numerically test the impact of market characteristics upon the manufacturers' equilibrium improvement efforts. We find that spillover effect often brings favorable improvement to the manufacturers' expected profits, regardless of whether the manufacturers are asymmetric or symmetric. When manufacturers are asymmetric, the ex ante more advantageous manufacturer typically exerts a higher proportion of improvement efforts, especially when the spillover effect is large. While such higher proportion of improvement efforts benefits the focal manufacturer, it may benefit, in terms of relative profit, its competitor more. When manufacturers are symmetric, we find that both manufacturers' improvement efforts decline in market competition, market uncertainty or spillover effect, although their expected profits increase in spillover effect.

The rest of this paper is organized as follows: we discuss related literature in Section 2, and develop the two-stage model in Section 3. In Section 4, we characterize the manufacturers' equilibrium service levels and the corresponding inventory decisions in the second stage. In Section 5, we study the manufacturers' supplier improvement efforts, and characterize sufficient conditions for the existence of the equilibrium in the first stage. In Section 6, we numerically test the impact of market characteristics upon the manufacturers' equilibrium improvement efforts and profit. In Section 7, we summarize our findings and conclude the paper. All proofs are relegated to Appendix A.

2. Literature review

Our research is related to three streams of literature: (1) economics and industrial organization literature on spillover effect; (2) empirical literature on supplier improvement, and (3) operations management literature on uncertain supply. In this section, we review these three streams of literature, and discuss their relationship with this paper.

First, a large body of economic and industrial organization literature studies spillover effect in the absence of supplier improvement, e.g., Spence (1984), D'Aspremont and Jacquemin (1988), Levin and Reiss (1988), Harhoff (1996), Gilbert, Xia, and Yu (2006) and Gupta (2008). Spence (1984) finds that spillovers increase industry-wide efficiency while lower the individual firm's incentive to innovate. Harhoff (1996) suggests that strategic spillovers from upstream to downstream enhance the upstream firm's innovation. D'Aspremont and Jacquemin (1988) study competing manufacturers' incentives to cooperate horizontally in the presence of R&D spillovers, and their work has been generalized by numerous studies, see Kamien, Muller, and Zang (1992), Suzumura (1992), etc. Gupta (2008) analyzes the role of channel structure in determining firms' investment in process innovation. D'Aspremont and Jacquemin (1988) and the follow-up work are primarily concerned with the impact of R&D cooperation on manufacturers' R&D investment level, industry outcome and social welfare, and evaluating whether the R&D investments by firms with and without cooperation is socially efficient under different cooperation and competition structures. Our work differs from this stream of research in terms of research focus. The existing literature studies the impact of spillover effect on cost reduction, while our research investigates the impact of spillover effect on supplier improvement efforts. Our research complements the existing literature by considering manufacturers' role in supplier reliability improvement, as opposed to the manufacturers' own cost reduction effort. Compared to the cost reduction setting, our model shows that manufacturers may not necessarily benefit from improving supplier's reliability even if the improvement is costless. In addition, we numerically investigate how the manufacturers' supplier improvement efforts and their expected profits are affected by market characteristics such as manufacturers' competitive advantage and demand uncertainty, which has not been examined in the existing literature that studies spillover effect on cost reduction.

Secondly, there is extensive empirical literature that examines manufacturers' role in supplier improvement effort, with a focus on antecedents of successful supplier improvement effort, e.g., Krause and Ellram (1997), Humphreys, Li, and Chan (2004), and Modi and Mabert (2007). Some common factors emerging from this stream of research include trust, buyer involvement, and communication that are likely to predict successful supplier improvement effort. Talluri, Narasimhan, and Chung (2010) proposes a decision model for assisting firms in making resource allocation decisions in supplier development initiatives. This stream of literature, however, focuses on dyadic buyer–supplier relationships and therefore does not explore spillover effect.

Thirdly, this research is also related with the vast literature on unreliable supply, including random yield (e.g., Anupindi & Akella, 1993; Dada, Petruzzi, & Schwarz, 2007; Federgruen & Yang, 2009; Inderfurth & Vogelgesang, 2013; Kazaz & Webster, 2011; Xu & Lu, 2013; Yeo & Yuan, 2011), random capacity (e.g., Chao, Chen, & Zheng, 2008; Ciarallo, Akella, & Morton, 1994; Erdem, 1999, chap. 4; Wang, Gilland, & Tomlin, 2010), and random disruption (e.g., Babich, Burnetas, & Ritchken, 2007; Gürler & Parlar, 1997; Parlar & Perry, 1996; Schmitt, Snyder, & Shen, 2010; Tomlin, 2006). This stream of research does not typically consider spillover effect or supplier improvement effort.

We adopt the most commonly used stochastically proportional yield model to describe supplier unreliability, which "applies to circumstances where yield losses occur because of limited capabilities of the production system to adapt to random environmental changes or variations in materials." (Yano & Lee, 1995, p. 313). This modeling approach allows us to capture scenarios where manufacturers may improve supplier reliability in different ways, such as lean production assistance aimed at reducing production variability and waste, or quality assistance aimed at improving process capability and quality.

Recently, Qi, Ahn, and Sinha (2011) study supplier improvement effort under random capacity, where manufacturers share the same supplier but they can stipulate capacity usage terms to partially mitigate the capacity spillover effect. They focus on how capacity usage restrictions affect manufacturers' equilibrium capacity investment, and find that rigid restrictions of capacity usage can lead to adverse market outcomes. Our research is complementary to their study, as we focus on reliability improvement and manufacturers' competition on service level.

To sum up, existing literature has considered, separately, (a) spillover effect in the absence of supplier improvement, (b) supplier improvement without spillover effect, and (c) supply uncertainty without the combined effects of supplier improvement and spillover. Our research is the first to investigate manufacturers' supplier improvement efforts under the combined effects of spillover, competition, random yield and uncertain demand.

3. Model

We consider a market where there are two manufacturers, each selling a single product to the final consumers. The products offered by the two manufacturers are imperfectly substitutable, which means that they are not fully interchangeable, and customers have to make a trade-off (either in price or in quality) when replacing one product with the other. This assumption reflects the reality that customers typically have different preferences over different products, which can be attributed to factors such as brand loyalty.

Manufacturers outsource production to a common, unreliable supplier, and the manufacturers compete on service level against each other. Service level, as measured by in-stock probability, is now recognized by many firms as one of the most important performance metrics. Bernstein and Federgruen (2004) have noted that an increasing number of companies attempt to obtain larger market shares by increasing the service level of their products.

3.1. Demand

Market demand is stochastic, imperfectly substitutable, and influenced by both manufacturers' in-stock probabilities, commonly known as Type-1 service levels. Let $D_i(\mathbf{f})$ denote the random demand of manufacturer i, given the vector of the in-stock probabilities $\mathbf{f}$ provided by both manufacturers. Following Bernstein and Federgruen (2004), we assume that demand uncertainty is of the multiplicative form, that is,

$$D_i(\mathbf{f}) = d_i(\mathbf{f})\epsilon, \tag{1}$$

where ϵ denotes market uncertainty. The multiplicative demand form in (1) implies that the market uncertainty (measured by coefficient of variation) is not affected by the in-stock probabilities $\mathbf{f}$, but the expected demand is. Let $G_\epsilon(\cdot)$ and $g_\epsilon(\cdot)$ denote the distribution and density of ϵ, respectively. Without loss of generality, we normalize ϵ such that $\mathrm{E}[\epsilon] = 1$ and interpret $d_i(\mathbf{f})$ as the expected demand of manufacturer i.

Assumption 1. $G_\epsilon(\epsilon)$ is log-concave.

