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Competitive investments in cost reducing process improvement: The role of managerial incentives and spillover learning

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A R T I C L E I N F O

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A B S T R A C T

We study the rivalry between two firms and consider the effect of spillovers when the firms' operations and technology managers are given bonuses for cost reduction. We model a game in which the firm owners independently offer their manager a bonus to stimulate cost reducing process improvement before the process improvement and production stage, and draw a comparison with the game in which these bonuses are not used. Several outcomes contrast strongly with existing literature. We find that cost reduction bonuses are generally only positive in equilibrium when spillovers are less than 50%. In case spillovers are higher, cost reduction bonuses are only positive when a firm's process improvement capability is relatively high. Also we find that the sensitivity of process improvement levels in the spillover parameter crucially alters when cost reduction bonuses are introduced. Prisoner's dilemma occurs in case spillovers are less than 50%, or when spillovers are higher and process improvement capability is relatively high.

1. Introduction

An important decision for many operations and technology managers is how much to invest in cost reducing process improvement, for instance by acquiring new manufacturing technologies (e.g. Hayes et al., 2005; Li and Rajagopalan, 2008). In order to stimulate managers to be aggressive in terms of effectuating process improvement, many firm owners employ bonuses for realized cost reductions (Masternak and Camuso, 2005). As process improvement decisions are typically chosen in a competitive landscape, recent research (e.g. Veldman et al., 2014) has addressed the interplay between the process improvement decisions of firms in rivalry, and the effect cost reduction bonuses might have in such settings. However, as cost reduction bonuses stimulate managers to conduct more process improvement, thereby altering the competitive dynamics between firms, it is important to also look at the factors that might influence the effectiveness of cost reduction bonuses. In particular, it is well-known from practice that firms have problems keeping the knowledge gathered from process improvement projects to themselves, especially firms that are spatially close to each other (Autant-Bernard et al., 2011). These so-called process improvement spillovers, which refer to "involuntary leakage or voluntary exchange of useful technological information (De Bondt, 1996: 2)" may demotivate a manager to invest in process improvement, as a percentage of the investment will leak away freely to a rival firm. They can occur when an industrial firm is unable to keep its technological knowledge that is the result of innovative activities all for himself (for instance when a rival is conducting corporate espionage or makes use of competitor analysis systems), or when firm employees leak information to the outside world. Firms can also set up horizontal or vertical process improvement collaboration in order to facilitate spillovers. Much research has been done on spillover learning in buyer–supplier relationships (e.g. Mesquita et al., 2008; Perols et al. 2013), firm-end customer relationships (Clark et al., 2013) and the relationships between competitors. The focus of this paper is on the latter category, as it arguably may be the most important spillover source (Czarnitzki and Kraft, 2012). In particular, the main objective of our research is seeing how the use of cost reduction bonuses in equilibrium changes when spillovers are considered, and discussing the profit implications.

Our work is based on Overvest and Veldman (2008) and Veldman et al. (2014) who model a two-stage setting of firms in rivalry. In the first stage, firm owners independently determine the cost reduction bonuses they offer to their operations and technology managers for realized process improvements. In the second stage, the managers decide on the process improvement investment levels, and simultaneously engage in Cournot competition. In both papers the assumption is made that there are always zero spillovers between the firms in rivalry. In the current paper we

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extend their models by considering spillovers. We find that the size of the cost reduction bonus crucially depends on the spillover parameter. More importantly, we find that when spillovers are larger than 50%, it is generally not optimal to use cost reduction bonuses. In this case, positive cost reduction bonuses are only used when process improvement capability is relatively high (i.e. the process improvement cost parameter is low) compared to the spillover parameter. Another finding is that the sensitivity of process improvement levels with respect to the spillover parameter crucially alters when cost reduction bonuses are introduced. Finally, whereas these delegation games typically lead to a prisoner's dilemma (Sengul et al., 2012), we find that in our framework that this does not necessarily occur. More precisely, when spillovers are larger than 50% and process improvement capability is relatively high, cost reduction bonuses are strategic complements, and prisoner's dilemma will not occur.

This article is organized as follows. In Section 2, we discuss the literature and how it relates to our work. In Section 3 we give the basic set-up of our model. In Section 4 we provide the study's main results. Conclusions and further avenues for future research are given in Section 5.

2. Related literature

Our work lies at the cross-section of two streams of literature. The first stream uses game-theoretic frameworks to model process improvement competition between firms. Most of the work in this area considers output spillovers: the leakage of technological knowledge of one firm directly lowers the cost per product of the other firm. The work by d'Aspremont and Jacquemin (1988) often serves as a basis. They model a simple two-stage game in which two rival firms chooses production quantities after a process improvement competition stage where a certain percentage of process improvement outcomes spills over to the rival firm. Several extensions to this model have been made. De Bondt et al. (1992) investigated how the model behaves when the number of firms in an industry and the degree of product differentiation in a Cournot market are varied. De Bondt and Henriques (1995) consider a duopoly with asymmetric spillovers (i.e. the spillovers from one firm to the other is larger than the other way around). They explicitly link spillover asymmetry to the sequence of which firms execute process improvement investments (i.e. which of the firms is a leader or follower in the process improvement stage). De Bondt (1996) provides an insightful overview of the literature on spillovers and innovative activities. Recent work has considered principal-agent approaches to this model. Lacetera and Zirulia (2012), for instance, model a duopoly game in which a firm's researcher determines his cost-reducing scientific efforts by maximizing a wage schedule with incentives for realized cost reduction. In a subsequent stage, the firms compete on the end market by choosing production quantities, whereby a firm's production is influenced by that firm's researcher efforts, as well as the efforts by a researcher from the other firm. Although the paper addresses the incentives given to the researcher for process improvement effort, the researcher's pay depends only on his own realized cost reduction, and not on the decisions made by his rival researcher. Therefore the incentives given to the researcher are only strategic in the sense that they influence product market competition in a subsequent stage.

The second stream we consider concerns strategic incentives. Fershtman and Judd (1987) were among the first to analyze the strategic effect of publicly observable incentive structures. They model a two-stage game where in the first stage, two rival firm owners determine the bonus weights linked to sales, after which Cournot competition takes place. They find that firm owners set positive sales bonuses in a Nash equilibrium, even though the collective use of these incentives is done at the expense of firm profits. Combining the work of d'Aspremont and Jacquemin (1988) and Fershtman and Judd (1987), Overvest and Veldman (2008) analyze a setting where firm owners can give managers a bonus for cost-reducing process improvement. Veldman et al. (2014) considered a case where two firms differ in terms of their abilities to reduce costs and find that the use of cost reduction bonuses typically (but not always) makes firm owners worse off in terms of profitability compared to the case where firms owners cannot commit to using such bonuses. Veldman and Gaalman (2014) investigated the interaction between cost reduction and product quality bonuses.

