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Abstract

Does competitive pressure foster innovation? Technical progress consists of numerous small improvements made upon the existing technology (*continuous improvement*) and innovative activities aiming at entirely new technology (*discrete innovation*). Continuous improvement is often of limited relevance to the new technology invented by successful discrete innovation. By capturing this interplay, our model predicts that, in contrast to previous theoretical findings, an increase in competitive pressure measured by product substitutability may *decrease* firms' incentives to conduct continuous improvement. Continuous improvement had been regarded as an important source of strength in Japanese manufacturing until the 1980s. However, several studies have found that levels of continuous improvement have recently decreased in a number of Japanese manufacturing firms. Through field research at two Japanese firms, we demonstrate the real-world relevance and usefulness of the model which offers new insights on possible mechanisms behind the declining focus on continuous improvement in Japan.

Keywords: Competitive pressure, continuous improvement, discrete innovation, field research, location model, product substitutability, small group activities, technical progress.

JEL classification numbers: L10, L60, M50, O30

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1 Introduction

Does competitive pressure foster innovation? This is an important research question which goes back at least to Schumpeter (1943) and Arrow (1962) and has been previously explored by a number of researchers. We offer a new perspective on this important question through exploring the interplay between *continuous improvement* and *discrete innovation* in the presence of competitive pressure. Technical progress consists of numerous minor improvements made upon the existing technology and innovative activities aiming at entirely new products and processes (see, for example, Kuznets, 1962; Rosenberg, 1982). In this paper, we label the former type of technical progress as *continuous improvement*, while the latter as *discrete innovation*.[1]

The objective of this paper is to explore the effects of competitive pressure on firms' incentives to undertake continuous improvement. Continuous improvement made upon the existing product or process is often of limited relevance to the new product or process invented upon success in discrete innovation. Nonetheless, firms invest in both types of innovation at the same time. For example, IBM has made substantial investments in developing the quantum computer, a device based on the quantum physics properties of atoms that allow them to work together as a computer's processor and memory.[2] At the same time, IBM has also continuously enhanced the computational power of its BlueGene series of supercomputer.[3] The underlying principles which quantum computers are based upon fundamentally differ from that of a conventional computer. For example, the use of superconductors has been shown promising in the new quantum computer.[4] Thus, continuous improvements made upon today's supercomputer, which is semiconductor based, are likely to be less applicable to quantum computers once the latter becomes commercialized and starts to replace the former.

Our model captures the key interplay between continuous improvement and discrete innovation by assuming that the improvement made upon the existing technology is less effective for the new technology introduced by a successful discrete innovation. Discrete innovation often involves significant uncertainty.[5] We capture the uncertainty by assuming that discrete innovation turns into a success with a certain probability. In contrast, continuous improvement involves no uncertainty in our analysis.

[1] The latter type of technical progress is also referred to as technological breakthroughs (see, for example, Fleming, 2002; Singh and Fleming, 2010).

[2] See "IBM develops world's most advanced quantum computer", August 15 2000, <http://edition.cnn.com/2000/TECH/computing/08/15/quantum.reut/index.html> and "IBM's Test-Tube Quantum Computer Makes History", December 19 2001, <http://www-03.ibm.com/press/us/en/pressrelease/965.wss>.

[3] This enhancement is apparent in the BlueGene series of supercomputer from BlueGene/L to BlueGene/P. For more details see, "IBM Triples Performance of World's Fastest, Most Energy-Efficient Supercomputer", June 26 2007, <http://www-03.ibm.com/press/us/en/pressrelease/21791.wss>.

[4] See, for example, Clarke and Wilhelm (2008) for details.

[5] According to Mansfield et al. (1971), a survey of 120 large companies doing a substantial amount of R&D indicated that, in half of these firms, at least 60% of the R&D projects never resulted in a commercially used product or process. See also, for example, Schmookler (1966), Aghion and Howitt (1992), and Grossman and Helpman (1991).

Effects of competition on deterministic investment in cost reduction (which is continuous improvement in our terminology) have been previously explored by a number of theoretical studies. A recent theoretical study by Vives (2008) has shown that, when competitive pressure is measured by product substitutability, an increase in competitive pressure (weakly) *increases* cost reduction expenditure per firm under all commonly used demand systems he considered, provided that the average demand for varieties does not shrink. See Section 2 for details on the related literature.

We introduce discrete innovation in a standard two-stage price-competition duopoly model à la Hotelling with deterministic investment in cost reduction (continuous improvement), and find that the interplay between continuous improvement and discrete innovation can overturn the previous finding. That is, we show that an increase in product substitutability *decreases* firms' incentives to invest in continuous improvement in a broad range of parameterizations, even when the average demand for varieties does not shrink.

The main logic behind our result can be explained as follows. For the sake of exposition, take the following extreme case: when discrete innovation succeeds and a new cost-reduction technology is introduced, continuous improvement made on the existing technology will become completely useless.[6] The firm with unsuccessful discrete innovation will have cost disadvantage over its rival firm with successful discrete innovation, and hence lose its market share to the rival firm. Increased competition, which manifests in our model as increased product substitutability and hence diminished product differentiation, results in an increase in the relative importance of cost as a determinant of market share. It follows that increased competition amplifies the cost disadvantage of the firm with unsuccessful discrete innovation, and therefore makes its loss of market share even greater.

Return to investment in continuous improvement will be zero ex post if discrete innovation succeeds. Hence, the firm's ex ante investment decision on continuous improvement will depend crucially on what will happen when discrete innovation DOES NOT succeed. As discussed above, as competition intensifies, the firm's loss of market share in the event of failed discrete innovation will increase. The increased loss of market share implies that the firm will further lose its opportunities to recoup investment in continuous improvement, and hence that return on investment in continuous improvement will fall.[7] That is, as competition increases, continuous improvement on the existing technology becomes less effective because of the possibility that the rival firm succeeds in discrete innovation. The firm, facing lower return from deterministic cost reduction, invests less in continuous improvement.

We explore the real-world relevance and usefulness of the model through field research in Section

[6]As stated at the end of Section 4, our results still hold for more realistic cases in which continuous improvement will be still somewhat useful even if discrete innovation succeeds, insofar as continuous improvement will be less useful for a new technology than for the existing technology.

[7]More precisely, increased competition lowers ex post return as well as ex ante return from investment in continuous improvement, given an exogenously-determined probability of discrete innovation failure. We will show in Section 5 that endogenizing the probability of discrete innovation failure will little affect our results.

6. Continuous improvement had been regarded as an important source of strength in Japanese manufacturing until the 1980s. However, several studies have found that levels of continuous improvement have recently decreased in a number of Japanese manufacturing firms. To understand the causes of the declining focus on continuous improvement in Japan, we conducted detailed field research at two Japanese manufacturing firms, AUTOPARTS and METAL.

In AUTOPARTS, competition intensified in the 1990s because of an increase in product substitutability, and the tie between AUTOPARTS and its main customer, AUTOMAKER, became weaker. About the same time, AUTOPARTS decreased the level of continuous improvement and increased its investment in product and process innovation. Through capturing a possible interconnection among these changes, our analysis suggests that the rise in competitive pressure can be a cause of the declining continuous improvement at AUTOPARTS.

How do changes in the nature of discrete innovation affect firms' incentives to conduct continuous improvement? Our analysis predicts that an increase in the size of discrete innovation decreases firms' incentives to conduct continuous improvement in a broad range of parameterizations. In Section 6, we discuss an application of this theoretical result to the findings from the other field research undertaken at METAL.

2 Relationship to the literature

Effects of competition on deterministic investment in cost reduction (continuous improvement in our terminology) have been previously explored by a number of theoretical studies (see, for example, Dasgupta and Stiglitz, 1980; Spence, 1984; Tandon, 1984; Boone, 2000; Vives, 2008). Recently, Vives (2008) contributed to the literature by investigating competitive pressure and innovation incentives under general functional specifications of demand system.[8,9]

Consider a price-competition oligopoly model with differentiated products, where each of n *ex-ante* symmetric firms decides how much to invest in R&D to reduce its constant marginal cost of production. In this class of models, firms' incentives to invest in R&D depend on the output per firm because the value of a reduction in unit cost increases with the output produced by the firm. Changes in product substitutability have direct effects on equilibrium outputs through affecting consumers' utility and indirect effects on them through changing the degree of price pressure. Regarding the indirect effect, Vives (2008) showed that an increase in competitive pressure caused by an increase in product substitutability decreases equilibrium prices under all commonly used demand systems he considered, and this works in the direction of increasing the equilibrium output

[8] Vives (2008) analyzed not only the degree of product substitutability but also the number of firms as a measure of competitive pressure, and analyzed not only the case of restricted entry but also the case of free entry.

[9] In models that analyze the timing of innovation (i.e. "patent race" type models), R&D investment either stochastically or deterministically affects the eventual date at which an innovation is successfully introduced, where higher level of investment results in faster innovation. See, for example, Loury (1979), Lee and Wilde (1980), Mortensen (1982), and Reinganum (1982, 1985). See also Reinganum (1989) for a survey on the literature.

per firm. Consequently, an increase in product substitutability (weakly) increases cost reduction expenditure per firm, as long as the average demand for varieties does not shrink through the direct effect.[10]

We consider a standard two-stage price-competition duopoly model à la Hotelling (1929) with deterministic investment in cost reduction (continuous improvement). In symmetric equilibria of the model, changes in product substitutability have no effects on each firm's output and hence have no effects on firms' incentives to invest in cost reduction, as long as the entire market is covered in the equilibrium. This result was shown by Baggs and de Bettignies (2007) (see also de Bettignies, 2006). Also, an equivalent result under the "circular city" model à la Salop (1979) was shown by Raith (2003) and constitutes a part of Vives' finding that an increase in product substitutability (weakly) increases cost reduction expenditure per firm, provided that the average demand for varieties does not shrink (see Table 1 of Vives, 2008).

We introduce discrete innovation in the Hotelling model, and find that the interplay between continuous improvement and discrete innovation can overturn the previous finding. As competition increases, the firm's return on continuous improvement on the existing technology falls because of the possibility that its rival firm succeeds in discrete innovation while its own discrete innovation fails, decreasing the equilibrium level of investment in continuous improvement. The driving force of our result is the idea that continuous improvement made upon the existing technology is less effective for the new technology introduced upon successful discrete innovation.

Several recent papers analyzed firms' incentives to invest in inventing new technologies and their incentives to improve production efficiency of the invented new technology in the presence of competitive pressure. In Boone's (2000) analysis of the effects of competitive pressure on firms' innovation incentives, each agent decides whether to enter the market with a new product and, if he/she enters, how much to invest to improve its production efficiency. Also, the patent-design literature has addressed two-stage innovation, where a second innovation builds upon the first (see, for example, Green and Scotchmer, 1995; Chang, 1995). These papers do not capture the idea that improvement made upon the existing technology becomes obsolete when new technology is introduced.