Assumption 2.

$$\frac{\partial d_i(\mathbf{f})}{\partial f_i} \geqslant 0, \quad \frac{\partial d_i(\mathbf{f})}{\partial f_j} \leqslant 0, \quad \frac{\partial^2 \log d_i(\mathbf{f})}{\partial f_i \partial f_j} \geqslant 0,$$
$$\text{and} \quad \frac{\partial^2 \log d_i(\mathbf{f})}{\partial f_i^2} + \frac{\partial^2 \log d_i(\mathbf{f})}{\partial f_i \partial f_j} \leqslant 0.$$

Assumption 1 is satisfied by many common distributions, including uniform, normal, exponential, and gamma distributions (see Bernstein & Federgruen, 2004). In addition, any concave cumulative distribution function is also log-concave. Although Assumption 2 is made for technical tractability, it is satisfied by many different forms of demand functions under mild conditions, including linear demand function, log-separable demand function, and the general class of attraction models. See Appendix B for details.

3.2. Supply

The supplier's production process follows the standard stochastically proportional yield model, reflecting variations in supplier's production process, limited production capabilities, or quality variations. In this setting, for any given order Q_i placed by manufacturer i, the delivered quantity is $q_i = Y_i Q_i$, where Y_i is the random yield factor with support on $[0, 1]$.

The distribution of the random yield factor Y_i is influenced by the supplier's reliability index p_i, an aggregate index reflecting factors (e.g., equipment, technical knowhow, and training) that may influence the supplier's yield. Let $\Phi_{Y_i}(\cdot, p_i)$ denote the distribution of Y_i. We adopt the convention that a higher p_i is associated with a more reliable production process, i.e., Y_i is first-order stochastically increasing in p_i. Thus, for any given $p_i > p_i'$, $\Phi_{Y_i}(y, p_i) \leqslant \Phi_{Y_i}(y, p_i')$ for any y.

3.3. Improvement efforts and spillovers

Both manufacturers may exert efforts, such as knowledge transfer or capital investment, to improve the supplier's reliability. If manufacturer i exerts improvement effort level at z_i and let $\mathbf{z} = (z_1, z_2)$, then the supplier's production reliability index for manufacturer i increases from p_i^0 to

$$p_i(\mathbf{z}) = p_i^0 + z_i + \alpha z_j, \quad i = 1, 2,\ j = 3 - i, \tag{2}$$

where $0 \leqslant \alpha \leqslant 1$ capturers the spillover effect in the supplier's production process.

We do not restrict the level of the spillover effect. Therefore, α can take any value on $[0, 1]$, and the extent of the spillover effect depends on the configurations of the supplier's production process. For example, if the supplier uses the same production line for both manufacturers' components, then it is possible that full spillover might occur, i.e., $\alpha = 1$. In contrast, if the supplier uses a shared production line for the early steps of the production process and performs additional customization steps to satisfy each manufacturer's specific requirement, then the knowledge gained from manufacturer i can partially spillover to manufacturer j, i.e., $0 < \alpha < 1$. It is also possible that the supplier maintains completely separate production lines such that there is no spillover and hence $\alpha = 0$.

It is natural to assume that manufacturer i's improvement cost $m_i(z_i)$ (weakly) increases in its effort level z_i, i.e., $dm_i(z_i)/dz_i \geqslant 0$. We do not consider other benefits associated with the manufacturer's improvement effort, such as improved efficiency or improved contract terms. As is common in game theory literature, we assume manufacturers' improvement costs are common knowledge. This typically occurs when the manufacturers have been working with the supplier for several years, and therefore each manufacturer has a good idea of the other's supplier reliability improvement capabilities. This assumption also reflects the reality that manufacturers can resort to business intelligence or industry association, or develop estimates based on their own experience to assess their competitors' improvement cost structure.

3.4. Problem formulation

3.4.1. Sequence of events

The competing manufacturers play a two-stage game with complete information. In the first stage, each manufacturer simultaneously decides its supplier improvement effort. In the second stage, after exerting supplier improvement effort but before yield and demand uncertainty is resolved, each manufacturer decides its in-stock probability f_i and its order quantity Q_i from the supplier. In the end, after observing realized production yield and demand, each manufacturer pays the supplier for quantities delivered and satisfies its demand as much as possible.

Given the above sequence of events, the manufacturers' decision problem can be formulated as a two-stage stochastic program. Let w_i, r_i, s_i, and π_i denote the wholesale price manufacturer i pays to the supplier, manufacturer i's unit price charged in the market, unit salvage value for leftovers, and unit penalty cost for shortages, respectively. Define $H_i(u,v) = r_i \min\{u,v\} + s_i(u-v)^+ - \pi_i(v-u)^+$.

3.4.2. The second stage problem

Since the supplier's production process is random, manufacturer i will choose an order quantity Q_i such that it will achieve the expected in-stock probability f_i ex-ante. Let $\mathbf{Y} = (Y_1, Y_2)$ and $\mathbf{p} = (p_1, p_2)$, manufacturer i's second stage problem is to find the optimal $\{f_i^*, Q_i^*\}$ that maximizes

$$v_i(f_i, Q_i|\mathbf{p}, f_j) = -w_i \mathsf{E}_{Y_i}[Y_i Q_i] + \mathsf{E}_{Y_i,\epsilon}[H_i(Y_i Q_i, D_i(\mathbf{f}))], \tag{3}$$

$$\text{s.t.} \quad \text{Prob}(D_i(\mathbf{f}) \leqslant Y_i Q_i) \geq f_i. \tag{4}$$

The in-stock probability f_i defined in (4) is commonly known as Type-1 service level in the literature. With random yield, the in-stock probability varies with different yield realizations, and therefore it needs to be conditioned and unconditioned over all possible yield realizations. The in-stock probability defined in (4) implies that manufacturers can credibly commit on their product availabilities.

3.4.3. The first stage problem

Let the supplier's initial production reliability index be $\mathbf{p}^0 = (p_1^0, p_2^0)$, the first stage problem for manufacturer i can be formulated as maximizing

$$J_i(z_i) = -m_i(z_i) + v_i(f_i^*, Q_i^*|\mathbf{p}(\mathbf{z}), f_j^*), \tag{5}$$

where $\mathbf{p}(\mathbf{z}) = (p_1(\mathbf{z}), p_2(\mathbf{z}))$ and $p_i(\mathbf{z})$ is given by (2).

We note that it is fairly straightforward to incorporate probabilistic supplier improvement results, e.g., an improvement effort may not always be fully successful. In this case, (5) can be modified by imposing an expectation operator on $v_i(f_i^*, Q_i^*|\mathbf{p}(\mathbf{z}), f_j^*)$ over all possible realizations of $\mathbf{p}(\mathbf{z})$.

In the following sections, we study the competition between the two manufacturers, and focus on characterizing pure strategy equilibrium of the two-stage game. Henceforth, the Nash equilibrium in the following context refers to pure strategy equilibrium.

4. Second stage: service level competition

In this section, we analyze the manufacturer's second stage problem, where manufacturer i chooses in-stock probability f_i and order quantity Q_i to maximize its expected profit (given by (3)) in the service level competition.