To the best of our knowledge, Chalioti (2015) has been the first to study strategic cost reduction bonuses in cases with non-zero spillovers between firms. She considers two rival firms, each consisting of a principal (i.e. firm owner) and an agent (i.e. the manager). Each principal makes a take-it-or-leave-it offer to the agent with regard to an incentive contract consisting of a base salary, an incentive for that firm's reduction of marginal cost (whereby marginal cost is comprised of the manager's research efforts, a fraction of the rival manager's research efforts and a noise term), as well as an incentive for the rival's reduction of marginal cost. She termed the latter incentive the 'pay-for-rival performance' incentive. After that, the agents simultaneously decide on cost reducing process improvement levels, based on the incentives given to them in the previous stage. As their payments not only depend on their own process improvement decisions, but also on the decisions made by the rival manager, the managers are in process improvement competition here in a way similar to the model of d'Aspremont and Jacquemin (1988). In the final stage, the principals simultaneously decide on production quantities.

The main differences between our model and the model by Chalioti (2015) are as follows. In contrast to her model, we let process improvement and production take place simultaneously instead of letting the process improvement stage serve as input of the production stage (a decision which we motivate in the next section). Furthermore, whereas the agents in Chalioti (2015) only make process improvement decisions, we let the managers choose both process improvement and production levels. Also, as we are primarily interested into the structure of the cost reduction bonuses given by a firm owner, we let the manager's compensation depend on only the cost reductions he/she realizes instead of being dependent on rival performance as well. Finally, we will refrain from incorporating agency issues such as moral hazard, as the consideration of information asymmetry makes the underlying models much more complex. Veldman et al. (2014) demonstrate that information asymmetry not fundamentally alters the provision of cost reduction bonuses.

3. The model

We consider a duopoly consisting of firms i and j ($i, j = 1, 2$; $i \neq j$). The firms are in Cournot competition with homogeneous goods and face an inverse demand function $p = a - b\sum_{i=1}^{2} q_i = a - b(q_1 + q_2)$, where p indicates the price of the good, q_i represents the production quantity of firm i, and $a, b > 0$ represent the demand parameters. Marginal costs are given by $C_i = c - y_i$, where c is the constant marginal cost and y_i is the realized cost reduction due to technological developments within and outside the firm. As is argued in Veldman et al. (2014), the terms $(a - c)$ and b can both be normalized to 1 without loss of generality. Similar to d'Aspremont and Jacquemin (1988), define $y_i = x_i + \beta x_j$, where x_i is firm i's realized cost reduction due to its own investment in process improvement. The knowledge generated within a single firm cannot be held privately in full, which is represented by the input spillover parameter β; $0 \le \beta \le 1$. The spillover parameter can be interpreted as the fraction of knowledge that flows between firms (i.e. the higher the spillover parameter, the higher the level of knowledge flowing between firms), the degree of absorptive capacity of firms (i.e. the higher the spillover parameter, the better a firm is at capturing the value from knowledge flows), or a combination thereof. Finally, process improvement investment costs equal $R_i = (\gamma/2)x_i^2$, which is quite standard in the literature (e.g. Tseng, 2004). The parameter γ, which will be labeled the (process improvement) cost parameter from this point on, can be interpreted as a firm's process improvement capabilities; the higher γ, the lower a firm's process improvement capabilities. Profits can now be written as

$$\pi_i = (p - C_i)q_i - R_i = (p + y_i)q_i - R_i. \tag{1}$$

In the next section, we will focus mostly on two games. The first game, which we will refer to as the owner-led game, is a baseline game in which no cost reduction bonuses are being used. It is a one-stage game in which both firms simultaneously but non-cooperatively choose production and process improvement levels. Instead of modeling (observable) cost reductions realized at a certain stage as inputs for production in a subsequent stage, as for instance d'Aspremont and Jacquemin (1988), Chalioti (2015) and Kamien et al. (1992), we consider the simultaneous choice of production and cost reducing process improvement. This reflects a situation where cost reductions occur during production. As we also argue in Overvest and Veldman (2008), these process improvement choices can be interpreted as the extent to which possible cost reductions are actually grasped by the firm. Furthermore, the choice of production quantities and process improvement in a single stage is consistent with practice as the outcomes of innovation processes are typically not observable between stages for the entire set of firms in an industry, as is typically assumed in multi-stage process improvement games. Finally, the simultaneous choice of these two decisions allows us to draw a comparison with recent literature (e.g. Veldman et al., 2014).

The second game, which we label the manager-led game, is a two-stage game in which firm owners delegate decision power (with regard to process improvement and production decisions) to managers using an incentive contract, of which the optimal incentive parameters are determined in the pre-process improvement/pre-production stage. We then continue with a comparison of profit levels in the different games, and we will also briefly reflect on the asymmetric game in which only one of the firm owners employs a cost reduction bonus. The superscripts 'O' and 'M' will be used to denote an equilibrium outcome in the owner-led game and the manager-led game, respectively.

4. Analysis

4.1. Analysis of the owner-led model

4.1.1. Equilibrium outcomes

We will first consider the owner-led game. In this game, both owners simultaneously choose process improvement and production levels to maximize their profits. The maximization problem of firm i becomes

$$\max_{q_i, x_i} \pi_i \equiv (1 - q_1 - q_2 + x_i + \beta x_j)q_i - \frac{1}{2}\gamma x_i^2. \tag{2}$$

To explain the interaction between x_i and q_i, the profit function can be rewritten as

$$\pi_i = -\left(\frac{1}{2\gamma}\right)\left[(2\gamma - 1)\left(q_i - \frac{A}{2\gamma - 1}\right)^2 + (\gamma x_i - q_i)^2\right] + \left(\frac{1}{2\gamma}\right)\left(\frac{A^2}{2\gamma - 1}\right), \tag{3}$$

with $A = \gamma(1 - q_j + \beta x_j)$. From (3), it follows that regardless of the value of q_i obtained from $\partial\pi_i/\partial q_i = 0$, the best choice of x_i is $x_i = q_i/\gamma$. Also the optimal q_i satisfies $q_i = A/(2\gamma - 1)$. These insights will be used in the next sub-section where the variables' inter-relationships are discussed. From (3) also follows that $\pi_i = A^2/(4\gamma^2 - 2\gamma)$. The economic intuition behind this expression is that profits of firm i are, in general, positively (and quadratically) affected by an increase of production of firm j, and negatively (and quadratically) affected by an increase of process improvement efforts of firm j.

The optimal q_i can be found using $\gamma x_j - q_j = 0 \Rightarrow x_j = q_j/\gamma$ obtained from $\partial\pi_j/\partial x_j = 0$, plugging this into $q_i = A/(2\gamma - 1)$ and imposing symmetry. We find that in a Nash equilibrium, the owners optimally set

$$q^O = \frac{\gamma}{3\gamma - \beta - 1}, \tag{4}$$

$$x^O = \frac{1}{3\gamma - \beta - 1}, \tag{5}$$

and earn profits

$$\pi^O = \left(\frac{1}{2\gamma}\right)\left(\frac{A^2}{2\gamma - 1}\right) = \frac{\gamma(2\gamma - 1)}{(3\gamma - \beta - 1)^2}. \tag{6}$$

We continue with identifying the feasible parameter region. First we inspect the second-order condition in order to verify where the outcomes are indeed a maximum. The second-order condition is satisfied if the determinant of the Hessian matrix is strictly positive. This is the case if $\gamma > 1/2$. Next we check the conditions needed to guarantee positivity of the equilibrium outcomes. From (4) and (5) it can be easily derived that q^O and x^O are strictly positive if $\gamma > (1 + \beta)/3$. Finally, it is necessary to verify the stability conditions of the equilibrium, which determine when the reaction functions cross correctly. Stability conditions and their importance are explained in the single variable case in e.g. Henriques (1990), De Bondt and Henriques (1995) and Seade (1980). Stability in the case with more than one decision variable is less straightforward. Suppose the equilibrium is slightly perturbed because one of the firms deviates from the optimal values of q_i, x_i. A stable equilibrium ensures that outputs q_i, x_i and q_j, x_j would converge back to the equilibrium. As we show in Appendix 1, we obtain $\gamma > 1 - \beta$ as an additional condition for the feasible parameter region due to stability considerations. We can now define F_O as the parameter region that satisfies $\gamma > 1/2$, $\gamma > (1 + \beta)/3$ and $\gamma > 1 - \beta$ for $0 \le \beta \le 1$.

