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# Developing a shared supplier with endogenous spillovers

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**Abstract**

Firms who buy from suppliers often engage in supplier development to reduce the supplier's production cost. Being aware that their efforts may benefit a rival firm when there is a shared supplier, some buyers only invest in "specific supplier development," that is, in those processes or technologies where spillover cannot occur. Other buyers willingly accept the spillover that arises from supplier development, and invest in "generic supplier development." Our game-theoretic model captures a buyer's choice to invest in these distinct supplier development types as a way to endogenize spillovers. In contrast to the literature, this paper considers the benefits of investing in a combination (i.e., portfolio) of cost-reducing generic and specific supplier development. We demonstrate how supplier development affects a shared supplier's wholesale pricing decisions; whereas generic supplier development lowers wholesale prices equally across buyers, specific supplier development only lowers the wholesale price of the investing party. Our model shows that buyers should treat the spillovers from generic supplier development as an investment opportunity rather than a threat. In equilibrium, a buyer will always invest in a portfolio of both supplier development types, and having a better generic than specific investment capability may even make generic supplier development the most prevalent option for him, depending on the level of competition. Moreover, even if the buyers can commit to only investing in specific supplier investment, the resulting equilibrium gives lower buyer profits than a portfolio that includes generic investments. We also find that the presence of specific investments may raise generic supplier development, benefiting all supply chain actors. However, incorporating specific supplier development into a supplier development portfolio or a commitment to investment in only specific supplier development can lead to a prisoner's dilemma in terms of buyer profits. We show how investment capabilities and competitive intensity drive the buyers' investment decisions and supply chain actors' profits. The paper's main results also hold for asymmetric generic investment capabilities, though we highlight that the least capable buyer will free-ride on his rival's investments, consequently making him earn higher profits.

**KEYWORDS**

cost reduction, shared supplier, spillover, supplier development

## 1 | INTRODUCTION

Many downstream firms engage in supplier development activities to help improve supply chain metrics such as supply base cost, quality, delivery performance, lead time, and productivity. For instance, in the automobile industry, Honda's supplier development program has raised suppliers' productivity and quality by about 50% and 30%, respectively, while much of the supplier's cost savings are shared with Honda (Liker & Choi, 2004). Similarly, firms like Toyota, Porsche, and Renault-Nissan have dedicated supplier improvement teams with key capabilities that the suppliers often lack. Interfirm competition seems to be an important factor pushing firms to raise their supplier development investments. For

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instance, when automaker Hyundai-Kia was lagging behind Toyota in terms of supplier management, they replicated its supplier development practices while aiming for similar benefits (Dyer et al., 2018).

Firms that compete often source their inputs from shared (or common) suppliers. This begs the question, what happens when the knowledge generated within a particular buyer–supplier relationship as a result of supplier development spills over to the rival buyer. Some buyers consider such spillovers a serious concern (Muthulingam & Agrawal, 2016). The tractor manufacturer John Deere, for example, made substantial investments in supplier development programs to establish a superior supplier base. However, the firm became suspicious of rivals' efforts to free-ride on their investments, leading them to reconsider their supplier development training program (Mesquita et al., 2008). At the same time, some investments in castings or information systems are unique to the relationship with an individual supplier, yielding cost savings that only benefit John Deere (Stegner et al., 2002). Some buyers value confidentiality in supplier development to such an extent that they even help the supplier physically separate manufacturing operations for the buyer, preventing competitors from getting deep insight into these processes (Handfield et al., 2000).

Other buyers in the automobile industry take quite the opposite stance. Honda managers take the perspective of "a rising tide lifts all boats," welcoming the knowledge transfer of supplier development to rivals such as Ford and GM (MacDuffie & Helper, 1999). Toyota is also well aware of the spillovers to rivals from supplier development and is willing to accept these (Dyer & Hatch, 2006). Moreover, Toyota embeds the supplier development activities that generate spillovers into a portfolio of supplier development types, as its supplier development program targets not only suppliers' generic production capabilities but also processes purely dedicated to Toyota such as tailored computer-aided design (CAD) systems and shared inventory systems (Liker & Choi, 2004).

The potential existence of spillovers in the context of supplier development is clearly recognized by buyers. Yet, the examples mentioned above illustrate that buyers have divergent ways of dealing with these. We devise a game-theoretic framework to explicitly capture these opposite choices. An important feature of the model is the consideration of investment spillover as an endogenous phenomenon, which is in line with practice because buyers have different investment options. To do so, the model accounts for the crucial difference between investment in knowledge exclusive to the relationship and those supplier development investments that spill over to a rival buyer. That is, we differentiate between supplier development investments into a shared supplier's specific production technology and generic production technology. An example of "specific supplier development" (also referred to as "specific investments") is a buyer purchasing a computer numerical control (CNC)-machine tailored to making parts for this buyer only, installing it at the supplier's site, and training the supplier to work with the machine. Examples of "generic supplier development" (or, "generic investments") include a buyer's investment in a part of a supplier's production line that also serves other buyers, or an investment into a supplier's corporate lean manufacturing program. Another novel feature of our model, in line with the Toyota example given above, is that the buyers have the opportunity to invest in a portfolio of supplier development types. This allows us to study the interaction between generic and specific supplier development decisions, whether the buyers and the shared supplier benefit from investing in a portfolio of investment types or prefer focusing on a particular supplier development type instead.

In our framework, the buyers invest in generic and/or specific supplier development, before the shared supplier decides on her optimal wholesale prices. In setting prices, the supplier can discriminate between the buyers and can decide for each of the buyers how much of the cost reductions resulting from supplier development she returns to the buyers in lowering her wholesale prices. In studying the buyers' investment decisions, we consider two important model elements that drive the paper's results. First, we allow a buyer's capability to invest in generic supplier development to be different from specific investment capability, which means that investment in one supplier development type may be costlier than investment in the other. This is quite natural as, for example, a buyer may excel in manufacturing engineering, making it easy to clearly pinpoint improvements at the supplier's side from which the buyer can directly benefit. But, at the same time, the buyer may implement a costly supplier development training program from which the rival benefits as well. These capability differences affect a buyer's preference to invest in one type over the other. We also study what happens when the buyers differ in terms of their generic investment capability. Second, this paper investigates the role of competitive intensity in the product market, which is modeled as product substitutability. If the buyers are monopolists in their own respective markets, then supplier development spillovers are unlikely to be a cause of concern as they do not harm the firm's competitiveness. Higher levels of rivalry raise the relative importance of specific supplier development as the buyer uses specific investments to differentiate himself from his rival (via a lower wholesale price).

Consequently, our analyses center around three main questions: (1) What choices will the buyers make, if they can invest in a portfolio of generic and specific supplier development? (2) How do the buyers' equilibrium choices depend on competitive intensity and supplier development capability? (3) What are the profit implications for the buyers and shared supplier given the equilibrium investments, and what happens if the buyers can commit to excluding specific or generic supplier development? In answering these questions, we obtain a range of new insights, which help to explain why different approaches are observed in practice:

First, we find that the buyers will always gain from using both generic and specific supplier development in their portfolio. The opportunity to make generic investments benefits both buyers equally and provides the buyers an incentive to raise their specific investments. For low levels of competition, generic supplier development levels—that is, the cost reductions resulting from generic investments—may exceed those of specific supplier development, but as competitive intensity grows, specific supplier development becomes a more important tool for the buyers, and this holds even when the buyer has greater capability for generic investments. An important insight is that when the buyers are asymmetric in terms of generic investment capability, the most capable buyer will invest more in generic supplier development, but at the same time, his profits are lower than the profits of the least capable buyer, who invests less but free-rides on his more capable rival.

Second, it is never beneficial for the buyers and shared supplier to exclude generic supplier development from the investment options. The results show that the presence of generic investments always pushes the buyers to raise their specific supplier development levels, and they do so in a way that never hurts them. The supplier benefits from the combination of supplier development investments by selling more products and improving her profit margins.

Third, we demonstrate that for high enough levels of competition and investment capabilities, both buyers and shared supplier would be better off not investing in specific supplier development, and should focus on only generic supplier development. In fact, investing in specific supplier development may trap the buyers into a prisoner's dilemma, both when the buyers invest in a portfolio of supplier development, or when the buyers only invest in specific supplier development. These insights are managerially relevant as they underline the positive role of spillovers from generic supplier development investment while showing that the presence of specific supplier development can actually hurt the supply chain.

This article proceeds as follows. The next section reviews the literature (Section 2). After that, the model is described (Section 3). The results are analyzed in Section 4, and we conclude in Section 5.

## 2 | LITERATURE

Supplier development refers to a buyer's effort to identify, measure, and improve supplier performance (Krause et al., 1998). Empirical studies have shown how site visits and training programs of supplier personnel positively influence performance dimensions such as on-time delivery and product design (e.g., Modi & Mabert, 2007). Supplier development has been studied frequently with analytical models. Many of these papers revolve around the decisions of a single buyer (e.g., Iyer et al., 2005; Lee & Li, 2018; Li, 2013). Our paper belongs to the strand of literature involving multiple buyers and one or more suppliers. An example is the study by Jin et al. (2019), who consider a setting with two buyers and two suppliers. The buyers compete in the market selling products that consist of two components, which may be sourced from either of the two suppliers. Their paper incorporates a variety of system structures, centering around the question whether the buyers should integrate with a supplier, and how this decision drives cost-reducing supplier development. Our model is different in that we consider supplier development spillovers, and the composition of the supplier development portfolio if buyers can invest in a combination of both relation-specific projects (i.e., specific investments) and generic supplier development projects (i.e., generic investments) that yield a spillover to a rival.

Studies involving spillovers have focused on horizontal competition and cooperation (d'Aspremont & Jacquemin, 1988), horizontal cooperation in supply chains (Gupta, 2008), and vertical cooperation (Ge et al., 2015). While these papers have advanced our understanding of how cooperation mode and locus of innovation affect innovative effort and firm profits when spillovers are exogenous, they provide little insight into supply chain actors' preferences in terms of spillovers, particularly when these spillovers are the focus of a firm's decisions, as in our paper.