4.1. Stocking factor

For analytical convenience and expositional ease, define $q_i(\mathbf{f}) = Q_i/d_i(\mathbf{f})$. Hereafter we refer to $q_i(\mathbf{f})$ as the *stocking factor*, which is the ratio of manufacturer i's order quantity and its expected demand for any given vector of in-stock probability $\mathbf{f}$. Using the stocking factor $q_i(\mathbf{f})$, we can rewrite (3) and (4) as

$$v_i(f_i, q_i(\mathbf{f})|\mathbf{p}, f_j) = -w_i d_i(\mathbf{f}) \mathsf{E}_{Y_i}[Y_i q_i(\mathbf{f})] + \mathsf{E}_{Y_i,\epsilon}[H_i(Y_i q_i(\mathbf{f}) d_i(\mathbf{f}), d_i(\mathbf{f})\epsilon)], \tag{6}$$

$$\text{s.t.} \quad \mathsf{E}_{Y_i}[G_\epsilon(Y_i q_i(\mathbf{f}))] \geqslant f_i, \tag{7}$$

where the service level constraint (7) follows from the fact that

$$\text{Prob}(D_i(\mathbf{f}) \leqslant Y_i Q_i) \geqslant f_i \iff \text{Prob}(\epsilon \leqslant Y_i q_i(\mathbf{f})) \geqslant f_i \iff \mathsf{E}_{Y_i}[G_\epsilon(Y_i q_i(\mathbf{f}))] \geqslant f_i.$$

Note that for any given f_i, $v_i(\cdot)$ is concave in $q_i(\mathbf{f})$; and for any given $q_i(\mathbf{f})$, $v_i(\cdot)$ is log-concave in f_i. We adopt a two-stage approach by first characterizing the optimal q_i^* as a function of f_i, and then characterizing the optimal service level f_i^*. Simplifying (6), we have

$$\begin{aligned} v_i(f_i, q_i(\mathbf{f})|\mathbf{p}, f_j) &= d_i(\mathbf{f}) \Big\{ q_i(\mathbf{f}) \big((r_i - w_i + \pi_i) \mathsf{E}_{Y_i}[Y_i] - (r_i - s_i + \pi_i) \mathsf{E}_{Y_i}[Y_i G_\epsilon(Y_i q_i(\mathbf{f}))] \big) \\ &\quad + (r_i - s_i + \pi_i) \mathsf{E}_{Y_i}\left[\int_0^{Y_i q_i(\mathbf{f})} \epsilon g_\epsilon(\epsilon) d\epsilon \right] - \pi_i \Big\}. \end{aligned} \tag{8}$$

Let $u_i(f_i, q_i(\mathbf{f})|\mathbf{p}, f_j)$ denote the terms in the curly bracket in (8), i.e., manufacturer i's expected profit per unit of demand. The following lemma characterizes the optimal stocking factor.

Lemma 1. *For any given vector of in-stock probability* $\mathbf{f}$, *(a)* $u_i(f_i, q_i(\mathbf{f})|\mathbf{p}, f_j)$ *is concave in the stocking factor* $q_i(\mathbf{f})$. *(b) The optimal stocking factor* $q_i^*(\mathbf{f})$ *satisfies one of the following conditions:*

$$\mathsf{E}_{Y_i}\left[Y_i G_\epsilon\left(Y_i q_i^*(\mathbf{f})\right)\right] = \frac{r_i - w_i + \pi_i}{r_i - s_i + \pi_i} \mathsf{E}_{Y_i}[Y_i]; \tag{9}$$

$$\mathsf{E}_{Y_i}\left[G_\epsilon\left(Y_i q_i^*(\mathbf{f})\right)\right] = f_i. \tag{10}$$

Notice that (9) gives an interior solution to $\partial u_i(f_i, q_i(\mathbf{f})|\mathbf{p}, f_j)/\partial q_i(\mathbf{f}) = 0$, and (10) gives a corner solution constrained by (7). Leveraging Lemma 1, the following lemma completely characterizes the properties of optimal stocking factor for any given in-stock probability f_i.

Lemma 2. *(a) Manufacturer i's optimal stocking factor* $q_i^*(\mathbf{f})$ *is independent of its competitor's in-stock probability* f_j *and is a function of* f_i *only. (b) There exists a unique threshold of in-stock probability* $\bar{f}_i \in (0,1)$ *such that if* $f_i \leqslant \bar{f}_i, q_i^*(f_i)$ *uniquely solves* (9) *and* $dq_i^*(f_i)/df_i = 0$; *and if* $f_i > \bar{f}_i, q_i^*(f_i)$ *uniquely solves* (10) *and* $dq_i^*(f_i)/df_i > 0$. *(c)* $\bar{f}_i$ *can be uniquely obtained by solving the system of equations specified by* (9) *and* (10) *simultaneously.*

Lemma 2 shows that if the in-stock probability is less than a critical threshold $\bar{f}_i$, the optimal stocking factor, $q_i^*(f_i)$, is a constant and independent of the chosen in-stock probability.[1] In contrast, if the in-stock probability $f_i > \bar{f}_i$, the optimal stocking factor $q_i^*(f_i)$ increases in f_i, i.e., a larger inflation of the expected demand is required to satisfy a higher service level.

[1] One should not confuse the stocking factor with the order quantity: even though the optimal stocking factor is constant in f_i and independent of f_j, the optimal order quantity $Q_i^* = q_i^*(f_i) d_i(\mathbf{f})$ increases in f_i and decreases in f_j, because $\partial d_i(\mathbf{f})/\partial f_i \geqslant 0$ and $\partial d_i(\mathbf{f})/\partial f_j \leqslant 0$. The rate of increase (decrease) in Q_i^* is exactly proportional to that of the expected demand as f_i increases (decreases).

4.2. Equilibrium in-stock probabilities

We now turn our attention to manufacturer i's in-stock probability decision, given its competitor's in-stock probability. It is immediate from Lemma 2(a) that u_i is independent of f_j, so we can rewrite (3) as a univariate function, i.e.,

$$v_i(f_i|\mathbf{p},f_j) = d_i(f_i|\mathbf{p},f_j)u_i(f_i|\mathbf{p}), \quad \text{where} \tag{11}$$

$$u_i(f_i|\mathbf{p}) = q_i^*(f_i)\big((r_i - w_i + \pi_i)\mathsf{E}_{Y_i}[Y_i] - (r_i - s_i + \pi_i)\mathsf{E}_{Y_i}\big[Y_i G_\epsilon(Y_i q_i^*(f_i))\big]\big) + (r_i - s_i + \pi_i)\mathsf{E}_{Y_i}\left[\int_0^{Y_i q_i^*(f_i)} \epsilon g_\epsilon(\epsilon)d\epsilon\right] - \pi_i. \tag{12}$$

The following proposition characterizes the necessary and sufficient condition for each manufacturer to enter the market.

Proposition 1. *(a) The best response $f_i^*|f_j \geqslant \bar{f}_i$ for all f_j. (b) A necessary and sufficient condition for manufacturer i to enter the market is*

$$(r_i - s_i + \pi_i)\mathsf{E}_{Y_i}\left[\int_0^{Y_i q_i^*(\bar{f}_i)} \epsilon g_\epsilon(\epsilon)d\epsilon\right] > \pi_i. \tag{13}$$

Proposition 1 shows that the best response $f_i^*|f_j$ can never be lower than the threshold service level $\bar{f}_i$. One can therefore interpret $\bar{f}_i$ as the minimum service level required for manufacturer i to compete in the market place. The manufacturer either enters the market and achieves a service level at least as high as $\bar{f}_i$, or exits the market altogether. Hereafter, we focus on the case where the market entry condition (13) holds for both manufacturers, and do not study the degenerate case where only one manufacturer enters the market.

Now we are ready to study the second stage problem on manufacturers' equilibrium service levels. Given the reliability index $\mathbf{p}$ for both manufacturers, manufacturer i's second stage expected profit v_i depends on both manufacturers' service levels. For the ease of exposition, we rewrite v_i as a function of $\mathbf{f}$, i.e., $v_i(\mathbf{f}|\mathbf{p}) = d_i(\mathbf{f}|\mathbf{p})u_i(f_i|\mathbf{p})$. For general yield distributions, the expected revenue per unit demand, $u_i(\cdot)$, is not necessarily concave in f_i, and hence $v_i(\mathbf{f}|\mathbf{p})$ is not necessarily log-concave in f_i. Nevertheless, by Assumption 2, $v_i(\mathbf{f}|\mathbf{p})$ is log-supermodular in $\mathbf{f}$, and thus the following proposition ensues.