4.1.2. Strategic complementarity/substitutability

To analyze the interrelationships between the decision variables, it can verified whether firms' process improvement levels are strategic complements or substitutes (see, for instance, De Bondt and Henriques (1995)). Generally, process improvement levels are said to be strategic complements (substitutes) if an increase in firm j's process improvement level would lead to an increase (decrease) in the process improvement level of firm i. It is well-known in the literature that the spillover level plays a crucial role in this distinction. In the two-stage non-cooperative model by d'Aspremont and Jacquemin (1988), for instance, process improvement levels are strategic complements (substitutes) in case $\beta > 0.5$ ($\beta < 0.5$). In their model, this can be easily determined based on the firms' reaction functions in process improvement levels, obtained in the first stage. In our one-stage owner-led model, such an analysis is more complicated as the reaction functions are an interplay of two pairs of decision variables.

Let $V_{q_i} = \partial\pi_i/\partial q_i = 1 - q_j + x_i + \beta x_j - 2q_i = 0$ and $V_{x_i} = \partial\pi_i/\partial x_i = q_i - \gamma_i x_i = 0$, and similarly for firm j. Using the Taylor approximation we can totally differentiate V_{q_i} and V_{x_i} to study the small deviation dzat a certain point. We now have

$$\begin{pmatrix} d(V_{q_i}) \\ d(V_{x_i}) \end{pmatrix} = \begin{pmatrix} \frac{\partial V_{q_i}}{\partial q_i} & \frac{\partial V_{q_i}}{\partial x_i} \\ \frac{\partial V_{x_i}}{\partial q_i} & \frac{\partial V_{x_i}}{\partial x_i} \end{pmatrix} \begin{pmatrix} dq_i \\ dx_i \end{pmatrix} + \begin{pmatrix} \frac{\partial V_{q_i}}{\partial q_j} & \frac{\partial V_{q_i}}{\partial x_j} \\ \frac{\partial V_{x_i}}{\partial q_j} & \frac{\partial V_{x_i}}{\partial x_j} \end{pmatrix} \begin{pmatrix} dq_j \\ dx_j \end{pmatrix} = 0, \tag{7}$$

which can be used to obtain the reaction function

$$\begin{pmatrix} dq_i \\ dx_i \end{pmatrix} = \frac{-1}{(2\gamma - 1)} \begin{pmatrix} \gamma & -\gamma\beta \\ 1 & -\beta \end{pmatrix} \begin{pmatrix} dq_j \\ dx_j \end{pmatrix}. \tag{8}$$

From (8) we see that a change in q_i or x_i depends on the combined effect of q_j and x_j. Using the fundamental property $x_j = q_j/\gamma$ we have $dx_j = (1/\gamma)dq_j$. Upon substitution we find

$$dq_i = \frac{\beta - \gamma}{(2\gamma - 1)} dq_j \Rightarrow \frac{dq_i}{dq_j} = \frac{\beta - \gamma}{(2\gamma - 1)}, \tag{9}$$

$$dx_i = \frac{\beta - \gamma}{(2\gamma - 1)} dx_j \Rightarrow \frac{dx_i}{dx_j} = \frac{\beta - \gamma}{(2\gamma - 1)}. \tag{10}$$

From (9) and (10), it follows that strategic complementarity or substitutability crucially depends on the interrelationship between β and γ. In particular, production quantities and process improvement levels are strategic complements (substitutes) in case $\beta > \gamma$ ($\beta < \gamma$). Fig. 1 provides an overview of the feasible parameter region $F_O = F_{O1} \cup F_{O2} \cup F_{O3}$. In $F_{O1} \cup F_{O2}$, process improvement levels are strategic substitutes, whereas in F_{O3}, they are strategic complements.

We can conclude that the decision variables are generally strategic substitutes. The complex interplay of decision variables results in a system in which an aggressive move by a competitor (i.e. production quantity or process improvement) will lead to less aggressive behavior by a firm, even if a relatively large amount of competitor activity spills over freely to that firm. Only in the closed region F_{O3}, which is characterized by low γ compared to β, will a competitor's move lead to a complementary response. Intuitively, in case spillovers are high, a firm's marginal cost of production is significantly reduced when a rival increases his level of innovative activity, potentially creating cost reduction incentives for the focal firm. In case process improvement is cheap, these incentives are strong enough for the focal firm to respond by innovating as well, which leads, in turn, to higher production.

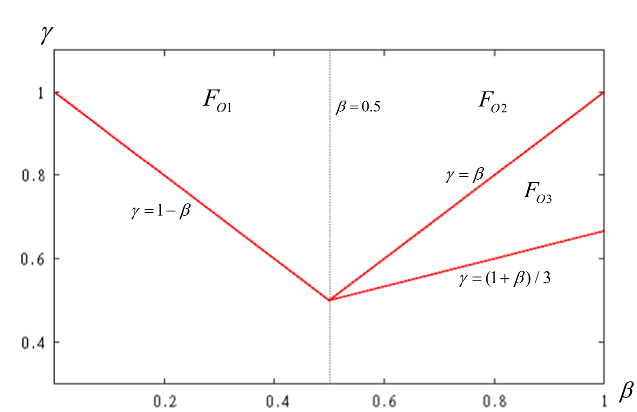

Fig. 1. Feasible parameter region $F_O = F_{O1} \cup F_{O2} \cup F_{O3}$, bounded by $\gamma = 1 - \beta$, $\gamma = (1 + \beta)/3$ and $0 \le \beta \le 1$.