Spillovers in supply chains are particularly relevant in networks with multiple buyers and a shared (or common) supplier. Similar to the papers cited above, the supplier development literature in shared supplier contexts has acknowledged the importance of spillovers, but generally assumes that spillover is not the choice of the buyer, or entirely exogenous. A common feature quite central to literature on exogenous innovation spillovers in general and supplier development spillovers in particular, is that some fraction of the investment results, such as unit reduction cost, yield, or product quality, benefits a rival or supply chain partner. Several papers within this stream focus on the context of buyer investments to develop shared suppliers, addressing issues such as investment timing. In the model of Agrawal et al. (2016), the supplier plays an active role in the quality improvement process, while the buyers initially have incomplete information on the quality improvement potential of the supplier. They study the question how the timing of the first investment into a shared supplier is affected by the interplay of spillovers, competition, and supplier capabilities, and they identify the conditions under which the investment is delayed or hastened. Kim et al. (2017) use a repeated model with deteriorating quality of a shared supplier's products. They show why this setting invokes inefficient supplier development delays. Rather than studying the timing of investments and their associated spillovers, our paper focuses on the level of spillover investments, and how they arise in the context of multiple investment types.

Other papers have looked more closely at the size of investments and profitability impacts. For example, Wang et al. (2014) study the effect of supplier development on a shared supplier's delivery reliability. They find that supplier development typically decreases with spillovers, but also that spillovers improve firm profits. In a paper somewhat closer to ours, Friedl and Wagner (2016) find that spillovers of cost-reducing supplier development hurt investments, although this is shown only for the case where investment costs are independent from the size of the spillover. Papers such as these typically find that firms prefer to suppress spillover investments to raise profits. Our paper, in contrast, paints a more positive picture of spillover investments and shows that by allowing specific and generic investments to be part of an investment portfolio, an investing party would never want to eliminate spillovers from his investments, possibly even to the extent that generic investments are preferred over specific investments.

Spillover endogeneity has been recognized as an important topic in general (e.g., Amir et al., 2003) though investigations in supply chains are unusual. Hu et al. (2020) model a game consisting of an innovative firm that outsources to a contract manufacturer that is possibly a product market rival. They find that the innovative firm may outsource to a product market rival in equilibrium, as outsourcing leads to an innovation spillover but simultaneously allows that firm to charge a price premium. In their study, the occurrence of voluntary spillovers is associated with the outsourcing decision, while in our study, spillovers arise as an investment decision by the buyer. In contrast to our work, none of the papers discussed so far consider investment portfolios, even though it is clear from the examples in the introduction that firms embed different investment types into such portfolios, involving investments with varying degrees of spillovers. Our paper finds the conditions under which firms prefer investment in multiple supplier development types.

Literature studying endogenous spillovers in supplier development investment models is more scarce. The paper most similar to ours is Qi et al. (2015), who model supplier development as capacity investment, and analyze the decisions of two buyers investing in a shared supplier. Their model differentiates between exclusive investment (where excess capacity cannot be used for supplying a rival) and the spillover effect caused by investment in capacity where the buyer is given first priority but where excess capacity can benefit a rival (first-priority investment). They find that a buyer may allow capacity spillover to a rival if that discourages a rival to invest himself. Qi et al. (2019) extend this work by considering stochastic demand, while the buyers' demands are exogenous but correlated. They obtain the interesting result that firms are more likely to consider the exclusive investment approach when demand correlation decreases. In both papers, the investment regime is a special example of spillover endogeneity.

Our model is different from Qi et al. (2015, 2019) by assuming that supplier development reduces the supplier's production cost. Our framework also differs in terms of the nature of spillovers. In their models, only one firm (with the smallest capacity) can potentially benefit from a (capacity) spillover, while in our model, the buyers can benefit from each other's investments. More importantly, in the context of their models, a buyer engages in either exclusive or first-priority investment, while simultaneously using both options has little meaning. In contrast, our paper considers cost reduction at the supplier's site as the main target, while these cost reductions can result from different investment types that may or may not benefit the other buyer. In practice, buyers can choose to combine different supplier development investments. Hence, our paper's main concern is studying the benefits of a buyer's investment portfolio, allowing us to consider whether buyers have an incentive to invest in both specific and generic supplier development, and if and how different investment types complement each other. In contrast to their papers, our model also examines how the composition of an investment portfolio is affected by competition and the buyers' distinct capabilities in terms of investing in specific and generic supplier development, which our model allows to differ within a company, but also across companies. This helps to gain managerial insight into how companies' supplier development portfolios should be aligned both with external conditions and the competencies of a firm's supplier development team.

## 3 | THE MODEL

Our game-theoretic model comprises a setting with one shared supplier and two buyers. A buyer (he) needs exactly one component for each product he produces. The supplier (she) manufactures a component for buyer $i \in (1, 2)$ at a unit cost of $C_i$, selling it at a wholesale price $w_i$. The buyers and supplier are tied via a straightforward "take it or leave it" contract, which has much theoretical and empirical support (e.g., Gupta & Loulou, 1998; Sluis & De Giovanni, 2016). The supplier can vary wholesale prices across buyers, while the buyers' supplier development investments lower the supplier's production cost. Studies in the automobile industry have showed how investments by downstream rivals in a shared supplier result in increased, differentiated, supplier performance (e.g., Dyer & Hatch, 2006), which is a reason for the supplier to use price discrimination. This is also in accordance with the U.S. Robinson–Patman Act, which allows price discrimination if the arguments for treating customers differently are valid (including differences in the costs of supplying both buyers). The buyers produce at a constant production cost, which we normalize to zero.

### 3.1 | Market demand

Buyer competition is based on prices, which is natural in a context where the buyer exerts effort into reducing the supplier's production cost. In line with past studies such as Anderson and Bao (2010), Cachon and Kök (2010), and Li and Liu (2021), we model buyer $i$'s demand as

$$q_i = a - p_i + d(p_j - p_i) \quad i = 1, 2; j = 3 - i, \tag{1}$$

where $p_1$ and $p_2$ are the prices charged by buyer 1 and 2, respectively. In this model, the parameter $a$ reflects a buyer's base demand, and $d$ is the level of product substitutability, which captures the competitive intensity between the buyers. The term $d(p_j - p_i)$ reflects the amount of supplier switching due to price differences. Naturally, because $d(p_1 - p_2) + d(p_2 - p_1) = 0$, price differences do not create extra demand.

We assume $d \in (0, \infty)$, which means that a buyer's demand can be more or less sensitive to price differences rather than the buyer's own price. When $d = 0$, there is no competition between the buyers. In many practical settings, demand is relatively inelastic and consumers have a limited set of options to choose from. For increasing $d$, consumers are more likely to select the cheapest option. When $d \to \infty$, competition is fierce and demand is driven only by price differences rather than absolute prices. Though this is less likely to occur in practice, we will analyze our results for the full range of $d$ values. To avoid trivial cases with negative demand, we assume that $a - p_i > -d(p_j - p_i)$ if $p_i > p_j$.

## 3.2 | Supplier development investments

When a buyer engages in supplier development, he reduces the supplier's unit production cost while carrying the investment cost. The cost reduction can be seen as the direct result of targeted process improvements. Similar to Hu et al. (2017), the supplier's pricing decisions are separated contractually from any supplier development investments. This reflects current practice in, for instance, the automobile industry (Sako, 2004). To incorporate endogenous supplier development spillovers, the buyers may invest into the supplier's generic and specific production technology. We denote $x_i$ as the supplier's unit cost reduction resulting from a *generic supplier development* investment of buyer $i$. Likewise, $s_i$ is the cost reduction achieved when buyer $i$ invests in *specific supplier development*. We will refer to $x_i$ and $s_i$ as buyer $i$'s supplier generic and specific development levels, respectively.

In the model, the results of generic investments yield a spillover to a rival buyer, while those of specific investments do not. Formally, the cost of supplying buyer $i$ is $C_i(s_i, x_1, x_2) = c - s_i - \sum_{j=1}^{2} x_j$, with $c > 0$ as the constant unit cost of production. To avoid unnecessary notation, we write this as $C_i$, noting that it is natural to require $C_i \geq 0$.

As typically organizational budgets are constrained, it is common to model investment costs of cost reduction projects, including supplier development, as convex functions that represent decreasing returns to scale (d'Aspremont & Jacquemin, 1988; Veldman et al., 2014). We will assume quadratic costs, and consider total investment costs for buyer $i$ to be $I_i = (\gamma x_i^2 + \sigma s_i^2)/2$. The cost parameters $\gamma$ and $\sigma$ reflect the buyers' capabilities of investing in generic supplier development and specific supplier development, respectively. In this formulation, generic and specific supplier development are separable in terms of investment cost, which is reasonable as the underlying cost reduction projects are typically quite different. It is also worth noting that the investment costs for the two buyers are unrelated, which is in line with, for example, d'Aspremont and Jacquemin (1988), Gupta (2008), and Arya and Mittendorf (2013). This is consistent with an interpretation of the buyers' supplier development efforts being carried out in different projects with their respective costs being associated with the individual projects. However, the nature of generic supplier development may also give rise to an interconnected cost structure, which applies when the buyers' efforts target the same part of a process, such that the combined efforts produce a return that depends on the total investment. We have obtained results under an alternative model formulation with buyer $i$'s generic investment costs given by $\gamma(x_i + \delta x_j)^2/2$ (with $\delta$ being the parameter to capture the extent to which the buyers' investment costs are connected) and see that the model's main results are qualitatively similar. To keep the analysis simple, we restrict our attention to those cases where $\delta = 0$.