Relationships between competition or market structure and innovation have been investigated in the empirical industrial organization literature as well. Recent papers in this literature pointed to a positive correlation between product market competition and innovative activity (see e.g. Geroski, 1990; Nickell, 1996; Blundell, Griffith and Van Reenen, 1999) or an inverted-U relationship (Aghion, Bloom, Blundell, Griffith, and Howitt, 2005). Geroski (1990) used data based on a study of 4378 major innovations in the UK, 1945-83, Blundell et al. (1999) used a count of "technologically

[10] It is known that an increase in product substitutability may decrease cost reduction expenditure per firm, if the average demand for varieties does shrink. For example, Sacco and Schmutzler (2009) found a U-shaped relation between competition and investment by studying a linear differentiated duopoly model (see Dixit, 1979; Singh and Vives, 1984), in which the average demand for varieties shrinks as the degree of product substitutability increases.

significant and commercially important" innovations commercialized by the firm, and Aghion et al. (2005) used the average number of patents taken out by firms in an industry where each patent is weighed by the number of times it has been cited by another patent. Nickell (1996) found that competition is associated with higher rates of total factor productivity growth. To the best of our knowledge, no papers in this literature addressed the kind of interplay between continuous improvement and discrete innovation captured by our analysis.

Distinctions between different types of technological change have been explored in several endogenous growth models. For example, Jovanovic and Rob (1990) formalized the distinction between extensive and intensive search, where extensive search seeks major breakthroughs while intensive search attempts to refine such breakthroughs. Also, Young (1993) developed a model that incorporates an interaction between invention and learning by doing, and Aghion and Howitt (1996) introduced the distinction between research and development into Schumpeterian growth model. Redding (2002) proposed a model of endogenous innovation and growth, in which technological progress is the result of a combination of "fundamental innovations" (which opens up whole new areas for technological development) and "secondary innovations" (which are the incremental improvements that realize the potential in each fundamental innovation). As in our model, Redding's model incorporates the idea that the secondary knowledge acquired for one fundamental technology has often limited relevance for the next. However, Redding focuses on path dependence and technological lock-in of technological progress, and does not incorporate competitive pressure in his analysis.

In summary, although relationships between competitive pressure and firms' innovation incentives have been previously investigated, existing analyses in the literature did not address the idea that continuous improvement made upon the existing technology is less effective for the new technology introduced upon successful discrete innovation. Distinctions between different types of technological change have been explored in endogenous growth models as well as in industrial organization models. However, to our knowledge, Redding (2002) is the only previous analysis that explored the kind of interplay between different types of technological change addressed by our analysis, and his analysis does not incorporate competitive pressure, which is a central element of our analysis. Our contribution, therefore, is to demonstrate that the interplay between continuous improvement and discrete innovation can overturn the previous findings concerning the effect of competition on deterministic investment in cost reduction. Furthermore, we explore the real-world relevance and usefulness of our model through field study.

3 Model

We consider a Hotelling-style duopoly model in which firms' locations are fixed. Assume that a unit mass of consumers are uniformly distributed on the line segment $[0, 1]$. Each consumer is indexed by her location $y \in [0,1]$ on the line, which represents her ideal point in the product characteristic space. Each consumer buys at most one unit of exactly one of the two varieties sold in the market. The price and location of variety i ($= A$, B) on the line are denoted by p_i and z_i respectively where $z_i \in [0,1]$ for all i ($= A$, B). The indirect utility for consumer $y \in [0,1]$ of purchasing one unit of variety i is given by $V_i(y) = R - p_i - t|z_i - y|$, where R is the gross utility from consuming one unit of any variety, $|z_i - y|$ denotes the distance between z_i and y, and $t > 0$ denotes per unit transport cost. The utility from not purchasing any variety is normalized to zero.

There are two firms, denoted A and B, located respectively at 0 and 1 (and hence $z_A = 0$ and $z_B = 1$). Firm i ($= A$, B) sells variety i at price p_i. Each firm i has a constant marginal cost c_i and no fixed costs of production. Each firm i can reduce its constant marginal cost under the existing technology from c (> 0) to $c - x_i$ by investing $d(x_i)$ in **continuous improvement** (CI), where $d(.)$ is a convex function and $x_i \in [0, X]$ ($X \in (0, c)$). To obtain closed form solutions in the analysis, let $d(x) = \frac{\gamma x^2}{2}$ ($\gamma > 0$).

Concerning **discrete innovation** (DI), in our base model we assume that each firm i has invested in DI at the same level and introduces the new technology with a success probability $s \in (0,1)$. We assume that the level of DI is not affected by competitive pressure and treat the cost for DI as a sunk cost. This simplifying assumption helps us focus our analysis on the effects of competitive pressure on firms' incentives to undertake CI in the presence of DI and grasp basic logic and intuition behind our results. In Section 5 we show that the qualitative nature of our results remains mostly unchanged when we endogenize the firms' investments in DI. As pointed out in Introduction, in general discrete innovation involves significant uncertainty, which is captured by s. Assume that the two firms' successes in DI are mutually independent. This assumption is for simplifying the algebra, and not crucial for our results.

The model incorporates the interplay between CI and DI as follows. Suppose that firm i invested in CI at the level of x_i, and that its investment in DI turns out to be successful. If firm i adopts the new technology introduced by the successful DI, its constant marginal cost is $c_i = c - \Delta$, where $\Delta \in (0, c)$ denotes the cost reduction associated with the new technology. If firm i stays with the old technology, then $c_i = c - x_i$. A simplifying assumption we are making here is that continuous improvement made on the existing technology is not at all effective for the new technology. The qualitative nature of our results, however, remains unchanged under a more general setup in which continuous improvement is less (rather than not at all) effective for the new technology (see the last two paragraphs of Section 4). We assume $X < \Delta$, which implies that the successful DI is more cost effective than the highest possible level of CI made upon the existing technology.[11] Each firm that has succeeded in DI chooses the new technology under this assumption.

[11] This assumption is not crucial for our results, but simplifies the description of our results by reducing the number of cases to be considered.

Following previous analyses in the industrial organization literature (see, for example, Raith, 2003; Aghion and Schankerman, 2004; Baggs and de Bettignies, 2007; Vives, 2008), we interpret that the per unit transport cost, t, captures the degree of competitive pressure between firms. That is, a reduction in t increases the substitutability between the products of firms A and B, which in turn intensifies the competition between them.

We consider the two-stage game described below:

Stage 1 [Investment]: Each firm i simultaneously and non-cooperatively chooses $x_i \in [0, X]$, the level of investment in CI.

Stage 2 [Price competition]: The outcomes of DI are realized and become common knowledge. Each firm i's constant marginal cost of production is $c_i = c - \Delta$ if DI turns out to be successful, and $c_i = c - x_i$ otherwise. Given (c_A, c_B), each firm i simultaneously and non-cooperatively chooses p_i to maximize its profit.

Investments in cost reduction versus quality enhancement

In our model, we incorporate both CI and DI as investments in cost reduction (process innovation). Our results, however, remain unchanged under alternative model setups in which CI and/or DI are investments in quality enhancement (product innovation), affecting the product's gross utility R instead of the constant marginal cost c. For instance, we can interpret DI to be an investment in the development of a new product. Suppose that, if firm i's investment in DI turns out to be successful, then firm i chooses the new product ($R_i = R + \Delta$ and $c_i = c$) or the existing product with a reduced cost due to CI ($R_i = R$ and $c_i = c - x_i$), where R_i denotes the gross utility of firm i's product. The results under this alternative setup are the same as the ones under the setup described above. The results also remain unchanged under two other possible combinations: (i) A success in DI increases R_i by Δ while CI increases R_i by x_i, or (ii) A success in DI reduces c_i by Δ while CI increases R_i by x_i.

In other words, the distinction between product innovation (quality enhancement) and process innovation (cost reduction) is not the focus of our analysis.[12] The focus is the idea that continuous improvement on the existing technology is less effective for the new technology introduced by a successful discrete innovation. Note also that our distinction between continuous improvement and discrete innovation is fundamentally different from the distinction between drastic (or major) innovation and nondrastic (or minor) innovation made in Tirole (1988).[13]

[12] A number of papers have previously studied product and process innovation theoretically as well as empirically. See, for example, Utterback and Abernathy (1975), Filson (2001), and Klepper (1996) for analyses on evolutionary pattern of product and process innovation, and Cohen and Klepper (1996) for a study of the effect of firm size on the two types of innovation. Also, Athey and Schmutzler (1995) studied the relationship between a firm's organizational structure and its implementation of product and process innovation, and Saha (2007) explored the relationship between consumer preferences and the two types of innovation.

[13] Tirole (1988) made a distinction between drastic and nondrastic innovation in his analysis of the gain from innovation to a firm that is the only one to undertake R&D, using a process innovation as an example. If the process innovation reduces the innovator's cost drastically, the innovator charges a monopoly price to maximize its profit

4 Analysis

We derive Subgame Perfect Nash Equilibria (SPNE) in pure strategies of the model described above, focusing on symmetric equilibria. Given that competitive pressure is a critical element in our analysis, we assume that the gross utility from consuming a variety (captured by R) is high enough so that the two firms compete over all consumers in the equilibrium.[14] We also assume that γ (the cost parameter for investment in CI) is large enough to ensure an interior solution for the equilibrium level of investment in CI.[15]

First consider stage 2 subgames. At stage 2, given a cost vector (c_A, c_B), each firm i simultaneously and non-cooperatively chooses p_i to maximize its profit. Let (p_A, p_B) be given, and suppose that R is sufficiently large so that all consumers purchase one unit of a variety. Then, consumer $y \in [0,1]$ purchases variety A from firm A if $p_A + ty \leq p_B + t(1-y) \Leftrightarrow y \leq \frac{1}{2} + \frac{p_B - p_A}{2t}$. We then find that demand for variety i, denoted $q_i(p_i, p_j)$, is given by $q_i(p_i, p_j) = \max\{0, \frac{1}{2} + \frac{p_j - p_i}{2t}\}$ if $\frac{1}{2} + \frac{p_j - p_i}{2t} \leq 1$, and 1 otherwise, where $i, j = A, B$, $i \neq j$. Each firm i chooses p_i to maximize $(p_i - c_i)q_i(p_i, p_j)$, where $c_i = c - \Delta$ if firm i succeeds in DI and $c_i = c - x_i$ otherwise. If $|c_A - c_B| \leq 3t$, the SPNE outcome of the stage 2 subgame is characterized as follows:

$$\tilde{p}_i(c_i, c_j) \equiv t + \frac{2c_i + c_j}{3}, \tilde{q}_i(c_i, c_j) \equiv \frac{1}{2} + \frac{c_j - c_i}{6t}, \tag{1}$$

$$\tilde{\pi}_i(c_i, c_j) \equiv (\tilde{p}_i(c_i, c_j) - c_i)\tilde{q}_i(c_i, c_j) = 2t\tilde{q}_i(c_i, c_j)^2, \tag{2}$$

where $i, j = A, B$, $i \neq j$, and $\tilde{p}_i(c_i, c_j)$, $\tilde{q}_i(c_i, c_j)$ and $\tilde{\pi}_i(c_i, c_j)$ denote firm i's equilibrium price, quantity and profit, respectively. Else, if $|c_A - c_B| > 3t$ then

$$\tilde{p}_i(c_i, c_j) = I(c_j - t) + (1 - I)c_i, \quad \tilde{q}_i(c_i, c_j) = I, \tag{3}$$

$$\tilde{\pi}_i(c_i, c_j) = I(c_j - c_i - t), \tag{4}$$

where the indicator variable $I = 1(0)$ if and only if $c_i < (>)c_j$.