4.1.3. The role of spillovers in the owner-led model

In the literature much attention has been devoted to the sensitivity of process improvement equilibrium outcomes with respect to changes in the spillover parameter. De Bondt et al. (1992) explain that the net effect of changes in the spillover parameter on total production cost reduction y_i of a firm is a combination of the effects on the own individual investments x_i and on the knowledge received βx_j. More precisely, in the two-stage non-cooperative model by d'Aspremont and Jacquemin (1988), "the disincentives of increased spillovers are more (less) than compensated by the increases in received knowledge as long as the leakage parameter is smaller (larger) than 1/2 (De Bondt et al., 1992: 41)". In other words, $dy/d\beta$ has an inverted u-shape with a maximum at $\beta = 1/2$. In our model, we have

$$\frac{dx^O}{d\beta} = \frac{1}{(3\gamma - \beta - 1)^2} > 0, \tag{11}$$

$$\frac{dy^O}{d\beta} = \frac{3\gamma}{(3\gamma - \beta - 1)^2} > 0. \tag{12}$$

Interestingly, we find a monotonic increasing effect of the spillover parameter on total production cost reduction, independent from complementarity/substitutability characteristics. Apparently, by merging the production and process improvement decisions into a single stage, the incentives to raise process improvement levels when spillovers increase more than outweigh the disincentives emerging from the fact that increasing process improvement also lowers the rival's cost. From a mathematical viewpoint, recall the reaction function in production quantities for firm i $q_i = A/(2\gamma - 1) = (\gamma/(2\gamma - 1))(1 - q_j + \beta x_j)$, and similarly for firm j. It follows that firm i would like both β and x_j to be as high as possible as the component βx_j pushes the reaction function of q_i further outwards. The same holds for firm j. These considerations give rise to the finding that in equilibrium, $dx^O/d\beta > 0$ and, by definition, $dy^O/d\beta > 0$. Proposition 1 summarizes.

Proposition 1. In the owner-led game, a firm's process improvement level x^O and total cost reduction y^O increase in the spillover parameter β.

It can be noted that the sensitivity with respect to γ is straightforward and in line with d'Aspremont and Jacquemin (1988). i.e.

$$\frac{dx^O}{d\gamma} = -\frac{3}{(3\gamma - \beta - 1)^2} < 0, \tag{13}$$

$$\frac{dy^O}{d\gamma} = -\frac{3(1 + \beta)}{(3\gamma - \beta - 1)^2} < 0. \tag{14}$$

These findings are easy to interpret as investments in process improvement are typically tempered by increasing investment costs.

4.2. Analysis of the manager-led model

4.2.1. Equilibrium outcomes

Let us continue with an analysis of the manager-led model. Suppose the firm owner wishes to stimulate the manager to become more aggressive towards his rival manager, by distorting his incentive scheme. In particular, suppose the owner provides the salary function $S_i = \pi_i + \lambda_i x_i$, where λ_i is the monetary return per unit of realized production cost reductions. The game now changes into a two-stage game, in which λ_i is chosen by the firm owner in the first stage. The appropriate solution concept here is the sub-game perfect Nash equilibrium, solved via backward induction. In the second stage, the manager chooses production quantities and process improvement levels based on his salary function, facing the maximization problem

$$\max_{q_i, x_i} S_i \equiv (1 - q_1 - q_2 + x_i + \beta x_j)q_i - \frac{1}{2}\gamma x_i^2 + \lambda_i x_i. \tag{15}$$

As described in the literature (e.g. Fershtman and Judd, 1987) the manager's actual salary would become $U_i = B + DS_i$, with B, D being constants. However, as it is marginal utilities that drive the manager's decisions, he acts so as to maximize S_i. Similar to the owner-led case, the function S_i can be rewritten to highlight the link between x_i and q_i. In particular we have

$$S_i = -\left(\frac{1}{2\gamma}\right)\left[(2\gamma - 1)\left(q_i - \frac{A}{2\gamma - 1}\right)^2 + (\gamma x_i - q_i - \lambda_i)^2\right] + \left(\frac{1}{2\gamma}\right)\left(\frac{A^2}{2\gamma - 1} + \lambda_i^2\right), \tag{16}$$

with $A = \gamma(1 - q_j + \beta x_j + \lambda_i/\gamma)$. From (16) follows that x_i satisfies $\gamma x_i - q_i - \lambda_i = 0$, and thus becomes also dependent on the λ_i chosen in the first stage. Also we have $q_i = A/(2\gamma - 1)$, similar to the owner-led game. This implies that the expression between squared brackets becomes zero. Looking at the most right part of (16) it can be seen that, compared to (3), the effects of q_j and x_j remain the same, but the final payout is now also affected (positively and quadratically) by the cost reduction bonus variable. Similar to the owner-led model, we can find the optimal q_i using $\gamma x_j - q_j - \lambda_j = 0 \Rightarrow x_j = (q_j + \lambda_j)/\gamma$ obtained from $\partial S_j/\partial x_j = 0$, and plugging this into firm i's reaction function of production quantities $q_i = A/(2\gamma - 1)$. Doing so we get

$$q_i = \left(\frac{\gamma}{2\gamma - 1}\right)\left(1 - q_j + \beta x_j + \left(\frac{1}{\gamma}\right)\lambda_i\right) = \left(\frac{\gamma}{2\gamma - 1}\right)\left(1 - \left(1 - \frac{\beta}{\gamma}\right)q_j + \left(\frac{\beta}{\gamma}\right)\lambda_j + \left(\frac{1}{\gamma}\right)\lambda_i\right), \tag{17}$$

showing a direct positive effect of the cost reduction bonus variables on q_i (i.e. positive λ_i and λ_j would push the reaction functions further outwards). However, knowing that q_j in the right-hand side of (17) also becomes a function of λ_i and λ_j, the net effect of the λ's is not immediately obvious. Note that the second-stage sufficient second-order conditions and stability conditions are similar to the ones obtained in the owner-led game, as λ_i drops out when any second-order derivative of S_i is taken.

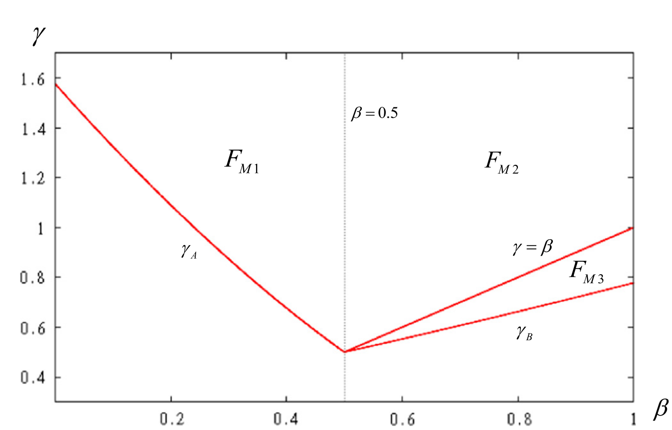

Fig. 2. Feasible parameter region $F_M = F_{M1} \cup F_{M2} \cup F_{M3}$, bounded by γ_A, γ_B and $0 \le \beta \le 1$.