## 3.3 | Decision sequence and information structure

In setting up our model, we need to make choices about the sequence of events, and the information that is available. A timeline of the game is given in Figure 1. In the first two stages, generic and specific supplier development decisions are made. It is most natural to assume that for each buyer the specific supplier development level that is achieved is private information and not available to the other buyer. A buyer's generic supplier development level on the other hand is most likely to be known to the other buyer, and this is consistent with the spillover benefit available to the other buyer. In practice, opportunities for investment will occur at different times, so that a model of simultaneous investment in both generic and specific supplier development is less appropriate. Because of the absence of information available to the buyers on the amounts of earlier specific investment, a model in which specific investment occurs before generic investment reduces to the case of simultaneous investment. A further observation here is that generic investments often take place over a relatively long term. For these reasons, we have concentrated on the case where generic investment occurs first while noting that the paper's main results are robust to alternative model formulations where generic and specific investments are made simultaneously.[1]

In the third stage, the supplier takes stock of the cost reductions stemming from supplier development before she decides on $w_1$ and $w_2$. This assumption is reasonable as the buyers would want the supplier to implement the underlying changes in her manufacturing system, and take the cost reductions into account while making price cuts on wholesale prices. Note that the supplier makes no explicit commitment as to how much of the cost reductions will be transferred back to the buyer(s).

In the last stage, the buyers observe $w_1$ and $w_2$ after which product market competition takes place. The notion that the supplier's pricing decisions are made before the buyers compete is quite common. Also, note that while buyer $i$ can correctly infer the size of the specific supplier development level $s_j$ from observing $w_j$, this is not vital for the model as the product pricing decisions in the fourth stage only depend

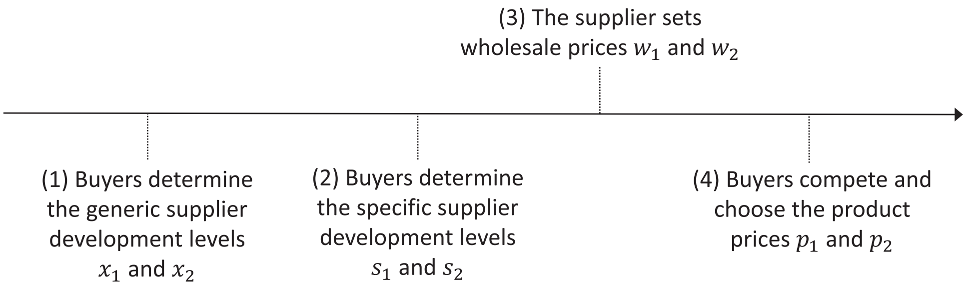


**FIGURE 1** Timeline of the game

on $w_i$ and $w_j$. Furthermore, in many industries, contract types and contract terms are known in the market, which justifies that buyer $i$ can observe $w_j$. This is a frequently made assumption in general (Jin et al., 2019), and in a shared supplier context with price discrimination in particular (e.g., Chen & Guo, 2014; Chen et al., 2016; Feng & Lu, 2013).[2]

In this multistage game between the buyers, we look for a Nash equilibrium in pure strategies. Subgame-perfect equilibrium outcomes are found using backward induction. Initially we assume that the buying firms are identical and we find that equilibria are symmetric, but our analysis is general and we later consider the asymmetric case. We use superscript $P$ to denote the outcomes in the portfolio investment model. To understand the effects of combining generic and specific investments, we compare the outcomes of the full model depicted in Figure 1 with several benchmarks. In particular, we solve the case where the buyers invest in generic supplier development only (superscript $G$), specific supplier development only ($S$), and no investment at all (0).

## 4 | ANALYSIS

We note that each of the cases we consider has an associated feasible parameter region $\Gamma_m$ in the $d, \gamma, \sigma$-space, $m \in \{0, G, S, P\}$, which is determined by the sufficient second-order conditions and stability conditions that may arise in the various stages of the game. Importantly, for each of the cases, it can be demonstrated that equilibrium outcomes are always positive if the sufficient second-order conditions and stability conditions hold. Technical details of the feasible parameter regions and proofs of the propositions can be found in the Appendix.

### 4.1 | Buyer and supplier pricing decisions

In the last stage, the supplier development investment costs are sunk, such that the buyer's problem is given by $\max_{p_i} \pi_i = (p_i - w_i)q_i$, where the optimal reaction functions are given by

$$p_i = \frac{1}{2}\left(w_i + \frac{a + dp_j}{d+1}\right) \quad i = 1, 2; j = 3 - i. \tag{2}$$

This shows that product market prices are strategic complements as $\partial p_i / \partial p_j = d/(2d+2) > 0$. Clearly strategic complementarity of product prices explains why $\partial p_i / \partial w_i > 0$ and $\partial p_i / \partial w_j > 0$ after solving the reaction functions. Product price differences can be expressed as a function of wholesale price differences:

$$\left(p_j - p_i\right) = \frac{d+1}{3d+2}\left(w_j - w_i\right) \quad i = 1, 2; j = 3 - i. \tag{3}$$

This demonstrates that the buyer that pays the lowest wholesale price also maintains the lowest product price, so that supplier development has strategic value if the resulting cost reductions induce the supplier to drop her wholesale prices. The equilibrium prices and quantities as functions of the supplier's wholesale prices are

$$p_i = \frac{a(3d+2) + (d+1)\left(2(d+1)w_i + dw_j\right)}{(3d+2)(d+2)},$$

$$q_i = \frac{(d+1)\left(a(3d+2) - (d^2+4d+2)w_i + d(d+1)w_j\right)}{(3d+2)(d+2)}$$

$$i = 1, 2; j = 3 - i. \tag{4}$$

In the preceding stage, the supplier determines her wholesale prices by solving $\max_{w_1, w_2} \pi_s = (w_1 - C_1)q_1 + (w_2 - C_2)q_2$. Throughout this paper, the subscript $s$ is used to denote the profits of the supplier. Equilibrium wholesale prices are given by

$$w_i = \frac{1}{2}(a + C_i) \quad i = 1, 2. \tag{5}$$

The expression in (5) shows that the wholesale price charged to buyer $i$ is insensitive to the cost of producing buyer $j$'s components, which is $C_j$. Like in Yoon (2016), the supplier will transfer only a fraction of the cost reductions obtained from the investments, back to the buyer(s). Given the structure of costs $C_i = c - s_i - x_1 - x_2$, we also observe that any possible differences in the wholesale prices offered to the buyers in equilibrium are driven only by differences in specific investments.

Substituting these wholesale prices into the supplier's profit function, we have positive supplier profit margins for supplying buyer $i$ (given by $m_i = w_i - C_i$) only if $a > C_i$. It can be shown that this condition always holds if equilibrium quantities are strictly positive (because of this observation, it is not necessary to a priori set $a > c$, as is commonly done).

## 4.2 | The structure of the portfolio investment

In the second stage, after values for $x_1$ and $x_2$ are fixed, the buyers independently invest in specific supplier development. Buyer $i$'s best response to his rival is given by

$$s_i = \frac{(d+1)(d^2+4d+2)\big((3d+2)(a-c+x_1+x_2) - d(d+1)s_j\big)}{2(3d+2)^2(d+2)^2\sigma - (d+1)(d^2+4d+2)^2}$$
$$i = 1,2; j = 3-i. \tag{6}$$

We can show that the denominator in (6) is positive. Thus, we see that $\partial s_i/\partial s_j < 0$, implying that the specific supplier development levels are strategic substitutes. This reveals the dual role that specific supplier development plays in changing wholesale prices: An increase in $s_j$ will lower $w_j$, as seen from (5), but also (6) shows that it will lower $s_i$, giving a higher value for $w_i$.

Using the superscript $P$ to denote outcomes in the portfolio case, the specific supplier development equilibrium as a function of the first-stage generic supplier development levels is the same for both buyers and is given by

$$s^P(x_1, x_2) = \frac{(d+1)(d^2+4d+2)(a-c+x_1+x_2)}{2(3d+2)(d+2)^2\sigma - (d+1)(d^2+4d+2)}. \tag{7}$$

Notice that always $\partial s^P/\partial x_1 = \partial s^P/\partial x_2 > 0$, which means that any strictly positive investment in generic supplier development raises $s^P$ symmetrically for both firms. We see that generic supplier development reduces wholesale prices in two ways: directly as we saw from (5) but also indirectly via specific supplier development as apparent from (6).

In the first stage, generic supplier development levels are chosen. From the reaction functions (which we do not show here for reasons of space), we can show that $\partial x_i/\partial x_j > 0$, which means that the generic supplier developments are strategic complements. This is in agreement with Gupta (2008), who finds that manufacturers' effort investments are strategic complements for high enough spillover levels.

The generic equilibrium supplier development levels are

$$x^P = \frac{(a-c)V(d,\sigma)}{\gamma W(d,\sigma)^2 - 2V(d,\sigma)}, \tag{8}$$

where $V(d,\sigma) \equiv (d+1)\sigma(2(3d+2)^2(d+2)^2\sigma - (d+1)(d^2+4d+2)^2)$, $W(d,\sigma) \equiv 2(3d+2)(d+2)^2\sigma - (d+1)(d^2+4d+2)$. Note that $s^P$ can be found by setting $x_1 = x_2 = x^P$ and substituting (8) into (7).

We can check that both $s^P$ and $x^P$ are strictly positive in equilibrium, no matter how much the cost of investment is skewed toward either generic or specific supplier development. Despite spillover effects and possibly very high generic supplier development costs, in the equilibrium, we find that there will always be some generic investment.

A comparison between $s^P$ and $x^P$ can now be made. From the literature (e.g., d'Aspremont & Jacquemin, 1988; Qi et al., 2015), we know that spillovers reduce innovative effort. The following proposition shows that this does not generalize to the setting where buyers choose a portfolio of supplier development investment activities.