In stage 1, each firm i chooses x_i to maximize its expected overall profit, which is given by

$$s\pi_i^S(x_i, x_j) + (1 - s)\pi_i^F(x_i, x_j) - \frac{\gamma x_i^2}{2}, \tag{5}$$

where $i, j = A, B$ $(i \neq j)$, $\pi_i^S(x_i, x_j)$ denotes each firm i's expected stage 2 profit conditional upon

because the presence of non-innovating firms impose no restrictions on its pricing strategy. The innovation is drastic in this case. And the innovation is nondrastic if the presence of non-innovators imposes restrictions on the innovator's pricing strategy.

[14] More precisely, we assume that the value of R is high enough so that the following property holds: Every consumer who purchases a product from firm i $(= A, B)$ in the equilibrium could enjoy a positive indirect utility by purchasing a product from firm j $(\neq i)$, instead, at its equilibrium price.

[15] In particular, we assume that $\gamma > \max\{\frac{1}{9t}, \frac{1}{3X}\}$.

its success in DI, and $\pi_i^F(x_i, x_j)$ is analogously defined conditional upon its failure in DI. Recall that $c_i = c - \Delta$ upon firm i's success in DI, while $c_i = c - x_i$ upon its failure. Hence we have

$$\pi_i^S(x_i, x_j) = s\tilde{\pi}_i(c - \Delta, c - \Delta) + (1 - s)\tilde{\pi}_i(c - \Delta, c - x_j), \tag{6}$$

$$\pi_i^F(x_i, x_j) = s\tilde{\pi}_i(c - x_i, c - \Delta) + (1 - s)\tilde{\pi}_i(c - x_i, c - x_j). \tag{7}$$

Given this, we find that the symmetric pure-strategy equilibrium of the entire game is unique, and in the equilibrium each firm i chooses $x_i = x^*$ (see Claim 1 in Appendix A), where

$$x^* \equiv \max\{\frac{(1 - s)(3t - s\Delta)}{9t\gamma - s(1 - s)}, \frac{(1 - s)^2}{3\gamma}\}. \tag{8}$$

We are now ready to present comparative statics results concerning x^*, the equilibrium level of CI. We first explore the effect of competitive pressure on x^*.

Proposition 1: The equilibrium level of continuous improvement, x^*, decreases as the degree of competitive pressure increases. More precisely, there exists a threshold value $\bar{\Delta} \equiv 3t + \frac{(1-s)^2}{3\gamma} > 0$ such that $\frac{dx^*}{dt} > 0$ if $\Delta < \bar{\Delta}$ while $\frac{dx^*}{dt} = 0$ if $\Delta > \bar{\Delta}$.

Recall that competitive pressure is measured by product substitutability (captured by t) in the model, where lower t is interpreted as higher competitive pressure. As detailed in Section 2, previous studies have shown that changes in product substitutability have no effects on firms' investments in deterministic cost reduction in the Hotelling model as long as the entire market is covered in the equilibrium. This result consists a part of Vives' (2008) finding that an increase in product substitutability (weakly) increases cost reduction expenditure per firm, provided that the average demand for varieties does not shrink. Proposition 1 tells us that the interplay between CI and DI overturns the previous result. That is, as product substitutability increases, the equilibrium level of CI decreases in the presence of DI (i.e., higher competitive pressure results in lower x^*).

To understand the logic, let $x_i = x_j = x$ and consider firm i's expected return from CI. Recall that CI made on the existing technology is not effective for a new technology introduced by a successful DI, and hence firm i's return to investment in CI is zero ex post if its discrete innovation succeeds.[16]

Suppose firm i fails in DI. If firm j ($\neq i$) succeeds in DI, firm i has cost disadvantage over firm j (i.e., $c_i = c - x > c_j = c - \Delta$), and hence firm i's equilibrium quantity is less than firm j's quantity; that is, $\tilde{q}_i(c - x, c - \Delta) < \frac{1}{2} < \tilde{q}_j(c - \Delta, c - x)$. We find that $\tilde{q}_i(c - x, c - \Delta)$ decreases as t decreases. An increase in product substitutability (i.e., a decrease in t) means a decrease in the degree of product differentiation, which implies an increase in the relative importance of cost as the source of competitive advantage. In other words, increased competition amplifies firm i's cost

[16]See the last two paragraphs in this section for robustness of our result with respect to this assumption.

disadvantage, and therefore reduces firm i's equilibrium quantity. In contrast, if both firms i and j fail in DI, there are no cost differences between them and hence firm i's quantity $\tilde{q}_i(c-x, c-x) = \frac{1}{2}$ remains unchanged as competition intensifies. Then, conditional upon firm i's failure in DI, firm i's expected quantity decreases as competition intensifies. We call it the *share-reduction effect* of competition, which is a new effect arising from the interplay between CI and DI.

At stage 1, firm i chooses the level of its investment in CI, anticipating that it will fail in DI with probability $1 - s$. Then, as competition intensifies, the share-reduction effect reduces firm i's incentive to invest in CI, because it can apply unit-cost reduction through CI to smaller expected amount of its production. The share-reduction effect, therefore, is an important driving force of our result.

There are two other effects at work: *business-stealing effect* and *rent-reduction effect.* These two effects have been explored by several recent studies in the literature.[17] As t decreases, consumers become more price sensitive. This implies that, by reducing its cost by CI, firm i can more easily increase its quantity at the expense of a reduction in its rival firm j's quantity (hence called business-stealing effect). At the same time, a decrease in t also leads to lower equilibrium prices, diminishing the price-cost margin (rent-reduction effect).

In the event that firm i fails but firm j succeeds in DI, the share-reduction effect works in the direction of reducing firm i's marginal return from CI as competition intensifies. Although the business-stealing effect works in the opposite direction, we find that this effect is dominated by the rent-reduction effect. Also, in the event that both firms fail in DI, the share-reduction effect is absent and the business-stealing effect and the rent-reduction effect exactly cancels out each other (see Raith, 2003; Baggs and de Bettignies, 2007). Hence, a decrease in t decreases each firm's expected marginal return from investing in CI, resulting in Proposition 1. See Appendix B for detailed explanation for the mechanism behind Proposition 1.

We now turn to the next question: How do changes in the nature of DI affect firms' incentives to invest in CI?

Proposition 2: The equilibrium level of continuous improvement, x^*, decreases as the size of discrete innovation increases. More precisely, $\frac{dx^*}{d\Delta} < 0$ if $\Delta < \bar{\Delta}$ while $\frac{dx^*}{d\Delta} = 0$ if $\Delta > \bar{\Delta}$, where $\bar{\Delta}$ is as defined in Proposition 1.

Competitive pressure plays a crucial role in driving this result. To see this, first consider what happens without competition by supposing that firm i is a monopolist, investing in CI and DI. Then, since firm i's investment in CI will be effective only when it fails in DI, the size of DI does not affect firm i's incentive to invest in CI.

[17] Rent-reduction effect is the terminology used by de Bettignies (2006) and Baggs and de Bettignies (2007). Raith (2003) labeled this effect as a *scale effect.*

The presence of competition changes the result. Firm i's expected return from investing $x_i = x$ in CI is affected by the size of DI, Δ, in the event that firm i fails and its rival firm j succeeds in DI. In this case, firm i's equilibrium quantity is $\tilde{q}_i(c - x, c - \Delta)$, where $c - x > c - \Delta$. Firm i's cost disadvantage increases as Δ increases, and this in turn reduces $\tilde{q}_i(c - x, c - \Delta)$. This implies that, conditional upon firm i's failure in DI, firm i's expected quantity decreases as Δ increases, reducing firm i's expected marginal return from CI. Hence the equilibrium level of CI is decreasing in the size of DI. In the presence of competition, it is the possibility of firm i's rival's success in DI that reduces firm i's incentive to invest in CI.

Finally, in Proposition 3 we consider the effect of a change in the success probability of DI (denoted s).

Proposition 3: The equilibrium level of continuous improvement, x^*, decreases as the success probability of discrete innovation increases. That is, $\frac{dx^*}{ds} < 0$.

Logic behind the result is simple. Given each firm i's investment in CI is effective only when it fails in DI, its marginal benefit of investing in CI decreases as the success probability of DI increases. This implies the result.

Partially effective CI ***for the new technology***

We have assumed that continuous improvement on the existing technology is not at all effective for a new technology introduced by successful DI. We have considered a more general setup in which continuous improvement is partially effective for the new technology. To this end, suppose that, if firm i invests in CI at the level of x_i, then its constant marginal cost upon its success in DI is $c_i = c - (\Delta + ax_i)$ where $0 \leq a < 1$. As a increases, continuous improvement on the existing technology becomes more applicable to the new technology. Note that in this setup, our base model is nested as a special case of $a = 0$. We have found that our main results, Propositions 1-3, still hold in this setup. See Supplementary Note for details.

What if $a = 1$? That is, what would happen in the model if the effectiveness of CI remains unchanged whether or not the firm succeeds in DI? In the model with $a = 1$, DI can be interpreted as random cost shocks that could reduce the firm's marginal cost by Δ. We find that our main results do not hold when $a = 1$. In other words, main insights of our analysis do not arise when DI is replaced by random cost shocks. This indicates that a key driving force of our results is the idea that the improvement made upon the existing technology is less effective for the new technology introduced by a successful discrete innovation.

5 Endogenizing the success probability of DI

In our base model we have assumed that each firm i has invested in DI at the same level and that the level of DI is not affected by competitive pressure, treating the success probability of DI, s, as a parameter of the model. In this subsection, we endogenize the success probability of DI by explicitly modeling firms' investments in DI, and discuss the robustness of our findings. Suppose each firm i $(= A, B)$ can increase the success probability by increasing its investment in DI. In particular, suppose that each firm i's success probability, denoted $s_i \in [0, \theta)$ (where $\theta \in (0, 1)$ is a given parameter), is determined by $F(s_i)$, where the investment cost function $F(.)$ is a twice continuously differentiable function with the following properties: (i) $F(0) = 0$, (ii) $F'(s) > 0$ and $F''(s) > 0$ for all $s \in (0, \theta)$, and (iii) $\lim_{s \to 0} F'(s) = 0$ and $\lim_{s \to \theta} F'(s) = \infty$. An example of $F(.)$ satisfying these conditions is $F(s) = ks/(\theta - s)$ for $s \in (0, \theta)$, where $k > 0$ is a given constant. For the remainder of this section we assume that $\Delta < 3t$, which ensures that each firm invests a strictly positive amount in continuous improvement. The timing of the game is as follows. At stage 1, each firm i $(= A, B)$ chooses $x_i \in [0, X]$ and $s_i \in [0, \theta)$, and incurs investment costs $d(x_i)$ and $F(s_i)$ respectively, where the cost function of continuous improvement $d(.)$ has the same property as in the original model and $F(s_i)$ is as described above. Stage 2 is the same as in the original model.

Corresponding to (s_i, s_j, x_i, x_j), let

$$\Pi_i(s_i, s_j, x_i, x_j) \equiv s_i \pi_i^S(s_j, x_i, x_j) + (1 - s_i)\pi_i^F(s_j, x_i, x_j) - \frac{\gamma x_i^2}{2} - F(s_i) \tag{9}$$

denote firm i's expected overall profit in stage 1, where $i, j = A, B$ $(i \neq j)$, and

$$\begin{aligned} \pi_i^S(s_j, x_i, x_j) &= s_j \tilde{\pi}_i(c - \Delta, c - \Delta) + (1 - s_j)\tilde{\pi}_i(c - \Delta, c - x_j), \\ \pi_i^F(s_j, x_i, x_j) &= s_j \tilde{\pi}_i(c - x_i, c - \Delta) + (1 - s_j)\tilde{\pi}_i(c - x_i, c - x_j). \end{aligned}$$

In stage 1, each firm i $(= A, B)$ chooses s_i and x_i to maximize its expected overall profit, $\Pi_i(s_i, s_j, x_i, x_j)$.