In the first stage, the two owners maximize their profit function, solving

$$\max_{\lambda_i} \pi_i \equiv (1 - q_1 - q_2 + x_i + \beta x_j)q_i - \frac{1}{2}\gamma x_i^2 = q_i^2 - \frac{1}{2}\gamma x_i^2, \tag{18}$$

and taking the second-stage outcomes into account. Note that the owner would normally make sure the actual salary U_i equals the manager's outside opportunity. As the value of this outside opportunity can be normalized to zero, it does not have to be taken into account in the owner's problem (e.g. see Fershtman and Judd (1987)). Taking the first-order derivative of π_i with respect to λ_i, $i = 1, 2$, and solving both first-order conditions simultaneously, we find that

$$\lambda^M = \left(\frac{1}{M}\right)\gamma(2\beta - 1)(\beta - \gamma), \tag{19}$$

where $M = 9\gamma^2 + \gamma(\beta - 2)(2\beta + 5) - 2(\beta + 1)^2(\beta - 1)$. Upon substitution we can calculate the optimal production and process improvement levels as

$$q^M = \left(\frac{1}{M}\right)\gamma(3\gamma + \beta - 2), \tag{20}$$

$$x^M = \left(\frac{1}{M}\right)2(\beta^2 - \beta\gamma + 2\gamma - 1), \tag{21}$$

whereas profits can be calculated as

$$\pi^M = \left(\frac{1}{M}\right)^2\left(\gamma(9\gamma^3 - 2\gamma^2(\beta - 2)(\beta - 5) + \gamma(4\beta^2 + \beta - 6)(\beta - 2) - 2(\beta^2 - 1)^2)\right). \tag{22}$$

To find the feasible parameter region, we need to consider the conditions regarding the positivity of x^M and q^M, the first-stage sufficient second-order conditions, and first-stage stability conditions. All the necessary technical derivations are given in Appendix 2. It is found that the convex functions in β

$$\gamma_A = \frac{1}{6}\left(2\beta^2 - 7\beta + 6 - (2\beta - 1)\sqrt{\beta^2 - 12\beta + 12}\right), \tag{23}$$

$$\gamma_B = \frac{1}{18}\left(-2\beta^2 - \beta + 10 + (2\beta - 1)\sqrt{\beta^2 + 20\beta + 28}\right), \tag{24}$$

form the boundaries of the feasible parameter region, next to the restriction $0 \le \beta \le 1$. We can now define the feasible parameter region F_M, which is characterized by $\gamma > \gamma_A$ for $0 \le \beta \le 0.5$, and $\gamma > \gamma_B$ for $0.5 \le \beta \le 1$. In F_M, positivity of x^M and q^M is guaranteed, first- and second-stage sufficient second-order conditions apply, as well as the stability conditions. It follows that always $\gamma > 0.5$. Also, $M > 0$ in F_M.

It is now quite straightforward to analyze positivity of $\lambda^M = M^{-1}\gamma(2\beta - 1)(\beta - \gamma)$. First, define $F_M = F_{M1} \cup F_{M2} \cup F_{M3}$. See Fig. 2.

In the semi-open area F_{M1}, which is characterized by $\beta < 0.5$, we clearly have $\lambda^M > 0$. Furthermore in the closed area F_{M3}, in which $\beta > 0.5$ holds, we have $\lambda^M > 0$ iff $\beta > \gamma$, i.e. for relatively small cost parameter values compared to β. Remarkably, in the semi-open area F_{M2} bounded by $\beta > 0.5$ and $\gamma > \beta$ we have a cost reduction bonus which is strictly negative. Negative bonus weights do not seem to be omnipresent in reality, but do bear some resemblance to clawback provisions, which are becoming more prevalent in the financial sector. Alternatively, a negative bonus weight may be interpreted as focusing managerial attention on revenues from sales rather than on the revenues derived from realized cost reductions.[2] Yet a $\lambda^M < 0$ demotivates the manager to be innovative, and it is for that reason that we assume throughout this paper that the actual bonus weight satisfies $\lambda^A = \max(0, \lambda^M)$. We summarize this result in the following proposition:

Proposition 2. The cost reduction bonus λ^M is only positive in $F_{M1} \cup F_{M3}$.

An immediate implication of Proposition 2 is that if spillovers are high in an industry (i.e. $\beta > 0.5$), it is hardly ever optimal for a firm to make use of a cost reduction bonus. This is interesting because in the case where spillovers are zero (e.g. reported in Overvest and Veldman (2008) and Veldman et al. (2014)) owners will always optimally set a positive cost reduction bonus. Intuitively the cost reduction bonus λ^M and the spillover parameter β work in opposite directions: whereas a cost reduction bonus makes a manager more aggressive in terms of cost reduction investments, spillovers would make him more careful because a percentage of every euro spent by the firm on process improvement would directly benefit the rival firm. Apparently a cost reduction bonus is only attractive for a firm owner when little process improvement knowledge is spilled over to the rival. An exception is the area F_{M3}. Here spillovers are high but so is process improvement capability. Even though much of the process improvement knowledge is spilled over, investing in process improvement is relatively cheap. The incentives for the use of cost reduction bonuses are such that again $\lambda^M > 0$.

A final remark is that the requirement $\lambda^A = \max(0, \lambda^M)$ implies that x^M, y^M, q^M and π^M only have meaningful interpretations in F_{M1} and F_{M3}. In F_{M2}, the game at hand is always the owner-led game.

4.2.2. Strategic complementarity/substitutability

Defining $V_{q_i} = \partial S_i/\partial q_i$ and $V_{x_i} = \partial S_i/\partial x_i$, it can be noted that λ_i would drop out in any second order derivative taken with respect to q_i, q_j, x_i or x_j. This means that the introduction of a λ_i would not affect the strategic complementarity or substitutability of our models in the second stage compared to the owner-led game.

From the first-stage first-order condition it can be derived that

$$\frac{d\lambda_1}{d\lambda_2} = \frac{(2\beta-1)^2\gamma(\beta-\gamma)}{(3\gamma-\beta-1)^2(\gamma+\beta-1)^2}, \tag{25}$$

implying strategic substitutes if $\beta < \gamma$, which occurs in F_{M1}, and strategic complements if $\beta > \gamma$, which happens in F_{M3}. Note that the conditions applying to the strategic complementarity/substitutability characteristics of q and x in the second stage (and the owner-led model) are equal: if $\beta < \gamma$, both process improvement and production quantities are strategic substitutes, otherwise they are strategic complements.

4.2.3. The role of spillovers in the manager-led model

In Section 4.1.3 we explained why x^O and y^O monotonically increase in the spillover parameter β. Let us verify the effect of β on x^M and y^M. For this purpose, it is convenient to utilize the effect of β on λ^M. We first focus on F_{M1}. It is easy to show that in F_{M1}, λ^M monotonically decreases in β. The interpretation behind this can be given using Proposition 2: cost reduction bonuses generally only make sense when the spillover rate is below 50%. Thus the incentive to use a cost reduction bonus decreases in F_{M1}, leading to $(d\lambda^M/d\beta) < 0$. This translates directly to the sign of $dx^M/d\beta$: the solution to $(dx^M/d\beta) = 0$ lies only in F_{M2} and thus does not play a role in F_{M1}.[3] A numerical check suffices to show that $(dx^M/d\beta) < 0$ in F_{M1}. Thus increasing spillovers make a firm owner more careful to use a cost reduction bonus, and makes a manager less aggressive in conducting process improvement. Due to the complex nature of inter-firm interactions, the effect of an increase in the spillover parameter on total cost reduction is not evident. Defining $y^M = (1+\beta)x^M$ and solving $(dy^M/d\beta) = 0$ yields one solution in F_{M1}. To be specific, this curve, given by

$$\gamma_C = \frac{1}{6}\left(4\beta + 7 - \sqrt{28\beta^2 + 32\beta + 13}\right), \tag{26}$$

monotonically increases from $\gamma \approx 1.7676$ at $\beta = 0$ to $\gamma = 2.5$ at $\beta = 0.5$. For $\gamma > \gamma_C$, $(dy^M/d\beta) > 0$, otherwise $(dy^M/d\beta) < 0$. Thus, in that part of F_{M1} where firms most actively conduct process improvement (i.e. the area where γ is relatively low), the sign of $dy^M/d\beta$ is similar to the sign of $dx^M/d\beta$.

