Does Productivity Respond to Exchange Rate Appreciations? A Theoretical and Empirical Investigation

Yao Tang*

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Abstract

Although real currency appreciations pose direct difficulties for exporters and import-competing firms as they will face more intense competition, is it possible that such competition spurs firms to improve productivity? To answer this question, the paper first constructs a theoretical model to show how the competitive pressures of currency appreciations induce firms to improve productivity by adopting new technologies. In addition, the model predicts that during appreciations there will be a positive relation between market concentration and improvements in productivity for industries highly exposed to trade, because the benefits of productivity improvement will be bigger for firms with a larger market share. The paper then examines Canadian manufacturing data from 1997 to 2006, and finds evidence consistent with model predictions. I find that growth rates of labor productivity were on average higher during the Canadian dollar appreciation between 2002 and 2006, after controlling for industry characteristics. Within the group of highly traded Canadian industries, the more concentrated ones experienced larger growth in labor productivity.

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*9700 College Station, Brunswick, Maine 04011-8497, USA. Email: ytang@bowdoin.edu. Web page: http://www.bowdoin.edu/~ytang/. I am grateful for comments from Werner Antweiler, Paul Beaudry, Michael Devereux, Viktoria Hnatkovska, Ross Hickey, Haifang Huang, Amartya Lahiri, Vadim Marmer, Anji Redish, and Henry Siu. I also thank Thomas Lemieux and Andrey Stoyanov for their help with data compilation. All errors are mine.

1 Introduction

Substantial exchange rate movements over the last few decades have raised a question: what are the impacts of a major real exchange rate appreciation on economic performance? Conventional wisdom suggests that such appreciation worsens terms of trade and weakens the competitiveness of home firms. Meanwhile, it is possible that to maintain competitiveness, firms will be forced to raise productivity by reducing their costs. Some scholars and economic commentators argue that a "hard currency", meaning a currency less prone to depreciation, can contribute to higher productivity growth. For instance, (Porter, 1990, p.640) suggests that the appreciations of the Yen in the 1980s had spurred the Japanese industry to become more competitive. Harris (2001) argues that the Canadian dollar depreciation in the 1990s was partially responsible for the Canadian productivity decline.

To answer the question of whether manufacturing productivity responds to real appreciations, I first construct a model in which currency appreciations can provide incentives for firms to improve productivity if they are in industries highly exposed to trade. The model also predicts that among highly traded industries, the highly concentrated ones will invest more in productivity improvements because the benefits of productivity gain will be greater for firms with a larger market share. Second, I test the predictions empirically by using Canadian manufacturing data from 1997 to 2006. The results suggest that manufacturing productivity growth responded positively to the appreciation of the Canadian dollar between 2002 and 2006. Within industries exposed to a substantial amount of trade, the highly concentrated ones experienced a larger gain in labor productivity during the appreciation period.

In a neoclassical framework, profit maximization by firms automatically implies cost minimization. However, some economists have long argued that product market competition forces firms to lower costs and thus improve productivity. Nickell (1996) contains a review of earlier contributions along this line of thinking. Some of the theoretical models are based on contract theory, for example Hart (1983) and Raith (2003). Vives (2008) examines a wide variety of industrial organization models, and concludes that, in general, increased competition encourages product and process innovations.

In this paper, I focus on how an increase in competition caused by real exchange rate appreciation lowers the opportunity cost a new technology. Specifically, this paper adapts the approach of Holmes, Levine and Schmitz (2008) who provide an explanation for the positive relation between competition and adoption of new technology, based on the empirical observation that technology changes are often disruptive in the sense that the marginal cost of production is initially highly before transitioning to a lower cost. In general various mechanisms, such as learning-by-doing or external increasing return to scale of adopting a new technology, can give rise to such a cost path. In the context of this paper, when the real exchange rate appreciates, there is less profit to be made in the short-run, and so profit loss due to adopting a new technology that initially raises cost of production is also smaller. Therefore, a real appreciation can provide a good timing for adopting the technilogy (cite Cabalero?). However, for firms in an industry shielded by high trade costs, their profitability is less influenced by appreciations, and their incentive to improve productivity provided by appreciations is smaller.