There always exists a symmetric equilibrium, i.e., $s_A = s_B = s^* \in (0, \theta)$ and $x_A = x_B = x^* \in (0, X)$, which satisfy the standard first order conditions,

$$\frac{\partial \Pi_i(s^*, s^*, x^*, x^*)}{\partial s_i} \equiv \frac{\Delta - x^*}{3}[1 - \frac{(2s^* - 1)(\Delta - x^*)}{6t}] - F'(s^*) \equiv G(s^*, x^*; t, \Delta) = 0, \tag{10}$$

$$\frac{\partial \Pi_i(s^*, s^*, x^*, x^*)}{\partial x_i} \equiv \frac{1 - s^*}{3}[1 - \frac{s^*(\Delta - x^*)}{3t}] - \gamma x^* \equiv H(s^*, x^*; t, \Delta) = 0, \tag{11}$$

and the following inequality:

$$\left|\frac{\frac{\partial G(s^*, x^*; t, \Delta)}{\partial x}}{\frac{\partial G(s^*, x^*; t, \Delta)}{\partial s}}\right| < \left|\frac{\frac{\partial H(s^*, x^*; t, \Delta)}{\partial x}}{\frac{\partial H(s^*, x^*; t, \Delta)}{\partial s}}\right|. \tag{12}$$

The inequality holds if the symmetric equilibrium is unique. If there are multiple symmetric equilibria, we find that the inequality holds for extremal equilibria — a class of equilibria often considered for comparative statics in an environment with multiple equilibria.[18] For the purposes

[18]See, for example, pp. 106-7 in Vives (1999) for a discussion of comparative statics on extremal equilibria in context of Cournot competition. Below, we briefly describe the extremal equilibria in context of our framework. Let $\hat{x}(s; t, \Delta)$

of comparative statics, we restrict our attention to (s^*, x^*) which satisfy (10), (11) and (12).

Now we are ready to explore the effect of competitive pressure on equilibrium level of continuous improvement, x^*.

Proposition 4: The equilibrium level of continuous improvement, x^*, decreases as the degree of competitive pressure increases (that is, $\frac{dx^*}{dt} > 0$ holds) in a range of parameterizations. In particular, $\frac{dx^*}{dt} > 0$ holds whenever $\theta < \frac{1}{2}$ holds.

Competitive pressure affects x^* not only directly but also indirectly through changing s^*. Thus we can decompose $\frac{dx^*}{dt}$ as follows:

$$\frac{dx^*}{dt} = \frac{\partial x^*}{\partial t} |_{s=s^*} + \frac{\partial x^*}{\partial s} |_{s=s^*} \frac{ds^*}{dt}. \tag{13}$$

The direct effect of competitive pressure is captured by $\frac{\partial x^*}{\partial t}$, and Proposition 1 tells us that $\frac{\partial x^*}{\partial t} > 0$ for any given s. Hence we have $\frac{\partial x^*}{\partial t} |_{s=s^*} > 0$. Also, Proposition 3 implies that $\frac{\partial x^*}{\partial s} |_{s=s^*} < 0$. Hence, a sufficient condition for $\frac{dx^*}{dt} > 0$ to hold is $\frac{ds^*}{dt} < 0$.

We find that $\frac{ds^*}{dt} < 0$ holds when s^* is small enough, and that $\theta < \frac{1}{2}$ is a sufficient condition to ensure $\frac{ds^*}{dt} < 0$ for all relevant t. To see the logic behind this result, let us consider firm i's marginal return from increasing its success probability in DI in the equilibrium, holding $s_j = s^*$ and $x_i = x_j = x^*$ fixed. The marginal return is

$$\begin{aligned} \frac{\partial}{\partial s_i}\Pi_i(s^*, s^*, x^*, x^*) &= s^*[\tilde{\pi}_i(c-\Delta, c-\Delta) - \tilde{\pi}_i(c-x^*, c-\Delta)] \\ &\quad +(1-s^*)[\tilde{\pi}_i(c-\Delta, c-x^*) - \tilde{\pi}_i(c-x^*, c-x^*)]. \end{aligned} \tag{14}$$

How is the marginal return affected by a change in competitive pressure? More specifically, what is the sign of $\frac{\partial^2}{\partial t \partial s_i}\Pi_i(s^*, s^*, x^*, x^*)$? We find that each firm's equilibrium profit is most sensitive to a change in competitive pressure when both firms have the same cost, and the profit becomes less sensitive to competitive pressure as cost asymmetry increases.[19] In the context of equation (14), this implies that $\frac{\partial}{\partial t}[\tilde{\pi}_i(c-\Delta, c-\Delta) - \tilde{\pi}_i(c-x^*, c-\Delta)] > 0$ and $\frac{\partial}{\partial t}[\tilde{\pi}_i(c-\Delta, c-x^*) - \tilde{\pi}_i(c-x^*, c-x^*)] < 0$, which in turn implies that $\frac{\partial^2}{\partial t \partial s_i}\Pi_i(s^*, s^*, x^*, x^*) < 0$ holds when s^* is small enough. Since an increase in t decreases firm i's marginal return from investing in DI, this results in $\frac{\partial s^*}{\partial t} < 0$ when

denote the unique value of x that solves $\frac{\partial \Pi_i(s,s,x,x)}{\partial x_i} = 0$ for given s, t, and Δ. Then, $G(s^*, \hat{x}(s^*; t, \Delta); t, \Delta) = 0$. Suppose there are $K(> 1)$ values of s^* which satisfy $G(s^*, \hat{x}(s^*; t, \Delta); t, \Delta) = 0$. Label those values as $s^*(1), s^*(2), .., s^*(K)$ such that $s^*(1) < s^*(2) < .. < s^*(K)$. Then $(s^*, x^*) = (s^*(1), \hat{x}(s^*(1); t, \Delta))$ and $(s^*, x^*) = (s^*(K), \hat{x}(s^*(K); t, \Delta))$ are extremal equilibria. Since $G(0, \hat{x}(0; t, \Delta); t, \Delta) > 0$ and $\lim_{s \to \theta} G(s, \hat{x}(s; t, \Delta); t, \Delta) < 0$, it follows that at the extremal equilibria, $\frac{dG(s^*, \hat{x}(s^*; t, \Delta); t, \Delta)}{ds} < 0$. This in turn implies that $|\frac{\frac{\partial G(.)}{\partial x}}{\frac{\partial G(.)}{\partial s}}| < |\frac{\frac{\partial H(.)}{\partial x}}{\frac{\partial H(.)}{\partial s}}|$.

[19]We have that $\frac{\partial}{\partial t}\tilde{\pi}_i(c_i, c_j) = \frac{1}{2} - \frac{(c_i - c_j)^2}{18t^2}$ as long as each firm produces a positive amount and the entire market is covered in the equilibrium. Hence $\frac{\partial}{\partial t}\tilde{\pi}_i(c_i, c_j)$ is monotone decreasing in $c_i - c_j$, which captures the degree of cost asymmetry.

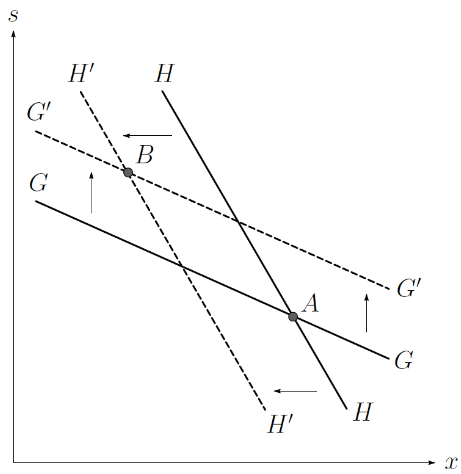

Figure 1: Effect of competition on CI and DI

s^* is small enough. Furthermore, we find that $\frac{\partial s^*}{\partial t} < 0 \Rightarrow \frac{ds^*}{dt} < 0$ under condition (12) (see Claim 3 in Appendix A).

Note that $\theta < \frac{1}{2}$ is sufficient but not necessary for the equilibrium level of continuous improvement to decrease as the degree of competitive pressure increases. If $\theta > \frac{1}{2}$, $\frac{ds^*}{dt} < 0$ can still hold but there is a probability of $\frac{ds^*}{dt} > 0$. In the latter case we have $\frac{\partial x^*}{\partial s}|_{s=s^*} \frac{ds^*}{dt} < 0$. However, as long as the direct effect of competition on x^* is dominant, i.e., $\frac{\partial x^*}{\partial t}|_{s=s^*} > \left|\frac{\partial x^*}{\partial s}|_{s=s^*} \frac{ds^*}{dt}\right|$, we still have $\frac{dx^*}{dt} > 0$.

Figure 1 illustrates the effect of competition on equilibrium CI and DI. HH comprises of all pairs of (x, s) that satisfy $\frac{\partial \Pi_i(s,s,x,x)}{\partial x_i} \equiv H(s, x; t, \Delta) = 0$. In other words, HH gives the level of CI in a symmetric equilibrium corresponding to a success probability s, which is assumed to be the same for both firms (i.e., $s_1 = s_2 = s$). Since an increase in s reduces the incentives to invest in CI (see Proposition 3), HH is downward sloping. Now consider GG which consists of all pairs of (x, s) that satisfy $\frac{\partial \Pi_i(s,s,x,x)}{\partial s_i} \equiv G(s, x; t, \Delta) = 0$. GG shows the level of DI in a symmetric equilibrium when $x_1 = x_2 = x$. An increase in x lowers the expected profits from DI which in turn lowers s. Hence GG is downward sloping.

Downward-sloping GG and HH capture the fact that CI and DI are strategic substitutes. Higher levels of CI reduce the marginal return from DI and vice versa. That GG is flatter than HH follows from the inequality in (12). Point A, the intersection of GG and HH, denotes (x^*, s^*) — equilibrium level of CI and DI — corresponding to a given degree of competitive pressure.

Suppose the degree of competitive pressure increases. Figure 1 illustrates how HH and GG shift in the neighborhood of initial equilibrium, (s^*, x^*). From Proposition 1 we know that for a given success probability, s, investment in CI declines as competition intensifies. So HH shifts to the left to $H'H'$. However GG can shift up or down. We have that

$$\frac{\partial^2}{\partial t \partial s_i}\Pi_i(s,s,x,x) = G_t(s,x;t,\Delta) = \frac{(2s-1)(\Delta-x)^2}{9t} < (>) 0 \;\Leftrightarrow\; s < (>) \frac{1}{2}.$$

Assume that $\theta < \frac{1}{2}$ which implies $s^* < \frac{1}{2}$. Since $G_t(s^*,x^*;t,\Delta) < 0$, GG shifts up to $G'G'$ in the neighborhood of (s^*,x^*). As HH shifts to the left and GG shifts up the equilibrium shifts northwest from A to B. Thus as the degree of competitive pressure increases, investment in DI increases while investment in CI declines.