In F_{M3}, $\beta > 0.5$ but γ is relatively low compared to β. Both firms seem to benefit from more process improvements, with little investment cost as a downside. Indeed, it can be easily checked that λ^M monotonically increases in β here. In addition it is not hard to verify that, as managers are increasingly stimulated to undertake process improvement efforts, both x^M and y^M monotonically increase in β. We summarize in Proposition 3.

Proposition 3. In F_{M1}, λ^M and x^M monotonically decrease in β. y^M decreases in β if $\gamma < \gamma_C$. In F_{M3}, λ^M, x^M and y^M monotonically increase in β.

Comparing the findings presented in this proposition with Proposition 1, we conclude that the introduction of a non-negative λ^M reverses the effect of β on the cost reduction level for spillover levels lower than 50%. According to Proposition 1 the cost reduction level increases in the spillover parameter. In F_{M1}, λ^M decreases in β, which decreases the incentives for process improvement, and which leads to decreasing x^M. In F_{M3}, λ^M increases in β, which increases process improvement incentives, and which leads to a sign of $dx^M/d\beta$ similar to Proposition 1.

Sensitivity with respect to γ is more straightforward to interpret. Regardless of the values of the spillover parameter, firm decisions will generally be taken more carefully as investment costs increase. Solving $(d\lambda^M/d\gamma) = 0$, $(dx^M/d\gamma) = 0$ and $(dy^M/d\gamma) = 0$ yields no solutions in F_M. A numerical check suffices to show that in F_{M1} and F_{M3}, λ^M, x^M and y^M decrease in γ.

4.3. Comparison of profit levels

In the previous section it was shown for which parameter constellations a firm owner will choose a positive cost reduction bonus to stimulate the manager to conduct more process improvement activities. In this section we analyze the effect of the use of such bonuses on firm level profitability in the owner-led and manager-led case. It is useful to note here that $F_M \subset F_O$. Therefore the results of our comparison apply only to F_M. Cost reduction bonuses are used to make managers more aggressive in terms of process improvement investments. Indeed, similar to Overvest and Veldman (2008) it is easy to verify that solving $x^O = x^M$ yields no solution in F_M, making it straightforward to show that $x^M > x^O$ and, by extension, $y^M > y^O$. Apparently the existence of process improvement spillovers does not influence the efficacy of cost reduction bonuses in any way.

The effect of using cost reduction bonuses on firm level profitability is harder to analyze. It is well-known from the literature

[2] We thank one of the referees for pointing this out.

[3] This curve monotonically increases from $\beta = \gamma = 0.5$ to $\gamma \approx 1.844$ when β approaches 1. It is not shown in Fig. 2.

Firm 1 \ Firm 2	O	M
O	$(\pi^O = \pi_1^O = \pi_2^O)$	(π_1^{OM}, π_2^{OM})
M	(π_1^{MO}, π_2^{MO})	$(\pi^M = \pi_1^M = \pi_2^M)$

Fig. 3. Profits in various games.

that managerial delegation through the use of bonuses often has negative effects on firm profitability. Fershtman and Judd (1987) already argued that a bonus given by a firm owner to its manager puts this owner into a Stackelberg position with respect to the rival manager. However, as the same goes for the other firm owner in a symmetric setting, such a dual Stackelberg position stimulates both firm owners to shift managerial attention away from profit maximization. A prisoner's dilemma often occurs as a result (e.g. see Veldman et al. (2014) and Veldman and Gaalman (2014)). Fig. 3 shows the different profits in the various games, including the asymmetric games in which one of the firm pre-commits to not using a cost reduction bonus (setting the managerial bonus to zero a priori), as for instance he is temporarily unavailable to change the firm's incentive system.

Let us first compare firm profits in the owner-led and manager-led game. Setting $\pi^O = \pi^M$ and solving leads to the solutions $\gamma = 0$, $\gamma = \beta$, and two other slightly more complicated expressions that are functions of β (not shown here to save space). Equating these solutions with the known boundaries of F_M yields no solutions. Thus a single numerical check is sufficient for the next result.

Proposition 4. In F_{M1}, $\pi^O > \pi^M$; in F_{M3}, $\pi^M > \pi^O$.

To analyze the existence of a prisoner's dilemma, we have to compare π^O and π^M to the profits earned in the asymmetric games. Outcomes in the asymmetric games are denoted with a double superscript. E.g. x_1^{MO} denotes the process improvement level of firm 1 in the game where firm owner 1 employs a positive cost reduction bonus (which is indicated by the first superscript, using the letter M), whereas firm owner 2 cannot use such a bonus (denoted by the second superscript, using the letter O). Note that in this example we also have $x_1^{MO} = x_2^{OM}$. As the asymmetric case is less restrictive, it follows that F_M is a subset of the feasible parameter region obtained in the asymmetric case. We will suppress any details thereof due to a lack of space.

In the asymmetric games, one of the firm owners optimally sets

$$\lambda_1^{MO} = \lambda_2^{OM} = \frac{(2\beta-1)(\beta-\gamma)\gamma(\gamma+\beta-1)}{9\gamma^3 - 2(\beta-5)(\beta-2)\gamma^2 + (\beta-2)\left(4\beta^2+\beta-6\right)\gamma - 2\left(\beta^2-1\right)^2}. \quad (27)$$

with a denominator >0. It is easy to see that in F_{M1} and F_{M3}, $\lambda_1^{MO} = \lambda_2^{OM} > 0$. Knowing this we can now obtain the equilibrium profits in the asymmetric games as well, and continue with the profit comparison. However, solutions to some of the profit equality equations (e.g. $\pi^O = \pi_2^{MO}$) are hard to analyze as higher order polynomials occur (i.e. order of 3 or higher). Using Mathematica 10.1 (Wolfram Research, 2015) we are able to plot the solutions (i.e. γ expressed as a complex function of β), based on which we can obtain our results by verifying whether the solutions lie in either F_{M1} or F_{M3}. In order to save space we suppress all derivations.