**Proposition 1.** *If the buyers can invest in both generic and specific supplier development, then there exists a threshold* $\bar{\gamma}^P(d,\sigma) = \sigma v(d,\sigma)$, *where*

$$v(d,\sigma) = \frac{2(d+2)^2(3d+2)^2\sigma - (d+1)(d^2+4d+2)^2}{2(d+2)^2(3d+2)(d^2+4d+2)\sigma - (d+1)(d^2+4d+2)^2} \le 1 \tag{9}$$

*and* $v(d,\sigma)$ *decreasing in* $d$, *such that the generic supplier development level is larger than the specific supplier development level, that is,* $x^P > s^P$, *if* $\gamma < \bar{\gamma}^P(d,\sigma)$, *and* $s^P > x^P$ *if* $\gamma > \bar{\gamma}^P(d,\sigma)$.

Figure 2 illustrates Proposition 1, for different values of $d$. We first note that if the two buyers are monopolists in the product market (i.e., $d = 0$), we have that $v(d,\sigma) = 1$, so that the generic and specific supplier development levels chosen in equilibrium are equal if both types are equally costly (i.e., if $\gamma = \sigma$). This is an interesting result, showing that the two mechanisms at work (noncompeting buyers benefiting from each others' spillovers, while also specific supplier development is raised due to generic supplier development investment) induce the buyers to consider their combined effect, such that the buyers set $x^P = s^P$. When the cost parameters differ, we have that $s^P$ is larger (smaller) than $x^P$ if $\sigma$ is smaller (larger) than $\gamma$.

When $d > 0$, the buyers engage in product market competition. Knowing that $v(d,\sigma)$ is decreasing in $d$, the parameter area where $s^P > x^P$ becomes larger as $d$ increases. Specific supplier development is the preferred mode of investment if $\gamma = \sigma$, and will also be preferred for a range of $\gamma$ values with $\gamma < \sigma$. For example, if $d = 1$ and $\sigma = 1$, $s^P > x^P$ if $\gamma > 88/133$. This indicates the importance of specific supplier development as compared to generic supplier development when the buyers compete, with specific supplier development being a buyer's only means to gain a cost advantage over his rival. For higher competition levels, the buyers' willingness to accept spillovers from generic supplier development is further reduced and the area where generic investment is preferred becomes smaller.

Now, we consider the way that the equilibrium outcomes change with the intensity of the buyers' rivalry.

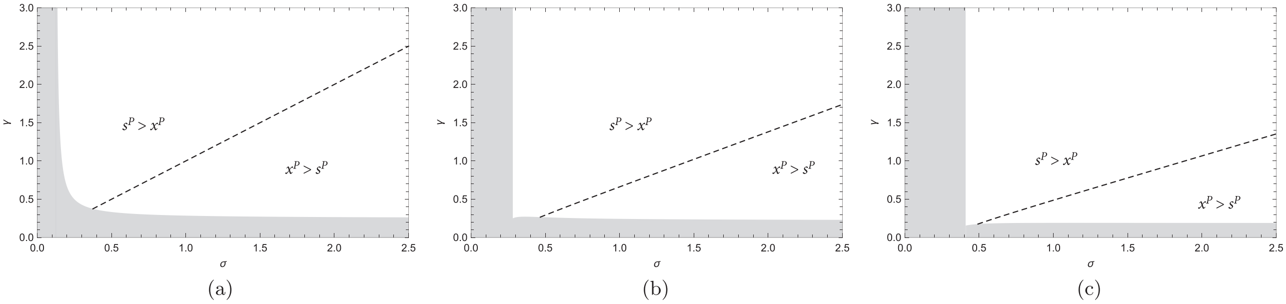


**FIGURE 2** The (dashed) switching curve $\bar{\gamma}^P(d,\sigma)$ on which $x^P = s^P$ for various values of $d$ (note: the gray area is outside the feasible parameter region $\Gamma_P$). (a) $d = 0$. (b) $d = 1$. (c) $d = 2$.

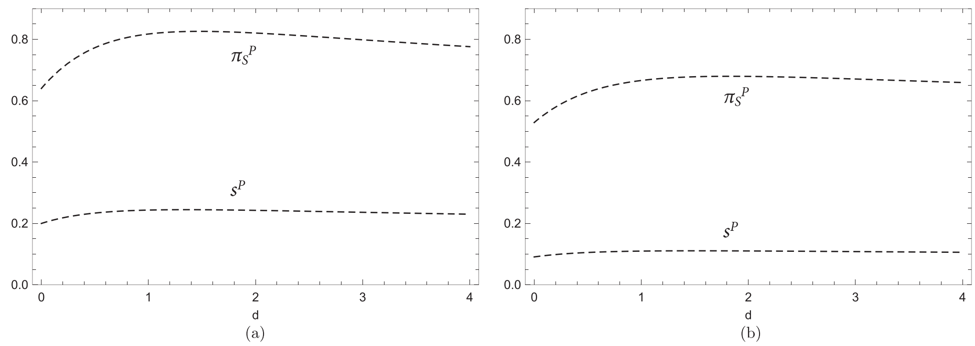


**FIGURE 3** Illustration of Proposition 2 to show how $s^P$ and $\pi_s^P$ change in $d$. (a) $\gamma = 1, \sigma = 1, a - c = 1$. (b) $\gamma = 1, \sigma = 2, a - c = 1$.

**Proposition 2.** *Product market competition has the following effects on the equilibrium outcomes for fixed values of $\gamma$ and $\sigma$:*

- (*i*) *Both the generic supplier development level $x^P$ and the buyer's profit $\pi^P$ always decrease in d;*
- (*ii*) *The specific supplier development level $s^P$ increases in d up to a threshold level $\tilde{d}(\gamma,\sigma)$ and then decreases;*
- (*iii*) *The supplier's profit $\pi_s^P$ increases in d up to a threshold level $\dot{d}(\gamma,\sigma)$ and then decreases.*

That generic supplier development decreases in $d$ is as expected: Increasing $d$ implies a more intense product market rivalry, which makes a buyer become more wary of helping his competitor reduce cost. Also, it can be easily shown that the buyers dislike competition in the absence of supplier development, and this effect remains under the portfolio investment regime. So buyer profits always decrease in $d$.

It is more surprising that the signs of $\partial s^P/\partial d$ and $\partial \pi_s^P/\partial d$ can be positive or negative. Figure 3 illustrates how $s^P$ and $\pi_s^P$ change in $d$ for varying levels of $\gamma$ and $\sigma$. This mixed behavior arises from the contrasting effect of generic and specific supplier development. In general, increasing levels of competition leads to increasing specific investment as this is the only way that a buyer can differentiate himself from a rival. However, there is a counteracting effect from the lower generic supplier development levels we have established in part (i), since this depresses the specific supplier development levels as we observed earlier. It turns out that this effect dominates as $d$ becomes larger.

The change in the supplier development levels leads to a change in supplier profits, which begin by increasing with $d$, before switching to decrease. In fact, the supplier benefits from competition, not only from increased specific investment, but also because competition leads to lower prices in the product market and higher volumes. So from the supplier's perspective, there is an ideal amount of product competition that maximizes supplier profit. In fact, we can show that this ideal point may be at a level of $d$ where the buyers' specific supplier development levels have already started to decrease.

An extended analysis with $\gamma_i \neq \gamma_j$ shows that the results of Propositions 1 and 2 are not driven by the fact that the buyers are symmetric. We can show that $x_i^{PA} > s_i^{PA}$ if $\gamma_i < \bar{\gamma}^P(d,\sigma)$, and $s_i^{PA} > x_i^{PA}$ if $\gamma_i > \bar{\gamma}^P(d,\sigma)$. Here, the added superscript $A$ denotes outcomes in the asymmetric setup. It is interesting to note that the comparison of $s_i^{PA}$ and $x_i^{PA}$ depends only on $\gamma_i$ and not on $\gamma_j$.

We can also analyze the relationships between the supplier development levels and profits for the two buyers in this asymmetric case, and we obtain the following proposition:

**Proposition 3.** *When buyer i is more capable than buyer j to make generic investments, that is, $\gamma_j > \gamma_i$, then in equilibrium,*

(*i*) *the generic supplier development level of buyer i is larger than that of buyer j, that is,* $x_i^{PA} > x_j^{PA}$*;*
(*ii*) *the profits of buyer i are smaller than the profits of buyer j, that is,* $\pi_j^{PA} > \pi_i^{PA}$.

The effect of asymmetric $\gamma$s on generic supplier development levels is straightforward: The buyer with the highest generic investment capability chooses the highest level of generic supplier development. The second part of the result, that the more capable buyer is always worse off than his rival, is interesting. This result is driven by the fact that $s_i^{PA} = s_j^{PA}$ in equilibrium, regardless of the size and differences of $x_i^{PA}$ and $x_j^{PA}$. This means that $w_i^{PA} = w_j^{PA}$, and, consequently, that the buyers choose the same product prices and produce equal amounts. Therefore, any profit differences depend only on the differences in the cost of generic supplier development investment, given by $\gamma_i(x_i^{PA})^2/2$. We can show that the most capable buyer (who has the lowest $\gamma$ but sets the highest generic supplier development level) always bears the highest investment cost, and the result in Proposition 3.ii follows.

## 4.3 | The impact of generic investment

We have seen how the portfolio investment situation, in which both types of investment are possible, will lead to both types of investment being made in equilibrium. However, this does not answer the question as to whether restricting investment to only one type might be beneficial if both buyers were to commit to this in advance. In practice, many buyers treat specific supplier development as the instrument of choice in trying to gain a cost advantage over rival buyers while other buyers resort to generic supplier development, which is why we investigate whether buyers who only invest in specific supplier investment have any incentive to introduce generic investment. Proposition 4 shows that it is never beneficial for the buyers to restrict investment to specific supplier development, nor is it beneficial for the supplier for this restriction to be in place (we use the superscript $S$ for outcomes in the case with specific supplier development investment only):

**Proposition 4.** *Introducing generic supplier development in addition to specific supplier development has the following effects:*

(*i*) *The specific supplier development level always increases, that is,* $s^P > s^S$*;*
(*ii*) *The buyer's profit always increases, that is,* $\pi^P > \pi^S$*;*
(*iii*) *The supplier's profit always increases, that is,* $\pi_s^P > \pi_s^S$.