From Figure 1 it is clear that an upward shift in GG (i.e. $G_t(s,x;t,\Delta) < 0$) is sufficient, but not necessary for CI to decline with an increase in competitive pressure. If GG shifts downwards, s^* can decline, but yet CI still increases as long as B, the intersection between HH and GG, lies in the left of A. It is nevertheless possible that CI increases with an increase in competitive pressure. If downward shift in GG is large, B may lie in the southeast of A implying that CI increases. In that case, from the diagram we can see that DI necessarily declines with an increase in competitive pressure. To see this algebraically, recall that

$$\frac{dx^*}{dt} = \left.\frac{\partial x^*}{\partial t}\right|_{s=s^*} + \left.\frac{\partial x^*}{\partial s}\right|_{s=s^*} \frac{ds^*}{dt}.$$

Since we have that $\frac{\partial x^*}{\partial t}\big|_{s=s^*} > 0$ (Proposition 1) and $\frac{\partial x^*}{\partial s}\big|_{s=s^*} < 0$ (Proposition 3), $\frac{dx^*}{dt} \leq 0$ holds only if $\frac{ds^*}{dt} > 0$.

Since HH never shifts to the right as competition intensifies, B never lies in the northeast of A. That is, an increase in competitive pressure can never increase both CI and DI, leading to the following corollary.

Corollary to Proposition 4: An increase in the degree of competitive pressure never increases both x^* and s^*. That is, at least one of $\frac{dx^*}{dt} > 0$ and $\frac{ds^*}{dt} > 0$ holds.

Concerning the effect of the size of DI, we find, as in Proposition 2, that the equilibrium level of continuous improvement decreases as the size of discrete innovation increases. To see why, decompose $\frac{dx^*}{d\Delta}$ as follows:

$$\frac{dx^*}{d\Delta} = \frac{\partial x^*}{\partial \Delta}|_{s=s^*} + \frac{\partial x^*}{\partial s}|_{s=s^*}\frac{ds^*}{d\Delta}.$$

Proposition 2 implies $\frac{\partial x^*}{\partial \Delta}|_{s=s^*} < 0$. This direct negative effect of Δ on x^* is reinforced by the impact of Δ on s^* if $\frac{ds^*}{d\Delta} > 0$, given Proposition 3 implies $\frac{\partial x^*}{\partial s}|_{s=s^*} < 0$. We found that $\frac{ds^*}{d\Delta} > 0$ holds for all relevant parameterizations. Thus $\frac{dx^*}{d\Delta} < 0$ holds as in Proposition 2 (see Claim 4 in Appendix A).

6 Applying the model to the real-world contexts

This section explores the real-world relevance and usefulness of the model. In particular, we present the findings from our field research at two Japanese manufacturing firms, and demonstrate that our model offers new insights on possible mechanisms behind the changing nature of innovation that we observed at these firms.[20]

Continuous improvement was once heralded as the hallmark of the Japanese manufacturing system; in particular, employees in typical Japanese firms had been strongly encouraged to improve their work methods by actively participating in SGAs (Small Group Activities) such as quality control (QC) circles, Zero Defects, and Kaizen in which small groups at the workplace level voluntarily set plans and goals concerning operations and work together toward accomplishing these plans and goals. However, several recent studies report that Japanese firms appear to have been downplaying the importance of continuous improvement lately.[21] To identify possible causes of the declining focus on continuous improvement in Japan, we conducted detailed field research at two Japanese manufacturing firms, AUTOPARTS and METAL.[22]

6.1 Findings from field research

6.1.1 AUTOPARTS

AUTOPARTS is a medium-size unionized manufacturing firm with sales of over 40 billion yen and employment of close to 1200 in 2004. It is a privately-held company with six plants. AUTOPARTS joined a supplier group of a major auto manufacturer, AUTOMAKER in 1949. The tie between the two firms continued to strengthen and by the end of 1980s, over 90 percent of sales of AUTOPARTS went to AUTOMAKER (a supplier group with a strong tie between a manufacturer and its suppliers is often called vertical *keiretsu* in Japan). Specifically, AUTOMAKER used unique types of engine parts that no other auto maker used, and AUTOPARTS was the only firm that supplied such unique types of engine parts. As such, AUTOPARTS faced little competition in the market for their engine parts. In part due to the overall trend in weakening keiretsu and the increased global competition, however, at the beginning of the 1990s AUTOMAKER declared its decision to switch gradually from the unique type of engine parts to the universal type of engine parts which not only AUTOPARTS

[20] For a good example of using case study to enhance the relevance and usefulness of a theoretical model, see Carmichael and MacLeod (2000).

[21] For instance, according to a recent survey conducted by Chuma, Kato and Ohashi (2005), nearly one in two SGA participants believe that SGAs are LESS active now than 10 years ago whereas only 17 percent think SGAs are MORE active now in the industry. Furthermore, the same survey reveals that 30 percent of workers experienced the termination of their small group activities in the last ten years. An extensive case study of the Japanese semi-conductor industry by Chuma (2002) also demonstrates vividly the declining focus on traditional small group activities by Japanese semi-conductor firms.

[22] Our confidentiality agreements with AUTOPARTS and METAL prohibit us from revealing the actual names of these firms.

but also many other auto part suppliers produce. AUTOMAKER began telling AUTOPARTS that they may start buying engine parts from other suppliers and that AUTOPARTS is encouraged to sell its products to other auto manufacturers. In 2004, close to 30 percent of AUTOPARTS' sales went to other auto makers (a considerable rise from less than 10 percent at the end of the 1980s).

While leaving a cocoon of keiretsu in the 1990s and facing more competition, the nature of innovation in AUTOPARTS changed considerably. AUTOPARTS used to have effective small group activities of operators with small, incremental process improvements. As in many manufacturing firms in Japan during the postwar high growth era, SGAs at AUTOPARTS were small problem-solving teams in which front-line workers in the same work team meet regularly (normally after regular hours) and engage in problem-solving activities (see, for instance, Cole, 1979 and Kato, 2003). Maintenance workers are invited to such meetings from time to time. We collected a number of actual examples of such problem-solving activities. They were all typical continuous improvement projects. For instance, a team of operators producing an engine part noticed frequent scratches in their final product. Through SGAs, they were able to identify the main cause of the scratches and devise a cost-effective solution (padding a number of key contact surfaces with rubber). Another example involved a different team solving another quality problem of frequent dents on their final product by identifying the cause of the dents and proposing the use of a different type of steel which is less vulnerable to physical contact.

In the 1990s, such small group activities became less effective and less active as management continued to lower its expectation for the contributions of such activities and place less emphasis on them. At the time of our most recent site visit (July 2005), our informants declared that "management expected operators to simply do what management tells them to do, nothing more nothing less", and as such their small group activities were "almost dead". In fact, AUTOPARTS filled most new openings for operator positions in their workplaces with migrant workers from Brazil. Since nearly all of these migrant workers speak only Portuguese, even if AUTOPARTS decide to reinvigorate small group activities, it will be prohibitively costly to run such bilingual small group activities. At the time of our most recent visit to AUTOPARTS, there were around 900 regular employees and about 300 temporary employees with fixed-term contracts. Almost all of these 300 temporary employees were migrant workers from Brazil.[23]

At the same time, AUTOPARTS has been faced with an increased need for developing attractive products. Traditionally AUTOPARTS received from AUTOMAKER detailed specifications for specific engine parts used by AUTOMAKER, and sales of such parts to AUTOMAKER are almost guaranteed. In recent years, however, with the weakening role of keiretsu in Japan, AUTOMAKER demands AUTOPARTS to develop attractive products for them, and sales of their products to AUTOMAKER are no longer guaranteed. To respond to the enhanced need for product development,

[23]These migrant workers from Brazil are Brazilians of Japanese decent, and since the 1989 revision of the Immigration Control and Refugee recognition Act, such foreigners of Japanese decent have been exempt from regular restrictions imposed on foreign visitors (Ogawa, 2005).

AUTOPARTS has been actively recruiting engineers with 4-year degrees in the last two decades. The number of engineers working in product development has increased from 20 to 53 in the last decade.

Also, many traditional operator-oriented small group activities have been replaced with "technology groups." Such technology groups are comprised of professional staff (such as engineers) and they specialize in process innovation. This represents an example of a shift from bottom-up, operator-initiated, voluntary, self-directed problem-solving team activities to top-down, engineer-initiated, involuntary problem-solving group activities of process innovation specialists. Note that we observed a similar shift in METAL, as described below.

6.1.2 METAL

METAL is a large unionized manufacturing firm with sales of over 400 billion yen and employment of close to 4,000 workers in 2005. It is listed in the first section of Tokyo Stock Exchange. The corporation has nine plants. There have been four important changes at METAL in the last two decades which are relevant to their activities to facilitate continuous improvement and promote discrete innovation. First, METAL has recently focused its business on the high end of the product line. METAL used to be called "the department store of specialty metal" and well-known for its comprehensive product line supplying nearly all kinds of specialty metal to major users (such as auto manufacturers). However, the lower end of the product market has been dominated by Chinese firms in recent years, and METAL has been shifting its strategy from "all-round utility player" to "specialty player" focusing on the high end of the product line. A key component of this new strategy is to develop "Number one product" or "Only one product". For example, METAL has been working on developing a new high-quality, high-performance specialty metal used for jet engines while accelerating its exit from a line of more traditional low-cost metal.

Second, METAL has been experiencing a shortening cycle of their product in recent years. For example, METAL and a major auto manufacturer used to develop a new specialty metal (which a transmission will be made of) jointly under an implicit long-term (typically 2 years) contract which guarantees the eventual sale of the product to the auto manufacturer. In recent years, such long-term implicit contracts have been replaced with short-term (a few months) contracts with no guarantee for repeated transactions. As such, product cycles are now in months not in years. Another example is a new product area such as magnetic material and metal powders where METAL has been moving into lately. Users of such a new product area are closer to final consumers than traditional specialty metal users, and there are many more competitors. As such, the market is closer to a short-term spot market than a relational long-term contract market.

Third, rapid retiring of seasoned operators who are fully capable of engaging in traditional bottom-up, self-directed problem-solving activities, coupled with the recent downsizing of such operators, makes continuous improvement less effective.

Fourth, traditionally METAL's innovation strategy relied heavily on their conventional small group activities, JK Movement, which were aimed at small, incremental problem solving within the shopfloor. METAL's small group activities began in 1967. As in the case of many traditional small group activities in large Japanese firms, JK Movement was "voluntary" offline problem-solving teams in which front-line workers meet normally after regular hours and "voluntarily" engage in problem-solving activities with no or only token compensation. METAL stressed the importance of operator initiative in selecting themes, setting goals, scheduling meetings, writing up final reports and presenting them. It was clearly meant to be bottom-up, operator-initiated activities at the shopfloor level, aiming at small, incremental problem solving within the shopfloor.

In the 1990s, however, METAL reduced its dependence on JK Movement and started to shift the focus of their innovation strategy toward more top-down, engineer-centered, larger innovation activities involving multiple workplaces (and sometimes even METAL's suppliers and customers). Such new innovation activities were designed to tackle much bigger productivity and quality issues.

For example, in mid-1990s, METAL introduced a new program, called WANTED. Unlike JK Movement in which all problems to be solved are set by operators, WANTED begins with managers and engineers identifying "problems" to be solved. Such "problems" are often much larger in their scope, involving multiple workplaces and sometimes even METAL's suppliers and customers. As such, in WANTED, solutions tend to go beyond small, incremental improvement on the existing production process within the narrow workplace.