We first analyze profits in F_{M1}. It can be established that in F_{M1}, $\pi_2^{MO} < \pi^M < \pi^O < \pi_1^{MO}$ and $\pi_1^{OM} < \pi^M < \pi^O < \pi_2^{OM}$. This is in line with the standard prisoner's dilemma. The situation is different in F_{M3}. We establish that in F_{M3}, $\pi^O < \pi_1^{MO} < \pi_2^{MO} < \pi^M$ and $\pi^O < \pi_2^{OM} < \pi_1^{OM} < \pi^M$. Consider a shift from the owner-led game to the game in which firm owner 1 can give a non-zero cost reduction bonus. As he appears to optimally set a cost reduction bonus $\lambda_1^{MO} > 0$, it follows that $\pi^O < \pi_1^{MO}$. Interestingly, we also find $\pi^O < \pi_2^{MO}$ (and even $\pi_1^{MO} < \pi_2^{MO}$), implying that firm 2 benefits freely from the cost reduction bonus used by firm owner 1. This is intuitive, as such a bonus would induce manager 1 to conduct more process improvement, leading to additional benefits for firm 2 due to a high spillover level.[4] Still, firm owner 2 would prefer to use a non-zero cost reduction bonus as well, implying that $\pi_2^{MO} < \pi^M$. As in F_{M3} cost reduction bonuses are strategic complements, firm owner 1 further increases his manager's bonus as his rival owner does so as well, leading to a further increase in profits (i.e. $\pi_1^{MO} < \pi^M$). This result is in line with d'Aspremont and Jacquemin (1988), who also found a positive effect of equilibrium bonuses on profits in case the decision variables are strategic complements (i.e. in prices).

5. Conclusion

Spillovers are regarded as "one of the central constructs in the economics of innovation (Knott et al., 2009: 373)". In this paper we consider a duopoly and compare two models. In the owner-led model, the two rival managers make process improvement and production decisions and thereby maximize profits on behalf of the owner in a single stage. In the manager-led model, we add a (pre-process improvement/production) incentive stage in which the firm owners simultaneously decide on the compensation a manager is given for his realized cost reduction. In the second stage, the managers make process improvement and production decisions based on the altered incentive scheme. Our work resulted in several findings currently not reported in the literature:

i. In the one-stage owner-led model optimal process improvement choices and total cost reduction increase in the industry spillover parameter (Proposition 1). In the two-stage manager-led models, process improvement investments decrease when the spillover rate goes to 50% (Proposition 3). The implication is that process improvement bonuses reverse the positive correlation between process improvement investment and spillovers found in the owner-led game.
ii. In the manager-led model, bonuses for cost-reducing process improvement are strictly positive only when the spillover rate is below 50%, or when the spillover parameter is larger than the process improvement cost parameter (Proposition 2). As the focus of this paper is on positive bonus weights, the implication of this finding is that positive bonuses should never be used in industries with high spillovers (i.e. >50%) unless the firm has high process improvement capabilities (i.e. low γ compared to β).
iii. In line with the case without spillovers (e.g. reported in Overvest and Veldman (2008)), a prisoner's dilemma occurs in a large part of the feasible parameter region. The negative effect of the use of process improvement bonuses by both owners on firms' profitability does not hold in the case where both spillovers and process improvement capabilities are high (i.e. γ is low

[4] Indeed, it can be checked that firm 2 chooses production quantities $q_2^{MO} = q^O + \frac{\gamma(2\beta-1)\lambda_1^{MO}}{(3\gamma-\beta-1)(\gamma+\beta-1)}$, showing that for a larger spillover, firm 2 produces more when firm owner 1 uses a cost reduction bonus.

compared to β) (Proposition 4). This occurs in the parameter area where decision variables are strategic complements.

There is a wealth of future research that can be done. In order to obtain analyzable results we chose to let $\beta = \beta_1 = \beta_2$. Considering asymmetric spillovers $\beta_1 \neq \beta_2$, such as e.g. in De Bondt and Henriques (1995), might offer new insights. The consideration of asymmetric process improvement capabilities could be interesting as well, as this may alter our conclusions (see, for instance, Veldman et al. (2014) for insight into how the conclusions drawn by Overvest and Veldman (2008) change when firms are asymmetric in process improvement capabilities). Extensions such as the consideration of uncertainty, risk and moral hazard would better adapt our model to industrial reality as well. It would also be interesting to see how far our conclusions reach in case of more general demand and cost functions, if industries are analyzed with n firms, and what the effects of managerial incentives are in various cooperation modes. It would be worthwhile to consider spillovers as an (partially) endogenous managerial decision. Such an extension would be particularly interesting in a supply chain context (e.g. Cao and Zhang, 2011; Harhoff, 1996; Ge et al., 2014). Finally, it is important to recognize that so far we have focused on positive bonus weights (even though we find that negative bonuses are optimal in a part of the feasible parameter region). In the financial sector, upcoming practice is the use of clawbacks as a reduction of the bonuses awarded when the performance of financial products is below certain thresholds. This may inspire researchers to investigate the design of optimal incentive schemes with clawback-type of arrangements, suitable in the operations realm. Also future research could revolve around the optimality of relative bonus weights, such as the ones directing attention to either revenues or costs.

Appendix 1. Stability analysis owner-led game

The stability condition requires that the eigenvectors of the Jacobian matrix (which is a 4 × 4 matrix in this case) are negative and/or are complex with negative real parts. Let $V_{q_i} = \partial\pi_i/\partial q_i = 1 - q_j + x_i + \beta x_j - 2q_i = 0$ and $V_{x_i} = \partial\pi_i/\partial x_i = q_i - \gamma_i x_i = 0$, and similarly for firm j. The Jacobian matrix satisfies

$$J = \begin{pmatrix} \frac{\partial V_{q_i}}{\partial q_i} & \frac{\partial V_{q_i}}{\partial q_j} & \frac{\partial V_{q_i}}{\partial x_i} & \frac{\partial V_{q_i}}{\partial x_j} \\ \frac{\partial V_{q_j}}{\partial q_i} & \frac{\partial V_{q_j}}{\partial q_j} & \frac{\partial V_{q_j}}{\partial x_i} & \frac{\partial V_{q_j}}{\partial x_j} \\ \frac{\partial V_{x_i}}{\partial q_i} & \frac{\partial V_{x_i}}{\partial q_j} & \frac{\partial V_{x_i}}{\partial x_i} & \frac{\partial V_{x_i}}{\partial x_j} \\ \frac{\partial V_{x_j}}{\partial q_i} & \frac{\partial V_{x_j}}{\partial q_j} & \frac{\partial V_{x_j}}{\partial x_i} & \frac{\partial V_{x_j}}{\partial x_j} \end{pmatrix} = \begin{pmatrix} -2 & -1 & 1 & \beta \\ -1 & -2 & \beta & 1 \\ 1 & 0 & -\gamma & 0 \\ 0 & 1 & 0 & -\gamma \end{pmatrix}. \tag{A1}$$

The eigenvalues η_k can be found from $\det(J - \eta I) = 0$ resulting in

$$\frac{1}{(\gamma+\eta)^2}(\eta^2 + (\gamma+3)\eta + 3\gamma - \beta - 1)(\eta^2 + (\gamma+1)\eta + \gamma + \beta - 1) = 0, \tag{A2}$$

which is a product of two quadratic polynomials. Solving this equation gives the four solutions

$$\eta_1 = \frac{1}{2}\left(-3 - \gamma - \sqrt{\gamma^2 - 6\gamma + 4\beta + 13}\right), \tag{A3}$$

$$\eta_2 = \frac{1}{2}\left(-3 - \gamma + \sqrt{\gamma^2 - 6\gamma + 4\beta + 13}\right) \tag{A4}$$

$$\eta_3 = \frac{1}{2}\left(-1 - \gamma - \sqrt{\gamma^2 - 2\gamma - 4\beta + 5}\right), \tag{A5}$$

$$\eta_4 = \frac{1}{2}\left(-1 - \gamma + \sqrt{\gamma^2 - 2\gamma - 4\beta + 5}\right) \tag{A6}$$

which are all four real solutions because the terms under the square root are either zero or positive. Since $\gamma > 0$ we have $\eta_1,\ \eta_3 < 0$. Next $\eta_2,\ \eta_4 < 0$ for $\gamma > 1 - \beta$ and $\gamma > (1+\beta)/3$. As the latter coincides with the positivity condition that guarantees positivity of q^O and x^O, we obtain $\gamma > 1 - \beta$ as an additional condition for the feasible parameter region F_O.