Comparing $s^P$ and $s^S$ can be done by a direct inspection of (7), where $s^S$ can be found by setting $x_1 = 0$ and $x_2 = 0$. In equilibrium, $x^P$ is always strictly positive, so that the buyer would always raise $s^P$ beyond $s^S$. Generic supplier development lowers the buyers' purchasing costs symmetrically, allowing for a further increase of specific supplier development investment. This insight also makes for a stronger intuition with respect to the comparison of $\pi^P$ and $\pi^S$. The buyers may always set $x^P = 0$ so that $\pi^P = \pi^S$, while any $x^P > 0$ is chosen only if it allows the buyers to profitably balance the upsides and downsides of both investment types. The supplier also prefers the buyers to invest in a portfolio of supplier development types. After wholesale prices are set, the supplier's profits can be written in a general form as

$$\pi_s^{(\cdot)} = \left(\frac{d+1}{2(d+2)}\right)(a - c + 2x + s), \tag{10}$$

where $x \geq 0$ and $s \geq 0$, depending on which of the cases is considered. Clearly, the supplier would never reject any supplier development investment entirely. Knowing that $s^P > s^S$, while the supplier also benefits from the buyers' investments into generic supplier development (as always $x^P > 0$), the supplier will therefore always fare better if a portfolio of supplier development types is used.

We can revisit the results given in Proposition 4 to see whether these change when the buyers are asymmetric in their generic investment capabilities. It turns out that all the results of this proposition continue to hold in this asymmetric case.

## 4.4 | The impact of specific investment

The previous subsection showed that it is always beneficial for the supply chain actors to invest in generic supplier development as well as specific supplier development, while the resulting portfolio displays positive generic investments and increased levels of specific investments. In this section, we carry out a similar analysis, but now considering a situation in which the buyers choose to restrict themselves to generic investments only. We have seen how some companies such as Honda take a particularly favorable stance toward generic investments. We will show that if the product market competition is high enough, it will be beneficial for both the buyers to commit to only making generic investments. Recall we use the superscript $G$ to indicate outcomes in the case with generic supplier development investment only.

**Proposition 5.** *Let* $\bar{d}(\sigma)$ *be the increasing function of* $\sigma$ *defined by*

$$(\bar{d} + 1)(\bar{d}^2 + 4\bar{d} + 2) = 2\sigma(\bar{d} + 2)^2(-\bar{d}^2 + 2\bar{d} + 2). \tag{11}$$

(*i*) *If* $d < \bar{d}(\sigma)$*, then introducing specific investments in addition to generic investments raises generic supplier development levels and the buyer's profit, that is,* $x^P > x^G$ *and* $\pi^P > \pi^G$*; and if* $d > \bar{d}(\sigma)$*, then the reverse holds, that is,* $x^P < x^G$ *and* $\pi^P < \pi^G$*;*
(*ii*) *There is a switching curve* $\bar{\gamma}^{GP}(d, \sigma)$ *such that introducing specific investments in addition to generic*

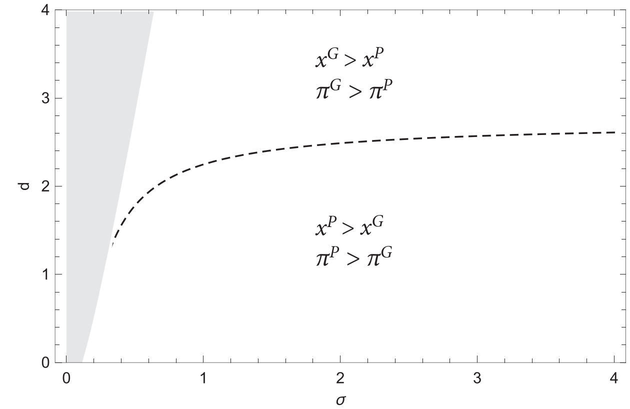


**FIGURE 4** The (dashed) switching curve $\bar{d}(\sigma)$ on which $x^P = x^G$ and $\pi^P = \pi^G$; note the gray area is not part of the feasible parameter region $\Gamma_G \cap \Gamma_P$.

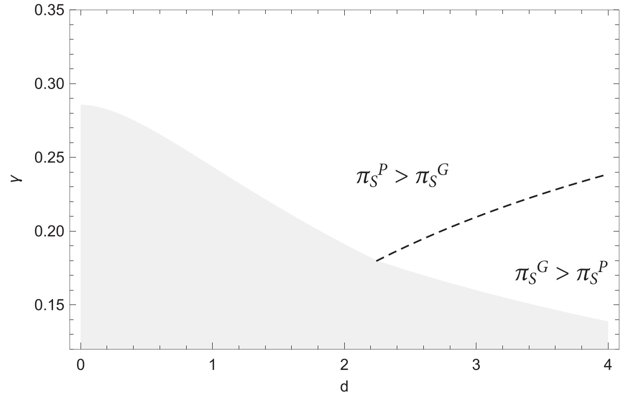


**FIGURE 5** The (dashed) switching curve $\bar{\gamma}^{GP}(d)$ on which $\pi_s^P = \pi_s^G$ for $\sigma = 1$; note that the gray area is not part of the feasible parameter region $\Gamma_G \cap \Gamma_P$.

*investments reduces the supplier's profits, that is, $\pi_s^P < \pi_s^G$ if and only if $d > \bar{d}(\sigma)$ and $\gamma < \bar{\gamma}^{GP}(d, \sigma)$.*

The effect of specific supplier development on generic supplier development can be demonstrated by comparing $x^P$ and $x^G$. The comparison is independent of $\gamma$, and is determined by the amount of product competition $d$ compared to the switching curve $\bar{d}(\sigma)$. This is shown in Figure 4. For small enough levels of competitive intensity (i.e., $d < (1 + \sqrt{17})/4$), the presence of specific investments leads to an increase in generic investments, $x^P > x^G$, regardless of the size $\sigma$. For higher levels of competition, that is, $(1 + \sqrt{17})/4 < d < 1 + \sqrt{3}$, this effect occurs only if $\sigma$ is high enough. For even higher levels of competition, $d > 1 + \sqrt{3}$, the buyers always choose $x^P$ less than $x^G$. The intuition here is that even though generic investments are generally beneficial to the buyers, they also serve as an instrument to control specific investments, as seen from (7). Apparently for large enough levels of competition, possibly in combination with high enough specific investment capability, the buyers prefer to reduce their generic investments to dampen specific supplier development.

Proposition 5.i also considers the buyers' profit. Interestingly, for those parameters where $x^P > x^G$, we also have that $\pi^P > \pi^G$. And, conversely, for higher levels of competition and low enough levels of $\sigma$ where $x^P < x^G$, it is better for the buyers to exclude specific investments from their investment portfolio, if they can commit to this in advance.

It is easier for the supplier to enforce a restriction on the types of investment that she will allow from buyers. This makes the second part of Proposition 5 of interest, since it shows that for $d > \bar{d}(\sigma)$ and given that buyers are sufficiently capable in generic investment, there is an advantage for the supplier in committing not to accept specific supplier development. According to the proposition, this depends on the size of $\gamma$ in comparison to the switching curve $\gamma = \bar{\gamma}^{GP}(d, \sigma)$. To illustrate this, Figure 5 shows $\bar{\gamma}^{GP}(d, \sigma)$ in the case that $\sigma = 1$. An important conclusion from Proposition 5.i and 5.ii is that the interests of the buyers and supplier in terms of the inclusion of specific investments in the investment portfolio may not be aligned when $d > \bar{d}(\sigma)$.

Finally, similar to the previous analysis, we can consider $\gamma_i \neq \gamma_j$ and analyze the implications for the results given in Proposition 5. Before doing so, we note that here with only generic investments, something similar happens to the case we saw in Proposition 3 and the most capable buyer sets the highest generic supplier development levels, yet suffers a profit loss compared to his less capable rival. Writing a superscript *GA* for the asymmetric case with only generic supplier development, we can show that $x_i^{PA} > x_i^{GA}$ under the same conditions as in Proposition 5. This is easy to understand as even though capability differences affect the level of supplier development of one buyer compared to his rival, for a single buyer, this does not alter the relative difference between his generic supplier development levels in the presence or absence of specific investments. It is also true that $\pi_i^{PA} > \pi_i^{GA}$ under the same conditions as Proposition 5. That is, for those parameters where $x_i^{PA}$ surpasses $x_i^{GA}$, buyer profits $\pi_i^{PA}$ are consistently larger than $\pi_i^{GA}$. The analysis is more complicated for supplier profits, though numerical analyses show that similar behaviors are observed. Notice that since there are two different values for $\gamma$, we cannot have a single switching curve. As an example, we can show that with $\gamma_1 = 1$, $d = 3$, and $\sigma = 1$, then $\pi_s^{GA} > \pi_s^{PA}$ if $\gamma_2 < 0.1171$.

## 4.5 | The buyers' prisoner's dilemma

We complete our analysis by considering the possibility that buyer profits are highest if both buyers can commit to not investing at all. Investment commitment games such as these can yield this type of prisoner's dilemma for the investing party. The following proposition identifies the parameters for which this may occur, using $\pi^0$ to denote a buyer's equilibrium profits if the buyers do not invest.