Compared to Holmes et al. (2008) and other previous papers which focus on when firms are likely to adopt new technologies to improve productivity, this paper also studies what types of firms are likely to invest more in productivity improvement. The model predicts firms will invest to achieve bigger productivity gain if they are in industries with a low trade cost and a high level of concentration. In industries with fewer firms, since the benefits of productivity improvements are greater, firms in these industries are likely to invest more in productivity improvements.

In the microeconomic literature on competition provides ample evidence of a positive correlation between competition and productivity improvement, with competitive pressure measured as the number of competitors, concentration ratio, trade barriers, or the effect of competition policy. MacDonald (1994) finds that import competition improved productivity in highly concentrated US industries. Nickell (1996) suggests that an increase in the number of competitors was associated with total factor productivity (TFP) gain in a sample of 700 firms in the UK. Symeonidis (2008) exploits the variation arising from the introduction of anti-cartel laws in UK industries, and finds that collusion reduced industry-level productivity growth. Galdon-Sanchez and Schmitz (2002) and Syverson (2004) are two papers that focus on individual industries. The former paper investigates Canadian and American iron ore producers, which doubled labor productivity, and increased material efficiency by 50% in response to intense price competition from Brazilian firms. The latter paper examines ready-mixed concrete plants in the US, and finds that an increase in local competition led to higher average productivity and lower productivity dispersion.

In international economics, a few recent firm-level studies examine the effect of exchange rate appreciation on firm performances. Fung (2008) finds that the productivity of Taiwanese firms increase after a major currency appreciation mainly due to the exit of less efficient firms and bigger production scale of surviving firms after the appreciation. Using a micro data set from Norway, Ekholm, Moxnes and Ulltveit-Moe (2008) report that net-exporting manufacturing firms experienced productivity gain after the appreciation of the Norwegian Krone in the early 2000s. They argue that the gain in productivity came from technological improvement, and employment cuts. Baggs, Beaulieu and Fung (2009) study the relation between firm performances and exchange rate in Canada between 1986 and 1997. They suggest that an appreciation decreased sales, profitability and survival rate, while a depreciation strengthened them. Studying the Canadian agricultural implements industry, Tomlin (2010) also reports evidence that an appreciation reduces the survival probability of plants, especially the less productive ones.

To test the predictions of the theoretical model, this paper use data on 237 Canadian manufacturing industries between 1997 and 2006 to study how industry-level labor productivity growth interacts with exchange rate movements, concentration, and trade costs. The Canadian dollar experienced substantial movements in the period, allowing me to investigate the productivity response to a major appreciation. I find that growth rates of labor productivity, measured as value added per production worker, were on average higher during the Canadian dollar appreciation between 2002 and 2006. Within the industries with a high trade-to-revenue ratio, the highly concentrated ones experienced greater growth in labor productivity. The empirical analysis controls for energy use growth, material use growth, R&D expenditure growth, productivity growth in corresponding US industries, industry fixed effects, and year fixed effects. My empirical work, based on industry-level data, complements the firm-level studies by building a model that links industry features to the size of productivity gain, and providing supporting evidence.

Relative to the aforementioned papers, this paper makes two contributions. First, it highlights that industrial organization is important to understanding productivity gains associated with an appreciation. It is firms in highly concentrated industries that want to invest more in new technology. Second, an appreciation provides incentive for technology adoption only when firms are not shielded by high trade cost. These predictions are supported by the empirical findings that the productivity responses of highly-traded and concentrated Canadian manufacturing industries to the Canadian dollar appreciation between 2002 and 2006 were positive and significant.

The next section lays out the basic modeling environment. Section 3 introduces the technological opportunity for home firms to improve productivity, and examines how home firms' choices interact with an appreciation. Section 4 tests the model predictions on Canadian manufacturing data and section 5 concludes.