Proposition 2. *The service level equilibrium $\mathbf{f}^*$ exists.*

While Proposition 2 shows the existence of service level equilibrium, it is challenging to prove the uniqueness of the service level equilibrium $\mathbf{f}^*$ under general yield distributions. The following condition ensures the uniqueness of the equilibrium in-stock probabilities $\mathbf{f}^*$, and we assume it holds for the rest of the analysis.

Assumption 3. $\Phi_{Y_i}(\cdot, p_i)$ follows a Bernoulli distribution with parameter p_i.

Such an assumption is fairly common in the random yield literature (see Anupindi & Akella, 1993; Swaminathan & Shanthikumar, 1999, etc.). Bernoulli random yield factors represent settings of a complete shutdown of the supplier's production process, as in the case of machine breakdown or contamination of raw materials. We focus on Bernoulli yield distribution for analytical tractability, but relax this assumption in our numerical experiment. In our extensive numerical study with general yield distribution, we obtain unique equilibrium in most cases, and therefore we believe the primary insight of our paper can be carried over to more general yield distributions.

Proposition 3. *Assume Bernoulli yield distribution. (a) There exists a unique Nash equilibrium on the in-stock probability $\mathbf{f}^*$, which satisfies*

$$\frac{q_i^*(f_i)\partial d_i(\mathbf{f}|\mathbf{p})/\partial f_i + d_i(\mathbf{f}|\mathbf{p})q_i^{*\prime}(f_i)}{d_i(\mathbf{f}|\mathbf{p})u_i(f_i|\mathbf{p})}\{(r_i - w_i + \pi_i)\mathsf{E}_{Y_i}[Y_i] - (r_i - s_i + \pi_i)\mathsf{E}_{Y_i}\big[Y_i G_\epsilon(Y_i q_i^*(f_i))\big]\} + \frac{\partial d_i(\mathbf{f}|\mathbf{p})/\partial f_i}{d_i(\mathbf{f}|\mathbf{p})u_i(f_i|\mathbf{p})}\left\{(r_i - s_i + \pi_i)\mathsf{E}_{Y_i}\left[\int_0^{Y_i q_i^*(f_i)} \epsilon g_\epsilon(\epsilon)d\epsilon\right] - \pi_i\right\} = 0. \tag{14}$$

(b) Each manufacturer's equilibrium in-stock probability is increasing in its own process reliability, and nondecreasing its competitor's process reliability. Moreover, an increase in a manufacturer's process reliability leads to a larger increase in its own equilibrium in-stock probability than its competitor's, i.e., $\partial f_i^*/\partial p_i - \partial f_j^*/\partial p_i > 0$.

5. First stage: supplier improvement competition

In this section, we characterize the manufacturers' equilibrium behavior of the first stage game, where each manufacturer chooses its improvement effort to maximize its objective function given by (5).

5.1. Do manufacturers benefit from higher supplier reliability?

In order to characterize the improvement effort $\mathbf{z}$, it is helpful to first understand the effect of *target* reliability index $\mathbf{p}$ (after improvement effort) on each manufacturer's expected profit. While a higher p_i benefits manufacturer i, it may also benefit manufacturer j through spillovers. In what follows we explore the role of spillover index α on the combined effect of $\mathbf{p}$.

Recall that the manufacturer i's second-stage expected profit at the equilibrium in-stock probabilities is given by $v_i(\mathbf{f}^*|\mathbf{p}) = d_i(\mathbf{f}^*|\mathbf{p})u_i(f_i^*|\mathbf{p})$, where $\mathbf{f}^* = (f_i^*, f_j^*) = (f_i^*(p_i,p_j), f_j^*(p_i,p_j))$ are implicitly given by (14). One can therefore treat $v_i(\mathbf{f}^*|\mathbf{p})$ as a function of target reliability index $\mathbf{p}$ only, and, for expositional ease we define $v_i^*(\mathbf{p}) \equiv v_i(\mathbf{f}^*|\mathbf{p})$.

5.1.1. The indirect effect

The following proposition proves that, as one might expect, the focal manufacturer's expected profit declines as its competitor's target reliability increases.

Proposition 4. *Manufacturer i's expected profit is (weakly) decreasing in its competitor's reliability index, i.e., $\partial v_i^*(\mathbf{p})/\partial p_j \leqslant 0$.*

The intuition for Proposition 4 is as follows. An increase in p_j affects manufacturer i's expected profit v_i^* by affecting both manufacturers' equilibrium in-stock probabilities f_i^* and f_j^*. However, v_i^* is not affected by its own equilibrium in-stock probability at $\mathbf{f}^*$. Hence, p_j influences v_i^* through its impact on f_j^* only. Since manufacturer i's demand is decreasing in f_j^*, the increase in p_j reduces manufacturer i's expected profit.

5.1.2. The direct effect

A more interesting question is whether manufacturer i always benefits from an increase in its own target reliability index p_i. Applying the envelope theorem to v_i^*, we have

$$\frac{\partial v_i^*(\mathbf{p})}{\partial p_i} = \frac{d v_i(\mathbf{f}^*|\mathbf{p})}{dp_i} = \underbrace{\frac{\partial v_i(\mathbf{f}^*|\mathbf{p})}{\partial f_i}}_{=0}\frac{\partial f_i^*}{\partial p_i} + \underbrace{\frac{\partial v_i(\mathbf{f}^*|\mathbf{p})}{\partial f_j}}_{-}\underbrace{\frac{\partial f_j^*}{\partial p_i}}_{+} + \underbrace{\frac{\partial v_i(\mathbf{f}^*|\mathbf{p})}{\partial p_i}}_{+}, \tag{15}$$

where $\partial v_i(\mathbf{f}^*|\mathbf{p})/\partial f_j = \underbrace{\frac{\partial d_i(\mathbf{f}^*|\mathbf{p})}{\partial f_j}}_{-} u_i$ follows from Assumption 2, $\partial v_i(\mathbf{f}^*|\mathbf{p})/\partial p_i = d_i \underbrace{\frac{\partial u_i(\mathbf{f}^*|\mathbf{p})}{\partial p_i}}_{+}$ follows from the proof of Proposition 3(b), and $\partial v_i(\mathbf{f}^*|\mathbf{p})/\partial f_i = 0$ follows from (14). It is evident from (15), the reliability index p_i affects $v_i^*(\mathbf{p})$ both directly and indirectly (through in-stock probabilities). The direct effect, $\partial v_i(\mathbf{f}^*|\mathbf{p})/\partial p_i$, is always positive. The indirect effect, $(\partial v_i(\mathbf{f}^*|\mathbf{p})/\partial f_i) \cdot (\partial f_i^*/\partial p_i) + (\partial v_i(\mathbf{f}^*|\mathbf{p})/\partial f_j) \cdot (\partial f_j^*/\partial p_i)$, is negative at equilibrium in-stock probabilities, since a manufacturer is always hurt by an increase in its competitor's in-stock probability. In general, (15) can be positive or negative, so manufacturer i may not necessarily benefit from an improvement in the supplier's reliability index p_i. Under certain conditions, however, we are able to unambiguously sign (15).

Proposition 5. *If demand function is log-separable with*

$$d_i(\mathbf{f}) = \psi_i(f_i)h_i(f_j), \tag{16}$$

where $d\psi_i(f_i)/df_i \geqslant 0, dh_i(f_j)/df_j \leqslant 0$ *and* $d^2 \log \psi_i(f_i)/df_i^2 \leqslant 0$, *then each manufacturer's second stage expected profit is strictly increasing in its own reliability index, i.e.,* $\partial v_i^*(\mathbf{p})/\partial p_i > 0$ $(i = 1, 2)$.

Proposition 5 and its proof show that, with log-separable demand, manufacturer i's expected profit $v_i^*(\mathbf{p})$ increases in its own target reliability index p_i, and the rate of increase $\partial v_i^*(\mathbf{p})/\partial p_i = d_i \cdot (\partial u_i/\partial p_i)$ depends on its own demand only.