**Proposition 6.** *Comparisons of buyer profits with no investment at all, $\pi^0$, to buyer profits under the investment regimes of generic investment only, $\pi^G$, specific investment only, $\pi^S$, or portfolio investment, $\pi^P$, are as follows:*

- (*i*) *Investment in generic supplier development only is always better for the buyer's profit than no investment at all, that is, $\pi^G > \pi^0$;*
- (*ii*) *If $d < \bar{d}(\sigma)$, investment in specific supplier development only is better for the buyer's profit than no investment at all, that is, $\pi^S > \pi^0$, and if $d > \bar{d}(\sigma)$, then the reverse holds, that is, $\pi^0 > \pi^S$;*
- (*iii*) *There is a switching curve $\bar{\gamma}^{P0}(d, \sigma)$ such that no investment at all is better for the buyer's profit than making portfolio investments, that is, $\pi^0 > \pi^P$, if and only if $d > \bar{d}(\sigma)$ and $\gamma > \bar{\gamma}^{P0}(d, \sigma)$.*

From Proposition 6.i, we see that if the buyers can commit to making generic investments only, then this is always preferable to not investing at all. The supplier development spillovers yield symmetric wholesale price reductions from which both buyers always benefit.

The situation is different for the buyers if only supplier-specific investment options are available (Proposition 6.ii). Given $\sigma$, for small enough levels of competition, the buyers refrain from overinvesting in specific supplier development, making them always better off if positive investments are made. Notice that the choice of $d$ at which $\pi^0 > \pi^S$ is exactly the point at which we already observed in Proposition 5 that buyers prefer excluding specific supplier development from the investment portfolio. For these parameter values, Proposition 6.ii shows that if the buyers' only choice is to invest in specific supplier development, they would rather commit to not investing at all.

Finally, according to Proposition 6.iii, a prisoner's dilemma can also occur when the buyers invest in a portfolio of supplier development types. The switching curve $\bar{\gamma}^{P0}(d, \sigma)$ (which is defined in the Appendix) that determines where this may occur only exists in the part of the feasible parameter region where $d > \bar{d}(\sigma)$. As seen from Proposition 6.ii, when $d > \bar{d}(\sigma)$, a prisoner's dilemma exists if the buyers commit to investing in specific supplier development only. Proposition 6.iii extends this logic when investment involves a portfolio of supplier development types, but whether or not the buyers face a prisoner's dilemma additionally depends on $\gamma$. In particular, for high enough $\gamma$, generic supplier development cannot be used effectively to flatten competition, such that having an investment portfolio is worse for the buyers than not investing at all. Managerially, it is important to observe from Proposition 6 that particularly those investments into specific supplier development (exclusively or as part of an investment portfolio) can make the buyers worse off, while generic investments alone do not.

# 5 | CONCLUSION

In many manufacturing industries, a buyer will invest in supplier development to reduce the supplier's production cost. At the same time, the cost reduction resulting from such investments often spill over to competitors that source from the same (shared) supplier. Buyers should make careful decisions about the nature of their supplier development activities and proactively manage these spillovers. Though there is a wealth of evidence that in practice buyers' stance toward supplier development spillovers differs significantly, the literature has largely treated such spillover as an exogenous phenomenon. We argue differently and let the spillovers generated from supplier development investments be a choice of the buyer. We do so by explicitly differentiating between specific and generic supplier development. A buyer's investment in specific supplier development yields benefits unique to the relationship, while an investment in generic supplier development benefits a buyer's rival equally. We constructed a simple model and investigate a buyer's equilibrium portfolio decisions under different levels of competition and investment capabilities. Moreover, we assess the effectiveness of incorporating generic and specific investments into the buyers' investment portfolio.

Several conclusions can be drawn from our analysis. We first observe that buyers make strictly positive generic investments, although specific investment is the buyers' main focus as competitive intensity increases if the buyers' investment capabilities are not too far apart. Buyer asymmetry in terms of differing generic investment capability does not fundamentally alter this result, though this does yield a remarkable outcome for the buyers, with the least capable buyer earning more than his more capable competitor. Thus, the spillovers resulting from generic supplier development persist even if the least capable buyer free-rides on his capable rival. We also conclude that while the buyers should always invest in generic supplier development, this may not hold for specific investments. Specific investments turn out to make competition particularly fierce. This may not be a concern for the buyers when specific investments are embedded in a portfolio of investments, as the buyers are able to establish a proper balance between them. Yet, a focus on specific investments alone may trap the buyers into a prisoner's dilemma, with committing to no investment at all or generic investment only clearly being the preferred option. Finally, we conclude that the buyers' preferences may be different from those of the supplier. That is, for those parameters where the buyers prefer excluding specific investment from their portfolio (if they can commit to doing so), the supplier's preference may be to keep them. While the buyers' concern may be not to overinvest in specific supplier development to keep competition in check, the supplier actually benefits from intense rivalry. Managerially, these and other insights suggest that the buyers' investment capabilities and level of competition present in the product market are important driving forces of supplier development levels, and the resulting buyer and supplier profits. For many companies, it is crucial to recognize that the spillovers resulting from supplier development are beneficial for them, and that the use of a supplier development portfolio can enhance their profits, compared to restricting their attention to one supplier development type only.

Several future research opportunities exist. The model could incorporate a supplier's efforts as a determinant of the success of supplier development endeavors. Those efforts may not be observable by the buyers (as in Iyer et al., 2005). It is expected that this will lead to increased generic supplier development investments while specific supplier development investments are likely to drop. Also, our model relies on cost reduction as the main result of buyers' investments. It is important for supplier development research to also focus on sustainability outcomes , while in such a context, it is likely that the mechanisms and preferences for generic and specific supplier development change. Our model can be adapted to cater for this, for instance, by incorporating the demand effects of a product's sustainability features, cost effects at the product level, alternative investment cost functions (e.g., fixed instead of quadratic cost), and contractual mechanisms that ensure that the supplier manufactures a sustainable product.

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## ENDNOTES

[1] We have analyzed the outcomes of a three-stage model in which buyers make both generic and specific investments at the same time. The main results of the paper continue to hold under this alternative model specification, with one notable exception. According to Proposition 5.i, there is a switching curve (illustrated in Figure 4) showing that for certain parameters, a buyer's generic supplier development level may be higher in the absence of specific investments than it is in the portfolio case (specifically, given a buyer's specific investment capability ($\sigma$), we see that $x^G > x^P$ for large enough competitive intensity $d$). This is driven by the effect of generic supplier development on the specific supplier development decisions, as evidenced by Equation (7). In the three-stage setup, in contrast, we always have that $x^P > x^G$. This shows that if competition is intense, the buyer's concern to lower generic investments when specific investments are present has vanished, since the simultaneous choices of specific and generic investments allow him to better balance the spillover benefits from generic investments with his specific investments that intensify product market competition.

[2] Nevertheless, there is a stream of literature that considers unobservable wholesale prices or, more generally, unobservable contract terms. In this case, we may still assume that the players determine the actions that match the usual equilibrium. However, the supply chain actors may also gain an advantage by behaving differently. This leads to different possible equilibrium concepts, centered around the different types of beliefs a downstream supply chain actor may hold with respect to the rival's contract terms (e.g., McAfee & Schwartz, 1994). Applications in the operations management context mostly rely on passive beliefs, suggesting that when a buyer receives an unexpected offer off the equilibrium path, it does not revise his beliefs about the offer made to the rival (e.g., see Arya & Mittendorf, 2013; Li & Liu, 2021). Throughout this paper, we assume the buyer has full information on his rival's contract terms, though we have results to show that the paper's main findings do not change qualitatively under passive beliefs.

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## APPENDIX A: CONDITIONS PER CASE

We consider the sufficient second-order conditions, positivity conditions of the equilibrium outcomes (where necessary), and stability conditions. An equilibrium is considered stable if at a small deviation of a player's decision around the equilibrium, the other players' response would be such that eventually all players' decisions would converge back to the original equilibrium. Stability in the multivariable case requires that the eigenvalues of the Jacobian matrix are negative, or have negative real parts.

For all cases, in the last stage of the game, we have $\frac{\partial^2 \pi_i}{\partial p_i^2} = 2(-1-d) < 0$. Product prices are positive for $w_1 \geq 0$ and $w_2 \geq 0$. Stability conditions in this stage are satisfied, as the eigenvalues are given by $-3d-2<0$ and $-d-2<0$.

In the supplier's pricing stage, the supplier chooses wholesale prices $w_1$ and $w_2$. The conditions for a negative definite Hessian matrix $H$ are satisfied if the determinant of the Hessian matrix is positive and the second derivatives are negative. We have $\frac{\partial^2 \pi_s}{\partial w_i^2} = -\frac{2(d+1)(d^2+4d+2)}{(d+2)(3d+2)} < 0$, $i=1,2$. We also have $\frac{\partial^2 \pi_s}{\partial w_i \partial w_j} = \frac{2d(d+1)^2}{(d+2)(3d+2)} > 0$. Finally $\det H = \frac{4(d+1)^2(2d+1)}{(d+2)(3d+2)} > 0$. Clearly, wholesale prices are positive for any $C_i \geq 0$, $i=1,2$.

In Case S, which is the case without generic investments, and Case P, which is the case with portfolio investments, specific supplier development levels $s_1$ and $s_2$ are chosen before wholesale prices are set. For each buyer, the sufficient second-order condition, given by $\frac{\partial^2 \pi_i}{\partial s_i^2} < 0$, $i=1,2$, is satisfied if $\sigma > \frac{(d+1)(d^2+4d+2)^2}{2(d+2)^2(3d+2)^2}$. The cross-partial derivative is $\frac{\partial^2 \pi_i}{\partial s_i \partial s_j} = -\frac{d(d+1)^2(d^2+4d+2)}{2(d+2)^2(3d+2)^2}$. The Jacobian matrix is given by

$$J = \begin{pmatrix} \frac{\partial^2 \pi_i}{\partial s_i^2} & \frac{\partial^2 \pi_i}{\partial s_i \partial s_j} \\ \frac{\partial^2 \pi_j}{\partial s_j \partial s_i} & \frac{\partial^2 \pi_j}{\partial s_j^2} \end{pmatrix}, \tag{A.1}$$

for $i=1,2; j=3-i$. Eigenvalues are given by $\frac{(d+1)(2d+1)(d^2+4d+2)}{2(d+2)(3d+2)^2} - \sigma$ and $\frac{(d+1)(d^2+4d+2)}{2(d+2)^2(3d+2)} - \sigma$, from which the conditions for negative eigenvalues can be easily obtained. We can now check that the strictest condition is

$$\sigma > \frac{(d+1)(2d+1)(d^2+4d+2)}{2(d+2)(3d+2)^2}. \tag{A.2}$$

This condition satisfies the second-stage sufficient second-order condition $\sigma > \frac{(d+1)(d^2+4d+2)^2}{2(d+2)^2(3d+2)^2}$.