2 Basic Model Setup

There are two countries, the home (h) and the foreign (f), and each has a representative household. The two households have the same given wealth W and consume a continuum of goods indexed by i with $i \in [0,1]$. labor supplies in both countries are perfectly inelastic. The home household's problem is to maximize

$$\sum_{t=1}^{2} \beta^{t-1} \int_0^1 log(C_{it}) di$$

subject to the life-time budget constraint

$$\sum_{t=1}^{2} \beta^{t-1} \int_0^1 P_{it} C_{it} di \leq W \tag{1}$$

C_{it} denotes the quantity of good i and P_{it} is its price. Similarly the foreign household maximizes

$$\sum_{t=1}^{2} \beta^{t-1} \int_0^1 log(C_{it}^*) di$$

subject to the life-time budget constraint

$$\sum_{t=1}^{2} \beta^{t-1} \int_0^1 P_{it}^* C_{it}^* di \leq W^* \tag{2}$$

Following the convention in international economics, the superscript $*$ denotes variables in the foreign country. The household preferences determine the demand functions for good i in both countries

$$C_{it} = \frac{W/(1+\beta)}{P_{it}} \tag{3}$$

$$C_{it}^* = \frac{W/(1+\beta)}{P_{it}^*} \tag{4}$$

where $W/(1+\beta)$ is normalized to be 1.

For each good i, there are n_i home firms and n_i foreign firms who can produce it. I will refer to these firms as firms in industry i. In both periods, all home firms are endowed with a constant marginal cost of $c_{iht} = c_h$ unit of labor and the foreign firms are endowed with a constant marginal cost of $c_{ift} = c_f$. Thus in the model, home and foreign labor productivities in any industry are $\frac{1}{c_h}$ and $\frac{1}{c_f}$. labor is the only input and is not mobile across countries. Every good is tradable, subject to an iceberg trade cost τ_i for good i, meaning that for each τ_i unit of good i shipped to the other country only one unit will arrive. τ_i and n_i are drawn from the joint CDF $F(\tau, n)$ with support $[1, \infty) \times [1, 2, \cdots, \overline{n}]$.[1]

The market structure within each industry is similar to that found in Brander and Krugman (1983). The home firms and foreign firms of industry i produce using labor in their respective countries. However, they are free to sell their production in both countries. For a given period, the home and foreign firms of industry i play a Cournot game in the home market to determine the quantities of good i produced by each firm for the home market. Simultaneously, the same firms also compete in a Cournot game in the foreign market. As mentioned before, in all periods both the home and foreign firm face an iceberg trade cost τ_i when they sell in the non-native market.

The problem of home Firm j of industry i is

$$\max_{x^j_{ih1}, x^{j*}_{ih1}, x^j_{ih2}, x^{j*}_{ih2}} \Pi^j_{ih} = \pi^j_{ih1} + e_1 \pi^{j*}_{ih1} + \beta(\pi^j_{ih2} + e_2 \pi^{j*}_{ih2}) \tag{5}$$

where x^j_{ih1} and x^{j*}_{ih1} are the quantities it produces for home and foreign markets in period 1, and x^j_{ih2} and x^{j*}_{ih2} are the quantities for home and foreign markets in period 2. π^j_{ih1} and π^j_{ih2} are profits from the home market in periods 1 and 2. π^{j*}_{ih1} and π^{j*}_{ih2} are profits from the foreign market, measured in the foreign currency. e_1 and e_2 are the real exchange rates in the two periods. They are defined as the price of one unit of real foreign money balance in terms of real home money balance, so a decrease in e_t is a real appreciation of the home currency.