5.1.3. The combined effect

Combining the indirect effect (Proposition 4) and direct effect (Proposition 5), we have

$$\frac{\partial J_i(\mathbf{p})}{\partial z_i} = \underbrace{\frac{\partial v_i^*(\mathbf{p})}{\partial p_i}}_{+} + \alpha \underbrace{\frac{\partial v_i^*(\mathbf{p})}{\partial p_j}}_{-} - \underbrace{\frac{dm_i(z_i)}{dz_i}}_{+}. \tag{17}$$

Since the spillover index α links the indirect effect (a negative impact) with the direct effect (a positive impact) of an increase in z_i, the net effect, i.e., whether the focal manufacturer is better off by exerting improvement efforts can be ambiguous. In fact, we have observed numerical examples in which the focal manufacturer is better off (or worse off) with a higher reliability index of the supplier. We thus conclude that the manufacturers may not necessarily benefit from improving supplier's reliability, even if the improvement is costless, due to the spillover effect.

5.2. Equilibrium improvement efforts

5.2.1. The case of no spillover effect (but with demand competition)

The case of no spillover effect with $\alpha = 0$ can be loosely interpreted as a market setting where two manufacturers compete on demand but with distinct technologies such that there is no "collaboration" on supplier improvement effort. In this case, if demand function is log-separable and satisfies Assumption 2, it can be shown that each manufacturer's expected profit, $J_i(\cdot)$, is submodular in improvement efforts $\mathbf{z}$. Since the set of manufacturers' feasible joint strategies is given by the nonempty convex and compact set: $z_i \in [0, 1 - p_i^0]$ $(i = 1, 2)$, there exists a Nash equilibrium on the improvement efforts.

5.2.2. The case of positive spillover effect (but without demand competition)

With positive spillovers, the manufacturers' set of feasible joint strategies is

$$z_i \in [0, 1 - p_i^0 - \alpha z_j], \quad i = 1, 2, \quad j = 3 - i.$$

We will show the existence of equilibrium using supermodular game approach, which requires that the set of joint feasible strategies is a lattice, see Topkis (1998). In the case of positive spillover effect, each manufacturer's feasible strategy set is dependent on the strategy adopted by its competitor, and the set of joint feasible strategies is not a lattice. We therefore consider a surrogate game with the following change of variables: $(\widehat{z_1}, \widehat{z_2}) = (1 - z_1, z_2)$. The set of feasible joint strategies in the surrogate game is the following:

$$\widehat{z_1} \in [p_1^0 + \alpha \widehat{z_2}, 1], \quad \widehat{z_2} \in [0, 1 - \alpha - p_2^0 + \alpha \widehat{z_1}],$$

which is a lattice. We will utilize this surrogate game to show existence of equilibrium improvement efforts in this subsection and next (Sections 5.2.2 and 5.2.3).

The special case of positive spillovers without demand competition captures settings where two manufacturers share a common supplier with similar technologies but they serve geographically separate markets. This case can be modeled by setting $h_i(f_j) = 1$ in the log-separable demand model defined in (16). In this case, Assumption 2 is reduced to $d_i'(f_i) \geqslant 0$ and $d^2 \log d_i(f_i)/df_i^2 \leqslant 0$. It follows from Proposition 5 that each manufacturer's second stage expected profit is independent of its competitor's reliability index and strictly increasing in its own reliability index.

If supplier improvement cost is fixed, we can further characterize each manufacturer's best response function in optimal improvement effort.

Proposition 6. *If supplier improvement cost is fixed, and each manufacturer's demand is a weakly increasing and log-concave function of its own in-stock probability only, then both manufacturers would either target perfect reliability or exert no improvement effort at all.*

(a) *If its fixed improvement cost is greater than the maximum gain in its second stage expected profit from improved supply reliability, i.e.,* $m_i > v_i^*(p_i = 1) - v_i^*(p_i = p_i^0)$, *then manufacturer i exerts no improvement effort.*
(b) *Otherwise, there exists a unique threshold* $\bar{z}_j \in [0, (1 - p_i^0)/\alpha]$ *such that manufacturer i would target perfect reliability if* $z_j < \bar{z}_j$, *exert no improvement effort if* $z_j > \bar{z}_j$, *and be indifferent between the two options if* $z_j = \bar{z}_j$.
(a) *Moreover, if* $\bar{z}_j > 1 - p_j^0$, *then manufacturer i will always target perfect reliability under any feasible strategy of manufacturer j.*

Leveraging Proposition 6, we can now characterize the equilibrium behavior of the manufacturers' improvement efforts.

Proposition 7. *Assume that each manufacturer's demand is a weakly increasing and log-concave function of its own in-stock probability only.*

(a) *If supplier improvement cost is fixed, then each manufacturer's optimal improvement effort in the surrogate game is increasing in its competitor's improvement effort. There exists at least one Nash equilibrium in the surrogate game. The set of equilibria is a lattice; there exists a componentwise smallest equilibrium* $\underline{\widehat{\mathbf{z}}^*}$ *and a componentwise largest equilibrium* $\overline{\widehat{\mathbf{z}}^*}$.
(b) *If the equilibrium improvement efforts exist and manufacturer i's equilibrium effort* z_i^* *is an interior solution,*[2] *then manufacturer i's expected profit at the equilibrium weakly increases in the spillover effect.*

Proposition 7 shows that, if manufacturers "collaborate" on supplier improvement but have no direct competition on demand, then the manufacturers' improvement effort is decreasing in each

[2] z_i^* is an interior solution means that $z_i^* \in (0, 1 - p_i^0 - \alpha z_j^*)$, $i = 1, 2$, $j = 3 - i$.

other and there exists one or more equilibria. Interestingly, despite the decrease in improvement effort, the spillover effect often leads to an increase in the expected profits.

5.2.3. The case of positive spillover effect with demand competition

When two manufacturers engage in general demand competition under positive spillover effect in improvement efforts, it is very challenging to characterize the equilibrium behavior. We therefore assume the Cobb-Douglas demand function, i.e.,

$$d_i(\mathbf{f}) = \gamma_i f_i^{\beta_i} f_j^{-\beta_{ij}} \tag{18}$$

with $\gamma_i > 0, \beta_i > 0$ and $\beta_{ij} > 0$ for all i and j. The Cobb-Douglas demand function is commonly used in the literature (e.g., Aydin & Porteus, 2008; Bernstein & Federgruen, 2004). By Lemma 4 in Appendix B, it is easily verified that the Cobb-Douglas function (i.e., constant elasticity) is a special form of log-separable function that satisfies Assumption 2. The following proposition gives sufficient conditions for the existence of Nash equilibrium in the manufacturers' improvement efforts.

Proposition 8. *Assume that there is no shortage penalty cost (i.e., $\pi_i = 0$) and each manufacturer's demand function is a Cobb-Douglas function (see (18)).*

(a) *The equilibrium in-stock probability satisfies $f_i^* = K_i p_i$, where K_i depends on cost parameters r_i, w_i, s_i and the distribution of ϵ only.*
(b) *Define*

$$M_i = \max\left\{\frac{\beta_i p_j^0}{\beta_{ij}} + \frac{\beta_{ij}+1}{(\beta_i+1)p_j^0}, \frac{\beta_i}{\beta_{ij} p_i^0} + \frac{(\beta_{ij}+1)p_i^0}{\beta_i+1}\right\},$$

$i = 1, 2,$ and $M = \max\{M_1, M_2\}$.