The conditions in the first stage of Case G and Case P differ. In Case G, the sufficient second-order condition is satisfied if $\gamma > \frac{d+1}{2(d+2)^2}$ while one of the eigenvalues is positive only if

$$\gamma > \frac{d+1}{(d+2)^2}. \tag{A.3}$$

It is clear that the latter is dominant, and ensures that $x^G > 0$.

In Case P, we obtain from the sufficient second-order condition $\frac{\partial^2 \pi_i}{\partial x_i^2} < 0$ that

$$\gamma > \frac{(d+1)\sigma\left(2(d+2)^2(3d+2)^2\sigma - (d+1)(d^2+4d+2)^2\right)}{\left((d+1)(d^2+4d+2) - 2(d+2)^2(3d+2)\sigma\right)^2}. \tag{A.4}$$

Clearly the numerator is strictly positive due to (A.2). The stability condition is obtained in the usual way and is

$$\gamma > \frac{2(d+1)\sigma\left(2(3d+2)^2(d+2)^2\sigma - (d+1)(d^2+4d+2)^2\right)}{\left(2(3d+2)(d+2)^2\sigma - (d+1)(d^2+4d+2)\right)^2}, \tag{A.5}$$

with a right-hand side (RHS) twice that of (A.4). Note that this can be written as $\gamma > \frac{2V}{W^2}$, where

$$V(d,\sigma) = (d+1)\sigma\left(2(3d+2)^2(d+2)^2\sigma - (d+1)(d^2+4d+2)^2\right),$$

$$W(d,\sigma) = 2(3d+2)(d+2)^2\sigma - (d+1)(d^2+4d+2). \tag{A.6}$$

It is straightforward to check that $V(d,\sigma) > 0$ and $W(d,\sigma) > 0$ if (A.2) holds. Also it follows from (8) that $x^P > 0$.

$$\frac{\partial \pi^P}{\partial d} = \frac{\gamma^3 d(d+2)^2\sigma^2 W^3\left(2(d+2)(3d+2)^3\sigma - d(d+1)(d(11d+16)+6)\right)(a-c)^2}{\left(\gamma W^2 - 2V\right)^3}. \tag{B.2}$$

Based on these considerations, we have the feasible parameter region $\Gamma_G$ given by (A.3), $\Gamma_S$ given by (A.2), and $\Gamma_P$ given by (A.2) and (A.5).

What remains are the conditions under which $C_i \geq 0$. We have $C_1^P = C_2^P = C^P$ and define $C^P = c - 2x^P - s^P$. Solving $C^P = 0$ for $a$ yields a solution in $c$, $d$, $\gamma$, and $\sigma$. We can rewrite the solution such that $\frac{a}{c} = f(d,\gamma,\sigma)$. It can verified that $f(d,\gamma,\sigma) = 1$ at the boundary of $\Gamma_P$, given by (A.5) with the equality sign. Within $\Gamma_P$, we always have $f(d,\gamma,\sigma) > 1$. It can be checked that $C^P > 0$ if $\frac{a}{c} < f(d,\gamma,\sigma)$. Knowing that we require $a > c$ and $f(d,\gamma,\sigma) > 1$, it follows that given any $c$, there always exists a small enough $a$ such that $C^P > 0$. A similar analysis can be made for the other cases.

## APPENDIX B: PROOFS

*Proof of Proposition* 1. Solving $x^P = s^P$ yields the solution $\gamma = \bar{\gamma}^P(d,\sigma) \equiv \frac{V}{(d+1)(d^2+4d+2)W}$, where $V$ and $W$ have been defined above. Then, $\bar{\gamma}^P(d,\sigma) = \sigma v(d,\sigma)$, where

$$v(d,\sigma) = \frac{2(d+2)^2(3d+2)^2\sigma - (d+1)(d^2+4d+2)^2}{2(d+2)^2(3d+2)(d^2+4d+2)\sigma - (d+1)(d^2+4d+2)^2}. \tag{B.1}$$

It is straightforward to check that $v(d,\sigma)$ is decreasing in $d$.

The function $\bar{\gamma}^P(d,\sigma)$ exists in $\Gamma_P$ if (A.2) holds, as $\bar{\gamma}^P(d,\sigma) > \frac{2V}{W^2}$, which is the RHS of (A.5). Having $\bar{\gamma}^P(d,\sigma)$ in $\Gamma_P$ implies that there are parameters for which $x^P > s^P$, while for others the reverse holds. From the inequalities, the result stated in the proposition follows. □

*Proof of Proposition* 2. We have $\frac{\partial x^P}{\partial d} = 0$ if $\sigma = \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(3d+2)}$ and $\sigma = \frac{d(d+1)(11d^2+16d+6)}{2(d+2)(3d+2)^3}$. A comparison with the lower boundary of $\sigma$, given in (A.2), shows that these solutions do not cross $\Gamma_P$. Therefore, the derivative does not switch sign in $\Gamma_P$. Any combination of parameters in $\Gamma_P$ can now be used to verify that $\frac{\partial x^P}{\partial d} < 0$. We also have

We know from (A.5) that the denominator of this expression is strictly positive. Setting the numerator to zero and solving for $\sigma$ yields four solutions. It is straightforward to see that none of these solutions are in $\Gamma_P$, which means that the derivative does not change sign in $\Gamma_P$. The result that $\frac{\partial \pi^P}{\partial d}$ is always negative is now easy to obtain.

We will define the $d$ value maximizing $s^P$ as the function $\tilde{d}(\gamma,\sigma)$, which solves $\frac{\partial s^P}{\partial d} = 0$. Thus, we deduce that $\tilde{d}(\gamma,\sigma)$ solves the following equation, which we have rewritten in terms of $\gamma$,

$$\gamma = \tilde{\gamma}^P(d,\sigma) \equiv \frac{4(d+1)^2\sigma\big((d+1)^2(d^2+4d+2)(5d^3+10d^2+10d+4)-(d+2)^3(3d+2)^2(3d^2+4d+2)\sigma\big)}{(d^3-6d^2-10d-4)W^2}. \tag{B.3}$$

This solution is in $\Gamma_P$. For $\gamma > \tilde{\gamma}^P(d,\sigma)$, $\frac{\partial s^P}{\partial d} > 0$, and for $\frac{2V}{W^2} < \gamma < \tilde{\gamma}^P(d,\sigma)$, $\frac{\partial s^P}{\partial d} < 0$, where $\frac{2V}{W^2}$ is the RHS of (A.5). Equivalently for $d < \tilde{d}(\gamma,\sigma)$, $\frac{\partial s^P}{\partial d} > 0$ while for $d > \tilde{d}(\gamma,\sigma)$, $\frac{\partial s^P}{\partial d} < 0$. We also have that the term $d^3-6d^2-10d-4$ in the denominator of $\tilde{\gamma}^P(d,\sigma)$ may incur a sign switch. That is, for any $d > \frac{1}{3}(\sqrt[3]{6(\sqrt{114}+90)} + \sqrt[3]{540-6\sqrt{114}}+6) \approx 7.4203$, we have that $\tilde{\gamma}^P(d,\sigma)$ is negative regardless of the size of $\gamma$ and $\sigma$, in which case, $\tilde{\gamma}^P(d,\sigma)$ is outside $\Gamma_P$ while we conclude that $\frac{\partial s^P}{\partial d} < 0$.

Finally, solving $\frac{\partial \pi_s^P}{\partial d} = 0$ yields the single closed-form solution $\dot{\gamma}^P(d,\sigma)$ (not shown here to save space), which is in $\Gamma_P$. For any parameters in $\Gamma_P$ and $\gamma > \dot{\gamma}^P(d,\sigma)$, we have $\frac{\partial \pi_s^P}{\partial d} > 0$, while for $\gamma < \dot{\gamma}^P(d,\sigma)$, the reverse holds. We can equivalently obtain the function $\dot{d}(\gamma,\sigma)$ that solves $\frac{\partial \pi_s^P}{\partial d} = 0$. Accordingly, for $d < \dot{d}(\gamma,\sigma)$, $\frac{\partial \pi_s^P}{\partial d} > 0$, while for $d > \dot{d}(\gamma,\sigma)$, $\frac{\partial \pi_s^P}{\partial d} < 0$. □

*Proof of Proposition* 3. We first note that using the methods applied in Appendix A, the feasible parameter region $\Gamma_{PA}$ is given by (A.2) and $\gamma_j > \frac{\gamma_i V}{\gamma_i W^2 - V}$, $i = 1,2; j = 3-i$. Note that the latter inequality converts to (A.5) for $\gamma_j = \gamma_i = \gamma$. Equilibrium outcomes are

$$s_i^{PA} = \frac{(d+1)(d^2+4d+2)\gamma_i\gamma_j W(a-c)}{\gamma_i\gamma_j W^2 - \gamma_i V - \gamma_j V},$$
$$x_i^{PA} = \frac{\gamma_j V(a-c)}{\gamma_i\gamma_j W^2 - \gamma_i V - \gamma_j V} \quad i=1,2; j=3-i. \tag{B.4}$$

It is easy to see that $x_i^{PA} > x_j^{PA}$ if $\gamma_j > \gamma_i$.