More recently, in September 2004, METAL started experimenting with even larger and ambitious WANTED programs. METAL first identified 7 workplaces out of 80 as target workplaces. METAL then allocated considerable amount of money and professional staff to those target workplaces with an ambitious goal of 30 percent increase in productivity in 6 to 12 months. Most importantly METAL assigned key engineers from various parts of the firm to each of those seven target workplaces and such engineers initiated targeted problem solving activities with operators. With the relatively short time span (6-12 months) and hefty goal (30 percent increase in productivity), METAL was interested not in a steady accumulation of small incremental improvement on the existing production process (or continuous improvement) but rather in discrete innovation. By the time of our more recent visit to METAL (June 2005), 5 out of 7 target workplaces had already achieved their goal of 30 percent productivity increase.

In short, since the introduction of WANTED, METAL's innovation strategy has continued to depart from its traditional reliance on continuous improvement and go after bigger and quicker solutions, some of which involved replacement of at least a portion of the existing production process with a new process with more integrated and computer-controlled machines. Importantly, when the existing machines were replaced with new machines, much of past improvements made on the existing machines were lost. To this end, innovation that took place as a result of WANTED was largely discrete innovation.[24]

6.2 Applications of the model

We have observed that the level of continuous improvement has declined at both firms. Why did that happen? Below we will discuss how our model can be applied to explore this question. We will apply our result on the effect of competitive pressure (Proposition 1) to the case of AUTOPARTS, and our result on the effect of the size of discrete innovation (Proposition 2) to the case of METAL.

An application of the model to AUTOPARTS

Let us interpret firm A in our model as AUTOPARTS and firm B as its competitor where they produce different varieties of the engine part. Recall that at the beginning of the 1990s AUTOMAKER declared its decision to switch gradually from unique to universal engine parts which not only AUTOPARTS but also many other auto part suppliers produce. AUTOMAKER began telling AUTOPARTS that they may start buying engine parts from other suppliers and that AUTOPARTS is encouraged to sell its products to other auto manufacturers. A similar change of procurement policy took place in many other automobile manufacturers about the same time in Japan, and this trend is often referred to as "weakening of vertical *keiretsu*".[25]

In our model, this change can be captured by an increase in the product substitutability of the engine part; that is, a reduction in t. Our model then yields a prediction that an increase in product substitutability decreases suppliers' incentives to invest in continuous improvement in symmetric equilibria, provided that $\frac{ds^*}{dt} < 0$ holds (see Section 5). Recall that the number of engineers working in product development had more than doubled and traditional operator-oriented small group activities have been replaced with "technology groups" in AUTOPARTS, suggesting that AUTOPARTS increased its investment in DI. Since higher investment in DI increases the success probability of DI, we hypothesize that a reduction in t increased s^* (i.e., $\frac{ds^*}{dt} < 0$ holds) in the case of AUTOPARTS.[26]

Our model therefore indicates that the increase in product substitutability of the engine parts, which took place in the Japanese automobile industry in the early 1990s, can be an important cause of the drastic decline in the level of AUTOPART's continuous improvement. By capturing the interplay between CI and DI, our analysis uncovers a new possible reason for the declining focus of continuous improvement in Japanese manufacturing firms.

[24] Unfortunately, we are unable to provide more concrete examples of METAL's discrete innovation, due to its obviously sensitive nature.

[25] The "weakening of vertical keiretsu" is by now a widely-held view in Japan (see, for instance, Japan Small Business Research Institute, 2007). For quantitative evidence, for instance, see Ahmadjian and Robbins (2005). Fujiki (2006) provided an intriguing "insider" account of the change in the vertical keiretsu relationships in the auto-manufacturing industry.

[26] One might argue that higher investment in DI also increases the size of innovation Δ. As mentioned in Section 5, we found that an increase in Δ reduces the level of CI.

An application of the model to METAL

Let us interpret firm A in our model as METAL and firm B as its domestic competitor (i.e. another specialty metal producer in Japan) where they produce different varieties of the specialty metal. Recall that METAL has recently focused its business on the high end of the product line. We incorporate this shift into the analysis of our model by supposing that the return from discrete innovation (represented by Δ) for high-end products is higher than that for low-end products. This supposition can be justified, in the context of METAL, as follows. METAL's increased focus on high-end products often meant that the market for such products was still relatively unexplored and that discrete innovation in such high-end products when succeeded allowed METAL to carve out a significant share of the market.

During our field visits to METAL, we discovered several examples of such successful discrete innovation. METAL started to devote its financial and human resources to new product developments only in the 1990s. For each promising new product idea, METAL created a section in its R&D department, where each section consisted of a few engineers plus operators testing the new product idea. Many failed, yet some succeeded. When failed, METAL closed the failing section. When succeeded, METAL selected a plant suitable for the production of the new product and created a new product line within the plant (often led by those engineers and operators in the original section of the R&D department). Such new product lines often expanded over time and became significant sources of profit. Most recently, METAL's new product developments even went beyond its familiar speciality metal field by successfully developing ultra-thin disc magnet (METAL now has a new department producing magnet in its brand new plant). In short, it is conceivable that discrete innovation in high-end products may be risky yet when successful, it tends to yield higher return than that in low-end products.

In steel manufacturing processes, a variety of different products ranging from high-end products to low-end products can be produced in the same production facility. Then, the shifting focus on the high end of the product line implies that the return of DI, Δ, has increased at aggregate levels in firms A and B. Our model predicts that an increase in Δ reduces the equilibrium level of CI (Proposition 2). That is, our model proposes a hypothesis that the shift of METAL's strategy to the high-end products can be a driving force of METAL's declining focus on continuous improvement. Our model also predicts that an increase in Δ increases s^*, the equilibrium level of success probability of DI (see the last paragraph of Section 5). Recall that METAL has been experiencing a shortening cycle of their product in recent years. This finding is consistent with our theoretical prediction because, in the context of our model, the product-life cycle becomes shorter, in an expected sense, as the success probability of DI increases.[27]

[27] One might argue that the nature of discrete innovation for high-end products is not only higher return but also higher risk than that for low-end products. This idea can be incorporated in our model by assuming that each firm i's success probability of DI, denoted s_i, is determined by $\phi(\Delta)F(s_i)$ where $\phi(\Delta)$ (> 0) is an increasing function of Δ and $F(.)$ has properties analogous to those assumed in Section 5. In this version of the model, it can be shown that

Concluding remarks

To be sure, we do not assert that the mechanism mentioned above for each case is the sole cause of the declining focus on continuous improvement. For example, it is possible that at METAL, rapid retiring of seasoned operators, coupled with the recent downsizing of such operators, may have been making continuous improvement less effective and hence causing METAL to rely less on CI. Likewise, at AUTOPARTS, increasing reliance on migrant workers from Brazil could be considered a cause for the decline in CI. By applying our model to the real-world contexts, we go beyond such rather obvious labor-side mechanism and uncover possible new product market-side mechanisms based on a change in competitive pressure or a change in the size of discrete innovation. In other words, the application of our model to the real-world cases points to the possibility that changing product market characteristics are the underlying culprit for the decline in CI, and that the labor-market factors such as the aforementioned reliance on migrant workers from Brazil at AUTOPARTS may be a consequence rather than a cause for the diminishing attractiveness of continuous improvement.

7 Conclusion

Continuous improvement made upon the existing technology is often of limited relevance to the new technology invented upon success in discrete innovation. We have demonstrated that, in the presence of discrete innovation, firms can invest less in continuous improvement as competition intensifies. Previous theoretical studies have indicated that an increase in competitive pressure measured by product substitutability increases firms' deterministic investment in cost reduction (continuous improvement), provided that the average demand for varieties does not shrink. In contrast, the interplay between continuous improvement and discrete innovation can overturn the previous result. The share-reduction effect of competition implies that, as competition increases, the firm's return on continuous improvement on the existing technology falls because of the possibility that the rival firm succeeds in discrete innovation while its own discrete innovation fails, resulting in a greater loss of market share to the rival firm and hence a greater loss of the opportunity to recoup investment in continuous improvement. It follows that an increase in competitive pressure decreases the firms' incentives to invest in continuous improvement.

At the beginning of the 1990s, competitive pressure faced by AUTOPARTS increased as AUTOMAKER declared its decision to switch from the unique type of engine parts to the universal type of engine parts, an increase in product substitutability. This would lead to an increase in AUTOPART's investment in continuous improvement according to previous theoretical results on competitive pressure and innovation incentives. In contrast, our model has suggested that such

an increase in Δ reduces the equilibrium level of CI as long as an increase in Δ increases s^*. And, the shortening product-life cycle suggests that s^* has in fact increased. Hence this variant of the model also predicts that an increase in Δ can be a driving force of METAL's declining focus on continuous improvement.

an increase in product substitutability can be a cause of the drastic decline in the level of AUTOPART's continuous improvement. At METAL, we have observed that the firm has recently focused its business on the high end of the product line. Given that return from investment in discrete innovation tends to be higher for high-end products, our model indicates that this trend can be a driving force of METAL's declining incentive to invest in continuous improvement. The interplay between continuous improvement and drastic innovation plays key roles in our new theoretical predictions.

8 Appendixes

8.1 Appendix A: Proofs

In Appendix A we provide the proofs of the propositions as well as the proofs of several claims made in Sections 4 and 5.

First we establish the following claim, which is made in Section 4 prior to Proposition 1.

Claim 1: The symmetric pure-strategy equilibrium of the two-stage game described in section 3 is unique, and in the equilibrium each firm i chooses

$$x_i = x^* \equiv \max\{\frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)}, \frac{(1-s)^2}{3\gamma}\}, \quad i = A, B. \tag{15}$$

Proof: Stage 2 equilibrium outcomes are given by (1) and (2) if $|c_i - c_j| < 3t$, and by (3) and (4) if $|c_i - c_j| \geq 3t$. In stage 1, each firm i chooses x_i to maximize $s\pi_i^S(x_i, x_j) + (1-s)\pi_i^F(x_i, x_j) - \frac{\gamma x_i^2}{2}$ where $i, j \in \{A, B\}$, $j \neq i$. Since $\pi_i^S(x_i, x_j)$ is independent of x_i (see equation (6)), the maximization problem reduces to choosing x_i to maximize $(1-s)\pi_i^F(x_i, x_j) - \frac{\gamma x_i^2}{2} \equiv h_i(x_i, x_j)$. Using (1) - (4) we find that $h_i(x_i, x_j)$ is given by: $-\frac{\gamma x_i^2}{2}$ if $x_i \leq x_j - 3t$, $2t(1-s)^2(\frac{1}{2} + \frac{x_i - x_j}{6t})^2 - \frac{\gamma x_i^2}{2}$ if $x_j - 3t \leq x_i \leq \Delta - 3t$, and $2t(1-s)[s(\frac{1}{2} - \frac{\Delta - x_i}{6t})^2 + (1-s)(\frac{1}{2} + \frac{x_i - x_j}{6t})^2] - \frac{\gamma x_i^2}{2}$ if $x_i > \Delta - 3t$.