If $M \leqslant 2$, the first stage surrogate game is a supermodular game for all $\alpha \in [0,1]$; otherwise ($M > 2$), the first stage surrogate game is a supermodular game for $\alpha \in \left[0, \frac{2}{M+\sqrt{M^2-4}}\right]$.
(c) *When the first stage surrogate game is a supermodular game, it has at least one equilibrium. The set of equilibria is a lattice; there exists a componentwise smallest equilibrium $\underline{\hat{\mathbf{z}}}^*$ and a componentwise largest equilibrium $\overline{\hat{\mathbf{z}}}^*$.*

Proposition 8 shows that under certain conditions, the best response of one manufacturer's supplier improvement effort is again decreasing in its competitor's supplier improvement effort in the original game, and there exist one or more equilibria in the manufacturers' improvement efforts. An important implication of this result is that despite a fairly intense market competition as modeled by Cobb-Douglas demand function, equilibrium improvement efforts exist, as long as the spillover effect, α, is bounded from above by $2/(M + \sqrt{M^2 - 4})$, a constant that depends on demand parameters and initial reliability index.

In closing, we note that, under general demand functions, we have observed numerical instances with no equilibrium, unique equilibrium or multiple equilibria in the manufacturers' improvement efforts. The no-equilibrium case typically arises when spillover effect is large, demand is highly sensitive to in-stock probabilities (i.e., Cobb-Douglas demand function) and the manufacturers differ significantly in their market characteristics (i.e., wholesale prices charged by the supplier). Typically, the best response of a manufacturer is discontinuous in these settings, leading to the no equilibrium outcome. Mixed-strategy equilibrium might exist, but it is not the focus of our paper.

6. Managerial implications

Since the existence or uniqueness of manufacturers' equilibrium (in pure strategies) in general cannot be guaranteed, we do not analytically study the comparative statics of the equilibrium. Instead, we conduct a comprehensive numerical study to investigate market characteristics that influence manufacturers' equilibrium improvement efforts. In this numerical study, we employ uniform yield distributions and linear demand functions.

6.1. Endowed market advantage

Oftentimes manufacturers differ from one another in the expected market demand even if they set identical service levels. Such persistent differences in market demand can often be attributed to exogenous factors such as brand image, product design, and idiosyncratic consumer tastes. We refer to a manufacturer that enjoys a higher market demand with all else being equal as the one that has *endowed market advantage* (EMA). In our numerical study, EMA is measured by the difference in the base market demand of the two manufacturers.

It is unclear a priori whether the manufacturer with EMA would exert a higher or lower improvement effort relative to its competitor. On one hand, intuition suggests that it should exert less effort: it does not have to compete as aggressively since it already enjoys a market advantage. On the other hand, intuition also suggests that it should exert more effort to exploit its market advantage more effectively.

Fig. 1 illustrates the effect of EMA on manufacturers' equilibrium improvement efforts. (In Fig. 1, yield is uniform $Y_i \sim [1 - 0.6/p_i, 1]$, where $p_i^0 = 1.0$; demand is linear ($d_i(\mathbf{f}) = a_i + b_i f_i - c_{ij} f_j$), where the base values are $a_i = 0.5, b_i = 1.0$, and $c_{ij} = 0.5$; demand uncertainty ϵ is normal with $\mu = 1.0$ and $\sigma = 0.3$; the other base values are $r_i = 1.0, w_i = 0.5,\ s_i = 0.2,$ and $\pi_i = 0.3$; improvement cost is $m_i(z_i) = z_i^2$. Fig. 1 is obtained by varying α and a_1 while fixing all other parameter values.) Fig. 1(a) shows how the ratio of equilibrium improvement effort ($z1/z2 - 1$) varies by the spillover effect, and the arrow shows the direction when the EMA (as measured by the value of $a1 - a2$) increases or decreases. Fig. 1(b) shows how the ratio of equilibrium improvement effort ($z1/z2 - 1$) varies by the EMA ($a1 - a2$), and the arrow shows the direction when the spillover effect α increases.

Fig. 1 indicates that the manufacturer with EMA tends to exert a higher effort level relative to its competitor, and this phenomenon becomes more pronounced as the spillover index α increases. As the spillover effect increases, both manufacturers' improvement efforts decline, but the speed of decline is slower for the manufacturer with EMA. As a result, its *relative* improvement effort increases in α.

One naturally wonders whether the fact that the manufacturer with EMA exerts an increasingly higher proportion of improvement efforts also translates into a relative profit advantage. Fig. 2(a) shows that both manufacturers' expected profits increase in the spillover effect α, but the relative profit advantage of the manufacturer with EMA (manufacturer 1) declines as the spillover effect increases (Fig. 2(b)). Thus, the manufacturer with EMA may view the spillover effect with some sort of dilemma: in absolute profit terms, its increasingly higher proportion of improvement effort pays off because its expected profit increases in α; in relative profit terms, however, its profit advantage (over its competitor) declines, suggesting that its ever larger proportion of improvement effort benefits its competitor more than itself.

Back to the UTC's example, its Pratt & Whitney's ambivalence about the spillover effect is somewhat understandable. Although Pratt & Whitney trails GE and Rolls Royce in terms of overall

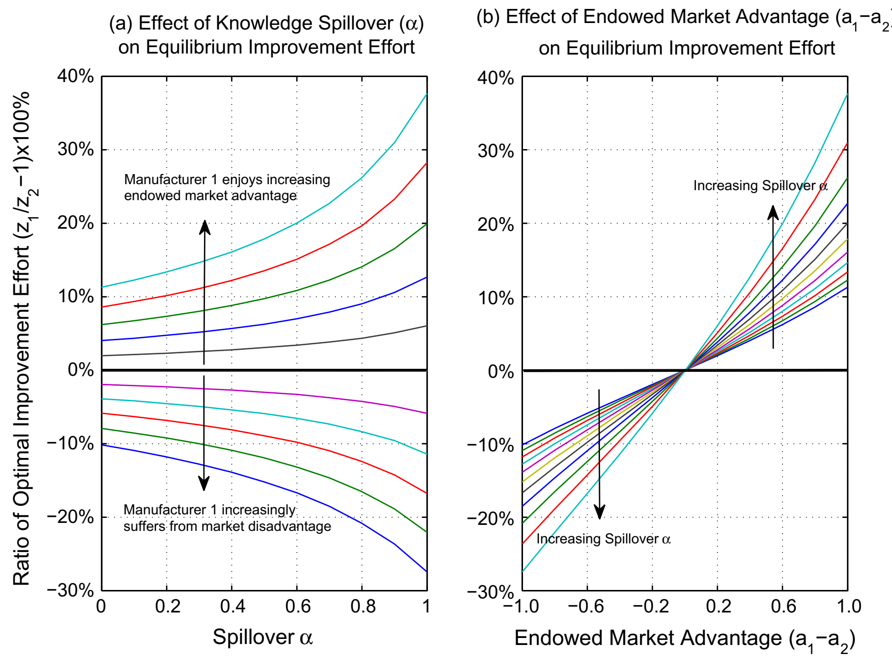

Fig. 1. Effect of EMA on manufacturers' equilibrium improvement efforts.