Note that it can be shown that the stability analysis can be extended to the case with n firms. The eigenvalues can be easily found from

$$\det J_{n\times n} = (-1)^{n-1}\left(\eta^2 + (\gamma+1)\eta + \gamma + \beta - 1\right)^{n-1} \times \left(-\eta^2 - (\gamma + (n+1))\eta - (n+1)\gamma + (n-1)\beta + 1\right) = 0. \tag{A7}$$

Appendix 2. Conditions in the manager-led game

Positivity conditions of the equilibrium outcomes require $M > 0$ and positive numerators. Using subscripts to denote solutions, the two zeroes of $M(\gamma)$ are

$$\gamma_1 = \frac{1}{18}\left(-2\beta^2 - \beta + 10 - (2\beta - 1)\sqrt{\beta^2 + 20\beta + 28}\right), \tag{A8}$$

$$\gamma_2 = \frac{1}{18}\left(-2\beta^2 - \beta + 10 + (2\beta - 1)\sqrt{\beta^2 + 20\beta + 28}\right). \tag{A9}$$

Since $0 \le \beta \le 1$, the term under the square root is positive, and the term $(-2\beta^2 - \beta + 10)$ is positive. It can be shown that for $1/2 \le \beta \le 1$ we have $\gamma_1 < 0$ and $\gamma_2 > 0$ and thus $M(\gamma) > 0$ if $\gamma > \gamma_2$. Equivalently for $0 \le \beta \le 1/2$ we have $M(\gamma) > 0$ if $\gamma > \gamma_1$.

With regard to the sufficient second-order conditions we require $(\partial^2\pi_i/\partial\lambda_i^2) < 0$ with

$$\frac{\partial^2\pi_i}{\partial\lambda_i^2} = \frac{-N}{(3\gamma - \beta - 1)^2(\gamma + \beta - 1)^2}, \tag{A10}$$

where $N = 9\gamma^3 - 2\gamma^2(\beta - 2)(\beta - 5) + \gamma(4\beta^2 + \beta - 6)(\beta - 2) - 2(\beta^2 - 1)^2$. N is a polynomial of the fourth degree in β and the denominator is a product of two quadratic polynomials with the zeroes $\gamma = 1 - \beta$ and $\gamma = (1+\beta)/3$. The denominator is always positive due to the second-stage stability conditions (which, due to the fact that λ_i does not yet play a role here, can be found in the single-stage owner-led model in Section 4.1). The numerator can be written as the product of two second-degree polynomials, namely

$$N = -2\left(\beta^2 - 1 - (1/\sqrt{2})(2-\beta)\sqrt{\gamma} + (2-\beta)\gamma + (3/\sqrt{2})\gamma\sqrt{\gamma}\right) \times \left(\beta^2 - 1 + (1/\sqrt{2})(2-\beta)\sqrt{\gamma} + (2-\beta)\gamma - (3/\sqrt{2})\gamma\sqrt{\gamma}\right). \tag{A11}$$

The numerator has four zeroes of the form $\beta = f(\gamma)$. It can be checked that one of these solutions, namely

$$\beta = \frac{1}{2}\left(\frac{\sqrt{\gamma}}{\sqrt{2}} + \gamma - \frac{1}{\sqrt{2}}\sqrt{2\gamma^2 + 14\sqrt{2}\gamma^{3/2} - 15\gamma - 8\sqrt{2}\sqrt{\gamma} + 8}\right), \tag{A12}$$

imposes a stricter condition on the feasible parameter region in the range $0 \le \beta \le 0.5$ compared to the conditions derived from $M > 0$. It can now be verified that if γ is high enough (and away from the curve given by (A12)), and $M > 0$, the managers choose positive process improvement and production levels, and the sufficient second-order condition $(\partial^2 \pi_i / \partial \lambda_i^2) < 0$ is satisfied.

The final step in identifying the feasible parameter region is checking the first-stage stability condition by looking at the eigenvalues η^k of the 2×2 Jacobian matrix. Solving the characteristic equation, we obtain

$$\eta_1 = \frac{-9\gamma^2 - (2\beta+5)(\beta-2)\gamma + 2(\beta+1)^2(\beta-1)}{(1+\beta-3\gamma)^2(\gamma+\beta-1)}, \tag{A13}$$

$$\eta_2 = \frac{3\gamma^2 - (2\beta-3)(\beta-2)\gamma + 2(\beta+1)(\beta-1)^2}{(1+\beta-3\gamma)(\gamma+\beta-1)^2}, \tag{A14}$$

which are polynomials of the second degree in γ. Since stability requires negative real eigenvalues and/or negative real parts of complex eigenvalues we first analyze the zeroes of the eigenvalues. This results in four expressions $\gamma = f(\beta)$, given by

$$\gamma_{\mathrm{I}} = \frac{1}{6}\left(2\beta^2 - 7\beta + 6 - (2\beta-1)\sqrt{\beta^2 - 12\beta + 12}\right), \tag{A15}$$

$$\gamma_{\mathrm{II}} = \frac{1}{6}\left(2\beta^2 - 7\beta + 6 + (2\beta-1)\sqrt{\beta^2 - 12\beta + 12}\right), \tag{A16}$$

$$\gamma_{\mathrm{III}} = \frac{1}{18}\left(-2\beta^2 - \beta + 10 - (2\beta-1)\sqrt{\beta^2 + 20\beta + 28}\right), \tag{A17}$$

$$\gamma_{\mathrm{IV}} = \frac{1}{18}\left(-2\beta^2 - \beta + 10 + (2\beta-1)\sqrt{\beta^2 + 20\beta + 28}\right), \tag{A18}$$

with Roman numbers used to differentiate between the four solutions. Calculations show that in the β, γ-plane the first-stage solutions are stable if $\gamma > \gamma_{\mathrm{I}}$ for $0 \le \beta \le 0.5$ and if $\gamma > \gamma_{\mathrm{IV}}$ for $\beta \ge 0.5$. In addition, it is easy to show that γ_{I} and γ_{IV} dominate any other condition found earlier, so that they form the ultimate boundaries of the feasible parameter region. Note that the right-hand side of γ_{III} and γ_{IV} are exactly equal to the right-hand side given in (A8) and (A9). In the main text of the paper, we let $\gamma_{\mathrm{I}} = \gamma_A$ and $\gamma_{\mathrm{IV}} = \gamma_B$ for the sake of clarity.

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