Suppose $\Delta < 3t$. Then, $\Delta - x_i < 3t$ or equivalently $x_i > \Delta - 3t$ and consequently $h_i(x_i, x_j) = 2t(1-s)[s(\frac{1}{2} - \frac{\Delta - x_i}{6t})^2 + (1-s)(\frac{1}{2} + \frac{x_i - x_j}{6t})^2] - \frac{\gamma x_i^2}{2}$. We have that

$$\frac{\partial h_i(x_i, x_j)}{\partial x_i} = \frac{2}{3}(s(\frac{1}{2} - \frac{\Delta - x_i}{6t}) + (1-s)(\frac{1}{2} - \frac{x_j - x_i}{6t})) - \gamma x_i.$$

We find that (i) $x_i = x = \frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)}$ solves $\frac{\partial h_i(x_i,x)}{\partial x_i} = 0$, and (ii) $\frac{\partial^2}{\partial x_i{}^2} h_i(x_i, x_j) = \frac{1-s}{9t} - \gamma < 0$, where the inequality follows from footnote 15. Thus $x_i = x^* = \frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)}$ constitutes an equilibrium. Uniqueness follows from observing that (i) the two equations, i.e., $\frac{\partial h_i(x_i,x_j)}{\partial x_i} = 0$ for $i = A$ and $i = B$, are linear in x_i and x_j, and the fact that (ii) two linear equations in two variables can have at most one solution.

Now suppose $\Delta \geq 3t$. Then $|c_i - c_j| > 3t$ might hold in which case $\tilde{\pi}_i(c_i, c_j) = 0(1)$ if $c_i > (<) c_j$. Taking this into account and proceeding as outlined in the previous paragraph we find that for $\Delta \leq 3t + \frac{(1-s)^2}{3\gamma}$, $x_i = x = \frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)} (\geq \Delta - 3t)$ uniquely solves $\frac{\partial h_i(x_i,x)}{\partial x_i} = 0$. Furthermore, $\frac{\partial^2}{\partial {x_i}^2} h_i(x_i, x) \leq \frac{1-s}{9t} - \gamma < 0$.[28] Thus $x_i = x^* = \frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)} (< \Delta - 3t)$ constitutes the unique symmetric equilibrium for $\Delta \leq 3t + \frac{(1-s)^2}{3\gamma}$. Similarly, we find that $x_i = x^* = \frac{(1-s)^2}{3\gamma}$ constitutes the unique symmetric equilibrium for $\Delta \geq 3t + \frac{(1-s)^2}{3\gamma}$. Given that $\frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)} > (=, <) \frac{(1-s)^2}{3\gamma} \Leftrightarrow \Delta < (=, >) 3t + \frac{(1-s)^2}{3\gamma}$ the unique symmetric equilibrium in pure strategies can be characterized as $x^* = \max\{\frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)}, \frac{(1-s)^2}{3\gamma}\}$. *Q.E.D*

Proof of Proposition 1: Expanding (8) gives $x^* = \frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)}$ if $\Delta < 3t + \frac{(1-s)^2}{3\gamma}$ and $x^* = \frac{(1-s)^2}{3\gamma}$ if $\Delta > 3t + \frac{(1-s)^2}{3\gamma}$. Define $\bar{\Delta} \equiv 3t + \frac{(1-s)^2}{3\gamma}$. For $\Delta < \bar{\Delta}$, we have that $\frac{dx^*}{dt} = \frac{9\gamma s(1-s)(\Delta - \frac{1-s}{3\gamma})}{(9t\gamma - s(1-s))^2}$. Since $X - \frac{1}{3\gamma} > 0$ (by footnote 15) and $\Delta > X$ we have that $\Delta - \frac{1-s}{3\gamma} > 0$ which in turn implies that $\frac{dx^*}{dt} > 0$ for $\Delta < \bar{\Delta}$. If $\Delta > \bar{\Delta}$, $\frac{dx^*}{dt} = 0$ since $x^* (= \frac{(1-s)^2}{3\gamma})$ is independent of t. *Q.E.D.*

Proof of Proposition 2: If $\Delta < \bar{\Delta}$, $\frac{dx^*}{d\Delta} = -\frac{s(1-s)}{9t\gamma - s(1-s)} < 0$. If $\Delta > \bar{\Delta}$, $\frac{dx^*}{d\Delta} = 0$ since $x^* (= \frac{(1-s)^2}{3\gamma})$ is independent of Δ. *Q.E.D.*

Proof of Proposition 3: If $\Delta < \bar{\Delta}$, $\frac{dx^*}{ds} = -\frac{(3t-s\Delta)(9t\gamma - (1-s)^2) + \Delta(1-s)(9t\gamma - s(1-s))}{(9t\gamma - s(1-s))^2}$. By footnote 15, $9t\gamma - 1 > 0$. Hence $9t\gamma - (1-s)^2 > 0$ and $9t\gamma - s(1-s) > 0$. Finally, since $3t - s\Delta > 3t - s\bar{\Delta} (\equiv \frac{(1-s)(9t\gamma - s(1-s))}{3\gamma}) > 0$ we have that $\frac{dx^*}{ds} < 0$. If $\Delta > \bar{\Delta}$, $\frac{dx^*}{ds} = -\frac{2(1-s)}{3\gamma} < 0$. *Q.E.D.*

Next we turn to Section 5. We first establish the following claim, which is made in Section 5 prior to Proposition 4.

Claim 2: There exists a symmetric equilibrium, i.e., $s_A = s_B = s^* \in (0, \theta)$ and $x_A = x_B = x^* \in (0, X)$, which satisfy (10), (11), and (12).

Proof: Any symmetric equilibrium, i.e., $s_A = s_B = s \in (0, \theta)$ and $x_A = x_B = x \in (0, X)$, must satisfy the following:

$$\frac{\partial \Pi_i(s,s,x,x)}{\partial s_i} \equiv \frac{\Delta - x}{3}[1 - \frac{(2s-1)(\Delta - x)}{6t}] - F'(s) \equiv G(s, x; t, \Delta) = 0,$$

$$\frac{\partial \Pi_i(s,s,x,x)}{\partial x_i} \equiv \frac{1-s}{3}[1 - \frac{s(\Delta - x)}{3t}] - \gamma x \equiv H(s, x; t, \Delta) = 0.$$

Rearranging $H(s, x; t, \Delta) = 0$ gives $x = \frac{(1-s)(3t-s\Delta)}{9t\gamma - s(1-s)} \equiv x(s)$. We have that $G(0, x(0); t, \Delta) = \frac{\Delta - \frac{1}{3\gamma}}{3}[1 + \frac{\Delta - \frac{1}{3\gamma}}{6t}] > 0$, since $\Delta > \frac{1}{3\gamma}$. Also, $\lim_{s \to \theta} G(s, x(s); t, \Delta) = -\infty < 0$ since $\lim_{s \to \theta} F'(s) = \infty$. Furthermore, since $G(.)$ is differentiable in s, it follows that there exists s^* and $x^* \equiv x(s^*)$ such

[28] We find that $\frac{\partial^2}{\partial {x_i}^2} h_i(x_i, x) = -\gamma$ if $x_i \leq x_j - 3t$, $\frac{(1-s)^2}{3t} - \gamma$ if $x_i \in (x - 3t, \Delta - 3t)$ and $\frac{1-s}{3t} - \gamma$ if $x_i > \Delta - 3t$. Since $-\gamma < \frac{(1-s)^2}{3t} - \gamma < \frac{1-s}{3t} - \gamma$, we write $\frac{\partial^2}{\partial {x_i}^2} h_i(x_i, x) \leq \frac{1-s}{9t} - \gamma$.

that (i) $G(s^*, x(s^*); t, \Delta) = 0$, and (ii) $\frac{dG(s^*,x(s^*);t,\Delta)}{ds} \equiv \frac{\partial G(s^*,x(s^*);t,\Delta)}{\partial s} + \frac{\partial G(s,x;t,\Delta)}{\partial x}\frac{dx(s^*)}{ds} < 0$. Substituting $\frac{dx(s^*)}{ds} = -\frac{\frac{\partial H(s^*,x^*;t,\Delta)}{\partial s}}{\frac{\partial H(s^*,x^*;t,\Delta)}{\partial x}}$ in (ii) and rearranging gives (12), while (i) implies (10). By definition $H(s, x(s); t, \Delta) = 0$. Then (11) follows from substituting $s = s^*$ and $x = x^* \equiv x(s^*)$ in $H(.)$. *Q.E.D*

Proof of Proposition 4: Totally differentiating (10) and (11) (holding Δ constant) and subsequently solving for $\frac{dx^*}{dt}$ and $\frac{ds^*}{dt}$ we get:

$$\frac{dx^*}{dt} = -\frac{G_s(s^*,x^*;t,\Delta)H_t(s^*,x^*;t,\Delta) - G_t(s^*,x^*;t,\Delta)H_s(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)H_x(s^*,x^*;t,\Delta) - G_x(s^*,x^*;t,\Delta)H_s(s^*,x^*;t,\Delta)},$$
$$\frac{ds^*}{dt} = -\frac{H_x(s^*,x^*;t,\Delta)G_t(s^*,x^*;t,\Delta) - G_x(s^*,x^*;t,\Delta)H_t(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)H_x(s^*,x^*;t,\Delta) - G_x(s^*,x^*;t,\Delta)H_s(s^*,x^*;t,\Delta)},$$

where

$$\begin{aligned}
G_s(s^*,x^*;t,\Delta) &= -\frac{(\Delta-x^*)^2}{9t} - F''(s^*) < 0,\\
G_x(s^*,x^*;t,\Delta) = H_s &(s^*,x^*;t,\Delta) = -\frac{1}{3}[1 - \frac{(2s^*-1)(\Delta-x^*)}{3t}] < 0,\\
G_t(s^*,x^*;t,\Delta) &= \frac{(2s^*-1)(\Delta-x^*)^2}{9t} < (=,>)0 \qquad \Leftrightarrow s^* < (=,>)\frac{1}{2},\\
H_x(s^*,x^*;t,\Delta) &= \frac{s^*(1-s^*)}{9t} - \gamma < 0, H_t(s^*,x^*;t,\Delta) = \frac{s^*(1-s^*)(\Delta-x^*)}{9t^2} > 0.
\end{aligned}$$

Since (s^*, x^*) satisfy (12), (i) $G_s(.)H_x(.) - G_x(.)H_s(.) > 0$. Furthermore, if $\theta < \frac{1}{2}$, $s^* < \frac{1}{2}$ which implies $G_t(.) < 0$ and consequently (ii) $G_s(.)H_t(.) - G_t(.)H_s(.) < 0$. Then (i) and (ii) together imply that $\frac{dx^*}{dt} > 0$ if $\theta < \frac{1}{2}$.[29] *Q.E.D.*

We prove Claim 3, which is made in the last sentence in the paragraph after equation (14).
Claim 3: Consider the symmetric equilibrium (s^*, x^*) which satisfy (10), (11) and (12) in the text. Then $\frac{\partial s^*}{\partial t} < 0 \Rightarrow \frac{ds^*}{dt} < 0$.
Proof: We have that

$$\frac{ds^*}{dt} = \frac{\partial s^*}{\partial t}\mid_{x=x^*} + \frac{\partial s^*}{\partial x}\mid_{x=x^*}\frac{dx^*}{dt}.$$

Substituting the expression for $\frac{dx^*}{dt}$ from (13) in above and simplifying we get

$$\frac{ds^*}{dt} = \frac{\frac{\partial s^*}{\partial t}\mid_{x=x^*} + \frac{\partial s^*}{\partial x}\mid_{x=x^*}\frac{\partial x^*}{\partial t}}{1 - \frac{\partial s^*}{\partial x}\mid_{x=x^*}\frac{\partial x^*}{\partial s}\mid_{s=s^*}} = \frac{\frac{\partial s^*}{\partial t}\mid_{x=x^*} + \frac{G_x(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)}\frac{H_t(s^*,x^*;t,\Delta)}{H_x(s^*,x^*;t,\Delta)}}{1 - \frac{G_x(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)}\frac{H_s(s^*,x^*;t,\Delta)}{H_x(s^*,x^*;t,\Delta)}}$$

[29]Note that $\theta < \frac{1}{2}$ is not a necessary condition for $\frac{dx^*}{dt} > 0$. Even if $\theta > \frac{1}{2}$, s^* can be strictly less than $\frac{1}{2}$ which will give $G_t(.) < 0$, $G_s(.)H_t(.) - G_t(.)H_s(.) < 0$, and consequently $\frac{dx^*}{dt} > 0$. Second, even if $\theta > \frac{1}{2}$ and $s^* > \frac{1}{2}$, $G_s(.)H_t(.) - G_t(.)H_s(.) < 0$ can hold.