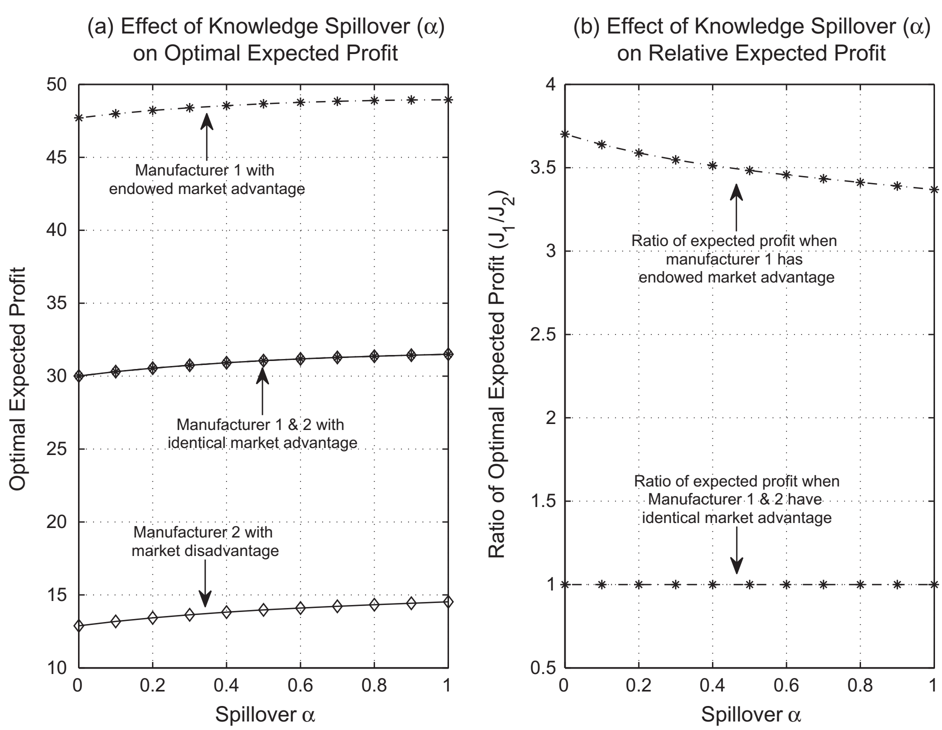

Fig. 2. Effect of EMA on equilibrium expected profits.

market share (Malone, 2010), it dominates "the commercial aircraft market with its jet engines" (Hinton, 2007). Thus, although its supplier improvement effort increases its own expected profit, such improvement effort may benefit its competitors more than itself. The latter concern may be the reason for Pratt & Whitney's hesitation. Nevertheless, the expected benefit seems to outweigh the latter concern, with a result that Pratt & Whitney reluctantly engages in improvement effort.

In the Toyota's example, existing evidence suggests that, despite significant spillover effects, Toyota expends much more improvement effort than its major competitors (Liker & Choi, 2004). Based on our results, one may conjecture that, all else being equal, Toyota enjoys an endowed market advantage, at least before the recent quality woes. Toyota's high level of improvement effort also suggests that Toyota is concerned perhaps more about its expected profit than its relative profit advantage over its competitors.

6.2. Manufacturer's pricing power with supplier

Manufacturers often can negotiate different wholesale prices w_i, depending on their relative power and their relationship

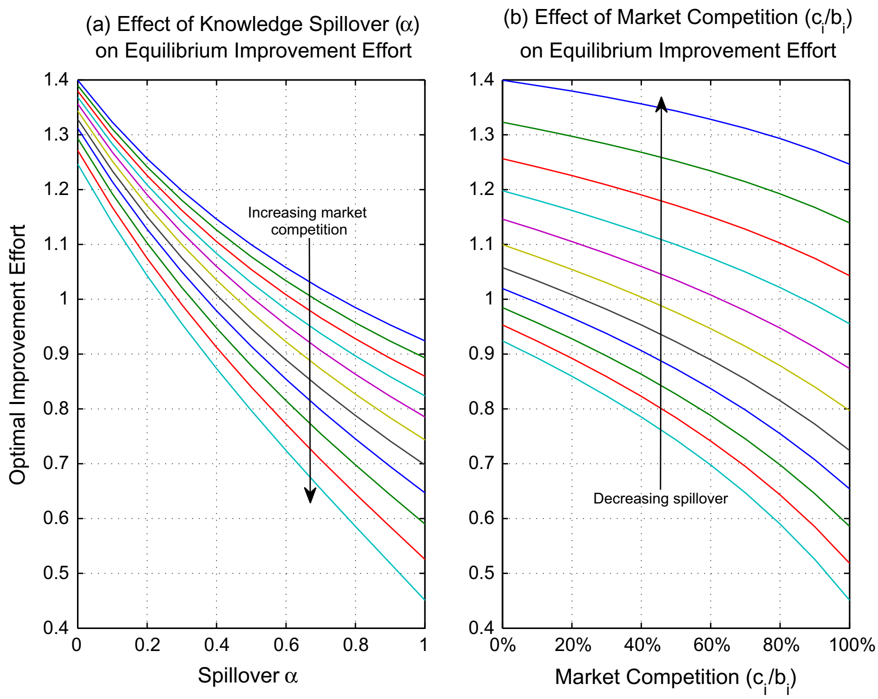

Fig. 3. Effect of market competition on manufacturers' equilibrium improvement efforts.

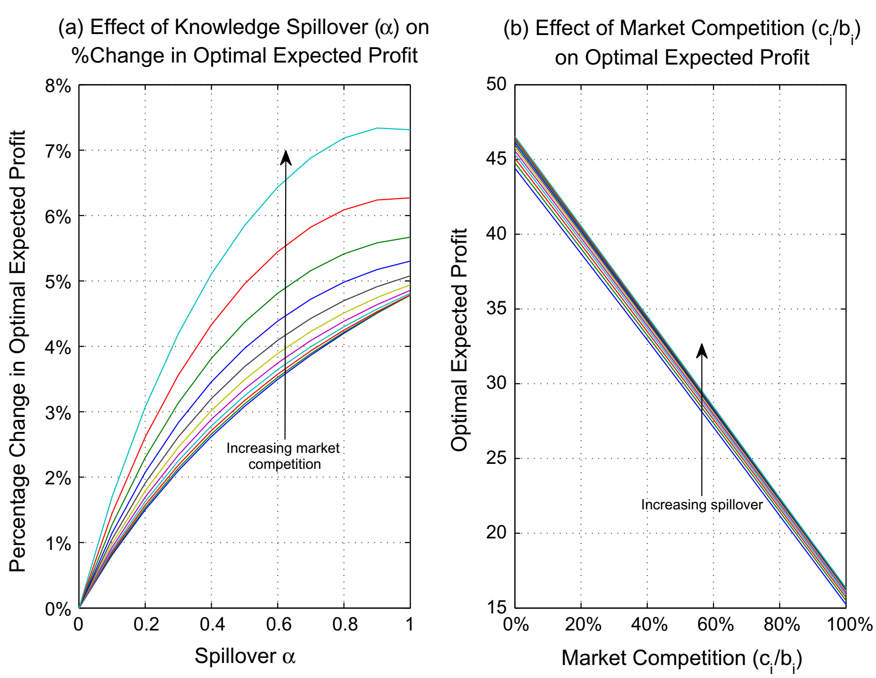

Fig. 4. Effect of market competition on equilibrium expected profits.

structure with the supplier. We refer to the manufacturer that can negotiate a lower w_i as the one with more pricing power. It is unclear whether the manufacturer with more pricing power would exert more or less improvement efforts relative to its competitors. Nevertheless, we can form some intuitions from the following proposition.