Finally, we can express the profits of buyer $i$ as

$$\pi_i^{PA} = \frac{(\gamma_i^2\gamma_j^2 VW^2 - \gamma_i\gamma_j^2 V^2)(a-c)^2}{2(\gamma_i\gamma_j W^2 - \gamma_i V - \gamma_j V)^2} \quad i=1,2; j=3-i. \tag{B.5}$$

From this expression, it follows that $\pi_j^{PA} > \pi_i^{PA}$ if $\gamma_j > \gamma_i$.

Furthermore, solving $s_i^{PA} = x_i^{PA}$ yields the solution $\gamma_i = \bar{\gamma}^P(d,\sigma)$. The main result follows in a way similar to Proposition 1. □

*Proof of Proposition* 4. The proof that the inequality $s^P > s^S$ always holds is straightforward from a direct inspection of (7), knowing that $x^P > 0$ in equilibrium.

Solving $\pi^P = \pi^S$ yields the solutions

$$\sigma = \frac{(d+1)(d^2+4d+2)^2}{2(d+2)^2(3d+2)^2},$$
$$\gamma = \frac{4(d+1)\sigma\big(2(d+2)^2(3d+2)^2\sigma - (d+1)(d^2+4d+2)^2\big)}{3((d+1)(d^2+4d+2) - 2(d+2)^2(3d+2)\sigma)^2}. \tag{B.6}$$

These expressions are dominated by the inequalities (A.2) and (A.5), respectively, so that the solutions to $\pi^P = \pi^S$ do not imply any change of sign for $\pi^P - \pi^S$ in the parameter region where (A.2) and (A.5) hold. We can then check the inequality anywhere in this region to obtain the result stated in the proposition.

The same approach can be used for supplier profits. Solving $\pi_s^P = \pi_s^S$ yields the solutions

$$\sigma = \frac{(d+1)(d^2+4d+2)^2}{2(d+2)^2(3d+2)^2},$$
$$\gamma = \frac{(d+1)\sigma\big(2(d+2)^2(3d+2)^2\sigma - (d+1)(d^2+4d+2)^2\big)}{((d+1)(d^2+4d+2) - 2(d+2)^2(3d+2)\sigma)^2}. \tag{B.7}$$

The $(\gamma,\sigma)$ pair is not in $\Gamma_S$ or $\Gamma_P$. The result from the proposition follows straightforwardly. □

*Proof of Proposition* 5. Solving $x^P = x^G$ yields the equation $(d+1)(d^2+4d+2) = 2\sigma(d+2)^2(-d^2+2d+2)$ determining $\bar{d}(\sigma)$. We can rewrite this to give $\sigma$ in terms of $d$: $\sigma = \bar{\sigma}(d) \equiv \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$. The proof is simpler working with $\bar{\sigma}(d)$ rather than $\bar{d}(\sigma)$.

It is easy to verify that $\bar{\sigma}(d)$ is positive only for $d < 1+\sqrt{3}$. Also $\bar{\sigma}(d) > \frac{(d+1)(2d+1)(d^2+4d+2)}{2(d+2)(3d+2)^2}$, which is the boundary of $\Gamma_P$ given in (A.2), if $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$. The result follows that $x^P > x^G$ for $d < (1+\sqrt{17})/4$, $x^P > x^G$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma > \bar{\sigma}(d)$, $x^P < x^G$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma < \bar{\sigma}(d)$, $x^P < x^G$ for $d > 1+\sqrt{3}$.

Solving $\pi^P = \pi^G$ yields the solutions $\sigma = \bar{\sigma}(d)$ and

$$\gamma = \hat{\gamma}(d,\sigma) \equiv \frac{(d+1)\big(8(3d+2)^2(d+2)^4\sigma^2 - 2(d+1)(d^2+4d+2)(d^2+10d+6)(d+2)^2\sigma + (d+1)^2(d^2+4d+2)^2\big)}{2(d+2)^2\big(2(d+2)^2(3d+2)\sigma-(d+1)(d^2+4d+2)\big)^2}. \tag{B.8}$$

It is important to note that the relevant parameter regions given by (A.3) and (A.5) overlap, while (A.2) should also hold. This means we should consider $\Gamma_G \cap \Gamma_P$ as the resulting feasible parameter region. In particular, the RHS of (A.3) and (A.5) cross at $\bar{\sigma}(d)$. As noted earlier, $\bar{\sigma}(d) > \frac{(d+1)(2d+1)(d^2+4d+2)}{2(d+2)(3d+2)^2}$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$. We see that (A.3) imposes a stronger condition than (A.5) if $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma < \bar{\sigma}$ and also if $d > 1+\sqrt{3}$. Otherwise (A.5) is a stronger condition than (A.3).

We now consider the $\gamma$ and $\sigma$ values at $\pi^P = \pi^G$. The solution $\sigma = \bar{\sigma}(d)$ does impose a sign change. That is, for any given $\gamma$ in $\Gamma_G \cap \Gamma_P$, we have $\pi^P > \pi^G$ for $0 \le d < (1+\sqrt{17})/4$, $\pi^P > \pi^G$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma > \bar{\sigma}(d)$, $\pi^P < \pi^G$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma < \bar{\sigma}(d)$, $\pi^P < \pi^G$ for $d > 1+\sqrt{3}$. The function $\hat{\gamma}(d,\sigma)$ never crosses $\Gamma_G \cap \Gamma_P$, so that it does not impose a sign change.

Solving $\pi_s^P = \pi_s^G$ yields the two solutions

$$\gamma = -\frac{2(d+1)\sigma\big((d+1)(d^2+4d+2)(d(d+7)+4) - 4(d+2)^2(3d+2)^2\sigma\big)}{2(3d+2)(d+2)^2\sigma\big(4(d+2)^2(3d+2)\sigma - 3(d+1)(d^2+4d+2)\big) + (d+1)^2(d^2+4d+2)^2},$$
$$\gamma = \bar{\gamma}^{GP}(d,\sigma) \equiv \frac{2d(d+1)^2\sigma}{2(d+2)^2(3d+2)\sigma-(d+1)(d^2+4d+2)}. \tag{B.9}$$

The former yields no relevant intersection with $\Gamma_G$ and $\Gamma_P$ but the latter function $\bar{\gamma}^{GP}(d,\sigma)$ intersects with $\Gamma_G$ and $\Gamma_P$ on the curve $\sigma = \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$ and exists in the feasible parameter region for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ if $\sigma < \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$. Furthermore, $\bar{\gamma}^{GP}(d,\sigma)$ always exists in the feasible parameter region if $d > 1+\sqrt{3}$. We see that if $0 \le d < (1+\sqrt{17})/4$, we have $\pi_s^P > \pi_s^G$; if $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma > \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$, we have $\pi_s^P > \pi_s^G$; if $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma < \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$, we have $\pi_s^P > \pi_s^G$ if $\gamma > \bar{\gamma}(d,\sigma)^{GP}$ while $\pi_s^P < \pi_s^G$ otherwise; if $d > 1+\sqrt{3}$, we have again $\pi_s^P > \pi_s^G$ if $\gamma > \bar{\gamma}^{GP}(d,\sigma)$ while $\pi_s^P < \pi_s^G$ otherwise. □

*Proof of Proposition* 6. If the buyers do not invest, then $\pi^0 = \frac{d+1}{4(d+2)^2}$. Solving $\pi^0 = \pi^G$ yields the solution $\gamma = \frac{2(d+1)}{3(d+2)^2}$, which does not impose any sign changes in $\Gamma_G$ given by (A.2). The result that the inequality $\pi^G > \pi^0$ always holds in $\Gamma_G$ follows in a straightforward way.

Solving $\pi^0 = \pi^S$ yields the solution $\sigma = \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$, which is equivalent to $\bar{\sigma}(d)$ from which $\bar{d}(\sigma)$ can be found. As mentioned before, $\bar{\sigma}(d)$ exists in the feasible parameter region only if $(1+\sqrt{17}/4) < d < 1+\sqrt{3}$. We have $\pi^S > \pi^0$ for $0 \le d < (1+\sqrt{17}/4)$, $\pi^S > \pi^0$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma > \bar{\sigma}(d)$, $\pi^S < \pi^0$ for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma < \bar{\sigma}(d)$, $\pi^S < \pi^0$ for $d > 1+\sqrt{3}$.

Finally, $\pi^P$ can be written as $\pi^P = \frac{V\gamma(W^2\gamma - V)}{2(W^2\gamma-2V)^2}$. Solving $\pi^0 = \pi^P$ yields two solutions of which

$$\gamma = \bar{\gamma}^{P0}(d,\sigma) \equiv \frac{\sqrt{(d+2)^2V^3\big((d+2)^2V + 4(d+1)W^2\big)} - (d+2)^2V^2 + 2(d+1)VW^2}{(d+1)W^4 - 2(d+2)^2VW^2} \tag{B.10}$$

has a relevant intersection with $\Gamma_P$. We also see that due to the denominator of $\bar{\gamma}^{P0}(d,\sigma)$, this curve exists in $\Gamma_P$ only for those $d > \bar{d}(\sigma)$, or, equivalently, for $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ if $\sigma < \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$, while it always exists in the feasible parameter region if $d > 1+\sqrt{3}$.

We see that if $0 \leq d < (1+\sqrt{17})/4$, we have $\pi^P > \pi^0$; if $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma > \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$, we have $\pi^P > \pi^0$; if $(1+\sqrt{17})/4 < d < 1+\sqrt{3}$ and $\sigma < \frac{(d+1)(d^2+4d+2)}{2(d+2)^2(-d^2+2d+2)}$, we have $\pi^P > \pi^0$ if $\gamma < \bar{\gamma}^{P0}(d,\sigma)$ while $\pi^P < \pi^0$ otherwise; if $d > 1+\sqrt{3}$, we have again $\pi^P > \pi^0$ if $\gamma < \bar{\gamma}^{P0}(d,\sigma)$ while $\pi^P < \pi^0$ otherwise. □