Condition (12) implies that the denominator is strictly positive. Furthermore, we have that $\frac{G_x(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)}\frac{H_t(s^*,x^*;t,\Delta)}{H_x(s^*,x^*;t,\Delta)} < 0$, since $G_s(.) < 0$, $H_s(.) < 0$, $H_x(.) < 0$ while $H_t(.) > 0$ (see the proof of Proposition 4). Then $\frac{\partial s^*}{\partial t} < 0 \Rightarrow \frac{\partial s^*}{\partial t}\mid_{x=x^*} + \frac{G_x(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)}\frac{H_t(s^*,x^*;t,\Delta)}{H_x(s^*,x^*;t,\Delta)} < 0 \Rightarrow \frac{ds^*}{dt} < 0$. *Q.E.D.*

Finally we show that Proposition 2 holds for the model considered in Section 5.

Claim 4: The equilibrium level of continuous improvement, x^*, declines as the size of discrete innovation increases.

Proof: Totally differentiating (10) and (11) (holding t constant) and subsequently solving for $\frac{dx^*}{d\Delta}$ we get:

$$\frac{dx^*}{d\Delta} = -\frac{G_s(s^*,x^*;t,\Delta)H_\Delta(s^*,x^*;t,\Delta) - G_\Delta(s^*,x^*;t,\Delta)H_s(s^*,x^*;t,\Delta)}{G_s(s^*,x^*;t,\Delta)H_x(s^*,x^*;t,\Delta) - G_x(s^*,x^*;t,\Delta)H_s(s^*,x^*;t,\Delta)}$$

where $G_\Delta(.) = \frac{1}{3}[1 - \frac{(2s^*-1)(\Delta-x^*)}{3t}] > 0$, $H_\Delta(.) = -\frac{s^*(1-s^*)}{9t} < 0$. Together with $G_s(.) < 0$, $H_s(.) < 0$ (see the proof of Proposition 4 above) this implies that the numerator, $G_s(.)H_\Delta(.) - G_\Delta(.)H_s(.)$, is strictly positive. From the proof of Proposition 4, we already know that the denominator, $G_s(.)H_x(.) - G_x(.)H_s(.)$, is strictly positive. Thus $\frac{dx^*}{d\Delta} > 0$. *Q.E.D.*

8.2 Appendix B: Detailed explanation for the mechanism behind Proposition 1

In Appendix B we explain the mechanism behind Proposition 1 in detail for the case of $\Delta < \bar{\Delta}$. Firm i's investment in CI will be effective only when it fails in DI. Anticipating that its DI will fail with probability $1-s$, at Stage 1 firm i chooses x_i to maximize $(1-s)\pi_i^F(x_i,x_j) - d(x_i)$, where we have

$$(1-s)\pi_i^F(x_i,x_j) = (1-s)s\tilde{\pi}_i(c-x_i,c-\Delta) + (1-s)^2\tilde{\pi}_i(c-x_i,c-x_j), \tag{16}$$

given $\pi_i^F(x_i,x_j) = s\tilde{\pi}_i(c-x_i,c-\Delta) + (1-s)\tilde{\pi}_i(c-x_i,c-x_j)$ by equation (7). In the equilibrium we have $\frac{\partial}{\partial x_i}(1-s)\pi_i^F(x^*,x^*) - d'(x^*) = 0$. How does an increase in competitive pressure (i.e., a decrease in t) affect $\frac{\partial}{\partial x_i}(1-s)\pi_i^F(x^*,x^*)$, firm i's marginal return from CI? To answer this question, we need to find the sign of

$$\frac{\partial^2}{\partial t\partial x_i}(1-s)\pi_i^F(x^*,x^*) = s(1-s)\frac{\partial^2}{\partial t\partial x_i}\tilde{\pi}_i(c-x^*,c-\Delta) + (1-s)^2\frac{\partial^2}{\partial t\partial x_i}\tilde{\pi}_i(c-x^*,c-x^*). \tag{17}$$

First consider $\frac{\partial^2}{\partial t\partial x_i}\tilde{\pi}_i(c-x^*,c-\triangle)$, which appears in the first term of the RHS of equation (17) and corresponds to the case in which firm i fails but firm j succeeds in DI. We have

$$\tilde{\pi}_i(c-x^*,c-\triangle) = (p_{iFS}(x^*,t) - c_{iF}(x^*))q_{iFS}(x^*,t), \tag{18}$$

where $p_{iFS}(x_i,t)$ and $q_{iFS}(x_i,t)$ denote firm i's equilibrium price and quantity, respectively, when firm i fails but firm j succeeds in DI, and $c_{iF}(x_i) \equiv c - x_i$ denotes firm i's constant marginal cost when it fails in DI. We then have

$$\begin{aligned}\frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - \triangle) &= \underbrace{\frac{\partial}{\partial t}[q_{iFS}(x^*, t)\frac{\partial}{\partial x_i}(p_{iFS}(x^*, t) - c_{iF}(x^*))]}_{Share-reduction\ effect} \\ &\quad + \underbrace{\frac{\partial}{\partial t}[(p_{iFS}(x^*, t) - c_{iF}(x^*))\frac{\partial}{\partial x_i}q_{iFS}(x^*, t)]}_{Business-stealing\ and\ rent-reduction\ effects}. \qquad (19)\end{aligned}$$

Equation (19) captures three effects of competition, *share-reduction effect*, *business-stealing effect*, and *rent-reduction effect*, and these effects together result in $\frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - \triangle) > 0$.
(i) *Share-reduction effect*: This is the new effect captured by our analysis as mentioned above, represented by the first term of the RHS of (19). Firm i's equilibrium quantity $q_{iFS}(x^*, t) = \frac{1}{2} - \frac{\Delta - x^*}{6t}$ decreases as t decreases, because more competition magnifies the impact of firm i's cost disadvantage represented by $\Delta - x^*$. At the same time, we have $\frac{\partial}{\partial x_i}(p_{iFS}(x^*, t) - c_{iF}(x^*)) = \frac{1}{3}$. That is, firm i's incremental investment in CI increases its price-cost margin, and the incremental price-cost margin $\frac{\partial}{\partial x_i}(p_{iFS}(x^*, t) - c_{iF}(x^*))$ is independent of t. The result is that, as competitive pressure increases, $q_{iFS}(x^*, t)\frac{\partial}{\partial x_i}(p_{iFS}(x^*, t) - c_{iF}(x^*))$ decreases, working in the direction of reducing firm i's marginal return from CI. Hence we have $\frac{\partial}{\partial t}[q_{iFS}(x^*, t)\frac{\partial}{\partial x_i}(p_{iFS}(x^*, t) - c_{iF}(x^*))] > 0$.

(ii) *Business-stealing effect and rent-reduction effect*: These two effects have been explored by several recent studies in the literature, and are captured by the second term of the RHS of (19). Firm i's incremental investment in CI reduces its cost disadvantage against firm j. This increases firm i's equilibrium quantity by $\frac{\partial}{\partial x_i}q_{iFS}(x^*, t) = \frac{1}{6t} > 0$, which in turn increases its profit by $(p_{iFS}(x^*, t) - c_{iF}(x^*))\frac{\partial}{\partial x_i}q_{iFS}(x^*, t)$. Differentiating this term with respect to t yields

$$\underbrace{(p_{iFS}(x^*, t) - c_{iF}(x^*))\frac{\partial^2}{\partial t \partial x_i}q_{iFS}(x^*, t)}_{Business-stealing\ effect} + \underbrace{\frac{\partial}{\partial t}(p_{iFS}(x^*, t) - c_{iF}(x^*))\frac{\partial}{\partial x_i}q_{iFS}(x^*, t)}_{Rent-reduction\ effect}. \qquad (20)$$

Concerning the first term, we have $\frac{\partial^2}{\partial t \partial x_i}q_{iFS}(x^*, t) = -\frac{1}{6t^2} < 0$. As t decreases, consumers become more price sensitive. This implies that, by reducing its cost by CI, firm i can more easily increase its equilibrium quantity. Hence, as competition intensifies, the business-stealing effect works in the direction of increasing firm i's incentive to invest in CI; that is, $(p_{iFS}(x^*, t) - c_{iF}(x^*))\frac{\partial^2}{\partial t \partial x_i}q_{iFS}(x^*, t) = (t - \frac{\Delta - x^*}{3})(-\frac{1}{6t^2}) < 0$ holds, given $\Delta < \bar{\Delta} \Rightarrow t > \frac{\Delta - x^*}{3}$. At the same time, as competition intensifies, the price-cost margin becomes smaller; that is, $\frac{\partial}{\partial t}(p_{iFS}(x^*, t) - c_{iF}(x^*)) = 1 > 0$, implying $\frac{\partial}{\partial t}(p_{iFS}(x^*, t) - c_{iF}(x^*))\frac{\partial}{\partial x_i}q_{iFS}(x^*, t) = 1(\frac{1}{6t}) > 0$. This is the rent-reduction effect. We have that $(t - \frac{\Delta - x^*}{3})(-\frac{1}{6t^2}) + \frac{1}{6t} = \frac{\Delta - x^*}{18t^2} > 0$; that is, the business-stealing effect is dominated by the rent-reduction effect.

In sum, concerning the case in which firm i fails but firm j succeeds in DI, the share-reduction effect works in the direction of reducing firm i's marginal return from CI as competition intensifies. Although the business-stealing effect works in the opposite direction, this effect is dominated by the rent-reduction effect. Hence, the three effects together result in $\frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - \triangle) > 0$.

Next consider $\frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - x^*)$, which appears in the second term of the RHS of equation (17) and corresponds to the case in which both firms i and j fail in DI. The share-reduction effect is absent in this case, because each firm's equilibrium quantity is $\frac{1}{2}$ regardless of the level of t. Also, the business-stealing effect and the rent-reduction effect exactly cancels out each other in this case, consistent with previous findings in the literature (see Raith, 2003; Baggs and de Bettignies, 2007). Hence we find $\frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - x^*) = 0$.

Therefore we find $\frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - \Delta) > \frac{\partial^2}{\partial t \partial x_i}\tilde{\pi}_i(c - x^*, c - x^*) = 0$, implying $\frac{\partial^2}{\partial t \partial x_i}(1 - s)\pi_i^F(x^*, x^*) > 0$. That is, as competitive pressure increases, firm i's marginal return from CI decreases and hence the equilibrium level of CI also decreases. This results in $\frac{dx^*}{dt} > 0$ if $\Delta < \bar{\Delta}$, as stated in Proposition 1.

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