Proposition 9. *Assume Assumptions 1–3. Each manufacturer's equilibrium in-stock probability is (a) decreasing in its wholesale price, and weakly decreasing in its competitor's wholesale price; and (b) increasing in its unit price, unit salvage value and unit penalty cost, and weakly increasing in its competitor's unit price, unit salvage value and unit penalty cost.*

Proposition 9 proves that manufacturer i's equilibrium in-stock probability f_i^* increases if its wholesale price w_i decreases. This suggests that if manufacturer i has more pricing power, it will set a higher in-stock probability in equilibrium. Intuition suggests that the manufacturer would benefit more from an improvement

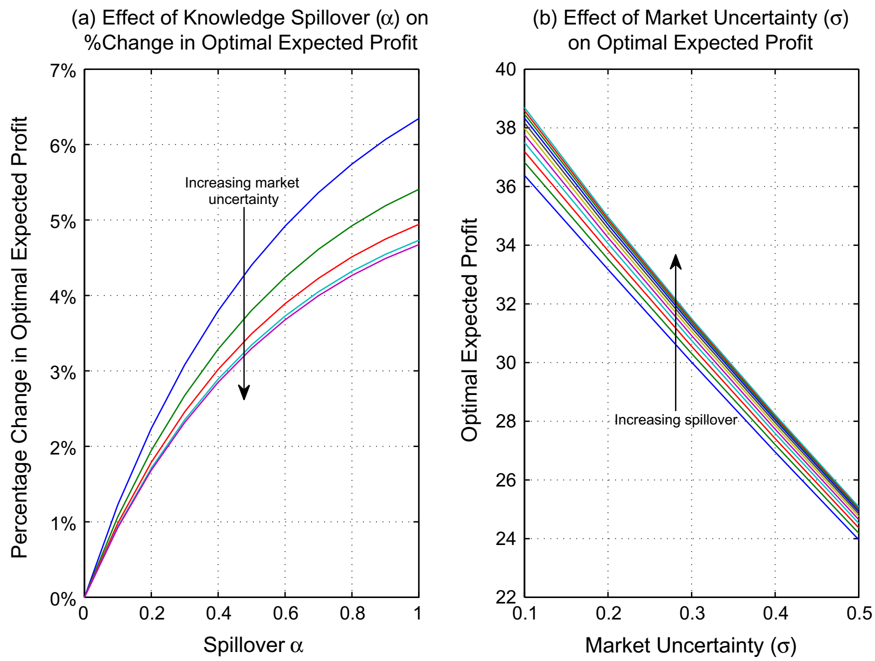

Fig. 5. Effect of market uncertainty on equilibrium expected profits.

in supplier yield, and exert a higher level of improvement efforts relative to its competitor.

Our numerical observation (not illustrated here) confirms the above intuition, i.e., the manufacturer with more pricing power exerts a higher proportion of improvement effort relative to its competitor. The implication on the expected profit is also qualitatively similar to our earlier observation in Section 6.1, that is, both manufacturers' expected profits increase in spillover effect, but the relative profit advantage (of the manufacturer with more pricing power) declines as spillover effect increases, suggesting that the increasingly higher proportion of improvement effort exerted by the focal manufacturer benefits its competitor more than itself.

6.3. Competition intensity

To study the impact of competition intensity, we consider the setting where two manufacturers are symmetric, i.e., $c_{ij} = c_{ji} = c_i = c, a_i = a$, and $b_i = b$. To capture the market competition effect, we use the ratio of c/b in the linear demand model (recall that $d_i(\mathbf{f}) = a_i + b_i f_i - c_{ij} f_j$) to measure the competition intensity, and we change the value of the ratio c/b by fixing b and varying c. If $c/b = 0$, then each manufacturer's demand depends on its own in-stock probability only (i.e., no direct competition), whereas if $c/b = 1$, then each manufacturer's demand depends on its own in-stock probability as much as it depends on its competitor's in-stock probability (i.e., perfect substitution/competition).

Fig. 3 illustrates the effect of competition intensity on the manufacturers' equilibrium improvement efforts. Fig. 3 suggests that the manufacturers' improvement efforts decline as competition intensifies. Moreover, under intense competition, both manufacturers significantly reduce their improvement efforts as spillover effect increases.

Fig. 4 illustrates the effect of market competition on the manufacturers' equilibrium profits. Fig. 4(a) illustrates the percentage change in the manufacturers' expected profits as spillover effect increases, where we use the expected profits under $\alpha = 0$ as the base case. Interestingly, the spillover effect improves the manufacturers' expected profits, and the *relative* benefit in expected profit is increasing in market competition. Fig. 4(b) shows that market competition has a detrimental effect on the manufacturers' expected profits, whereas spillover effect improves the manufacturers' expected profits.

In summary, intense market competition is often a characteristic of commodity products, where manufacturers use similar technologies and hence are more likely to experience spillover effects. Our numerical results suggest that spillover effect in this type of market should be viewed favorably, and manufacturers should not try to curb the supplier's spillover effect in this type of market.

6.4. Market uncertainty

Different industries often exhibit different levels of market uncertainty: some industries (e.g., fashion) exhibits considerably higher market uncertainty than others (e.g., aerospace). It is therefore of interest to understand how market uncertainty influences the manufacturers' equilibrium improvement efforts and the resulting expected profits.

In this section, we study the impact of market uncertainty by varying the standard deviation of the random term of the demand (ϵ) from 0.1 to 0.5, while keeping its mean constant at 1. It turns out that the effect of market uncertainty on the manufacturers' improvement efforts (not illustrated here) is very similar to the effect of market competition discussed in Section 6.3. That is, as in the case of market competition, both higher market uncertainty and spillover effect reduce the manufacturers' equilibrium improvement efforts.

Fig. 5 illustrates the effect of market uncertainty on the manufacturers' expected profits. Fig. 5 shows that market uncertainty reduces the manufacturers' expected profits, both in relative and absolute terms. However, at any level of market uncertainty, the spillover effect improves the manufacturers' expected profits. This suggests that the spillover effect may benefit the manufacturers, especially when manufacturers are similar in their characteristics.

7. Conclusion

Supplier reliability is one of the key determinant of manufacturers' competitiveness. To ensure reliable supply delivery, more and more companies take a proactive role and invest directly in their suppliers' reliability improvement. In this research, we investigate how potential spillover influences manufacturers' supplier improvement efforts in a competitive setting.

We analyze a supply chain with two manufacturers, who compete on service levels (measured by in-stock probability) in their end product market. The manufacturers share a common supplier whose production process is subject to random output. Each manufacturer may exert effort to improve the supplier's delivery reliability, but the enhanced reliability may spill over to its competitor. We develop a two-stage model that encompasses supplier improvement, spillover effect and random yield in a competitive setting. In the first stage, each manufacturer simultaneously decides its supplier improvement effort. In the second stage, after exerting supplier improvement effort but before yield and demand uncertainty is resolved, each manufacturer decides its in-stock probability and its order quantity from the supplier. In this complex model, we analytically characterize each manufacturer's equilibrium in-stock probability and order quantity in the second stage. Moreover, we characterize sufficient conditions for the existence of the equilibrium of the manufacturers' improvement efforts in the first stage. In addition, we conduct extensive numerical experiments and provide managerial insights on market characteristics that influence the manufacturers' equilibrium improvement efforts.

When there is spillover effect, we analytically show that the manufacturers may not necessarily benefit from increased supplier reliability, even if supplier improvement is costless. Under certain conditions, we prove that each manufacturer's expected equilibrium profit weakly increases in the spillover effect. Our extensive numerical study confirms that our analytical findings can be carried over to the more general settings. In particular, in all our numerical experiments, both manufacturers' expected equilibrium profits always increase in the spillover effect. Moreover, our numerical study also brings about additional insights on the impact of spillover effect and market characteristics. We find that manufacturers typically exert less efforts in the equilibrium as the spillover effect increases. When manufacturers are asymmetric, the ex ante more advantageous manufacturer typically exerts a higher proportion of improvement efforts compared to its competitor, especially when the spillover effect is large. While such higher proportion of improvement efforts benefits the focal manufacturer, it may benefit, in relative profit terms, its competitor more. When manufacturers are symmetric, both manufacturers' equilibrium improvement efforts and expected equilibrium profits decline in market competition or market uncertainty.

In the context of our modeling framework and numerical study, our results suggest that the presence of spillover effect may not necessarily be viewed as a negative thing. Manufacturers should have a more open-minded attitude and engage in supplier improvement without worrying too much about the spillover effect.

We hope this work encourages future research in the area of reliability improvement. A number of interesting extensions are worth further exploration. First, the supplier may initiate improvement effort as well. In this case, who is in a better position to improve process reliability, the supplier or the manufacturers? Second, manufacturers may procure from multiple suppliers, and it is of interest to contrast the effect of supplier competition with manufacturers' improvement efforts. We hope future studies by us and others will bring additional insights to this important area of research.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejor.2014.01.015.

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