The exchange rates are determined exogenously and known to all firms at the begin-

[1] In this model, the number of firms in an industry is exogenously given. This treatment can be viewed as a simplification of the case where firms can enter and exit an industry freely and the number of firms in equilibrium is determined by the exogenous fixed cost of entry.

ning of period 1. This assumption may appear surprising for economists familiar with the macroeconomic models of exchange rate determination. However, given that my interests are on the effect of exchange change rate on firms' behavior and that the macroeconomic models of exchange rate have enjoyed limited empirical success, I argue that treating the exchange rate as exogenous is appropriate in this paper.[2]

In setting up the firm's problem, I assume firms will discount future at the rate of time preference of the household, who is also the owner of the firms. In reality, firms may differ in the discount factor. For firms who place little value on future, there is very little incentive for them to adopt a technology that will bring a future benefit, holding other factors constant. The objective function also features no expectation operator, as I assume firms have perfect foresight of future. While expectation plays an important role in decision, I choose to suppress it here so as to focus discussion on how exchange rate lowers opportunity cost of adopting new technology. On empirical section, it is argued that firms in Canada have a good idea about the path of exchange rate since appreciations tend to be persistent and commodity prices are a good forecaster of exchange rate of the Canadian dollar.

At the beginning of period 1 all firms observe each other's marginal costs for all times. Then all firms in industry i play a game to determine quantities of output in the four markets (home and foreign markets in period 1 and 2). The strategy of home firm j in industry i is the set of quantities $\left\{x^{j}_{ih1}, x^{j*}_{ih1}, x^{j}_{ih2}, x^{j*}_{ih2}\right\}$, and the strategy of foreign firm j in industry i is the set of quantities $\left\{x^{j}_{if1}, x^{j*}_{if1}, x^{j}_{if2}, x^{j*}_{if2}\right\}$. There are four subgames, one for each market in each period. I focus on the subgame perfect equilibrium in which firms in industry i of each country play symmetric strategies. I assume firms have to determine simultaneously the quantities in both markets in a period, hence in each period, the two subgames for the two markets are independent. In period 2, firms have to play a Nash

[2]In Tang (2008), I endogenize the exchange rate and the income of the households in a theoretical model and find that firms have incentive to improve productivity when the exchange rate appreciates.

equilibrium in the subgames. By the standard backward induction principle, they will also have to play a Nash equilibrium in the subgames in period 1. Thus all four subgames are independent, so the subgame perfect equilibrium involves firms playing the symmetric Nash equilibrium in each subgame. The output quantities in each subgame are determined as the symmetric Nash equilibrium quantities in that subgame. We can calculate in the maximized total profit as the sum of maximized profits from each subgame.

Normalizing home wage to be 1, the profit of the home firm j of industry i in the home market at time t is

$$\pi^j_{iht} = (P_{it} - c_h)x^j_{iht} = (\frac{1}{\sum_{k=1}^{n_i} x^k_{iht} + \sum_{k=1}^{n_i} x^k_{ift}} - c_h)x^j_{iht} \tag{6}$$

where x^k_{iht} and x^k_{ift} are the quantities of good i produced by home firm k and foreign firm k for the home market. The last equality follows from (3) and the market clearing condition $C_{it} = \sum_{k=1}^{n_i} x^k_{iht} + \sum_{j=1}^{n_i} x^k_{ift}$. When the home firm j chooses x^j_{iht} to maximize (6), the first order condition is

$$\frac{\sum_{k\neq j} x^k_{iht} + \sum_{k=1}^{n_i} x^k_{ift}}{(\sum_{k=1}^{n_i} x^k_{iht} + \sum_{k=1}^{n_i} x^k_{ift})^2} - c_h \leq 0 \tag{7}$$

Similarly the profit of foreign firm j of industry i in the home market at time t is

$$\pi^j_{ift} = (P_{it} - e_t\tau_i c_f)x^j_{ift} = (\frac{1}{\sum_{k=1}^{n_i} x^k_{iht} + \sum_{k=1}^{n_i} x^k_{ift}} - e_t\tau_i c_f)x^j_{ift} \tag{8}$$

When the foreign firm j chooses x^j_{ift} to maximize (8), the first order condition is

$$\frac{\sum_{k=1}^{n_i} x^k_{iht} + \sum_{k\neq j} x^k_{ift}}{(\sum_{k=1}^{n_i} x^k_{iht} + \sum_{k=1}^{n_i} x^k_{ift})^2} - e_t\tau_i c_f \leq 0. \tag{9}$$

(7) and (9) implicitly define the best responses functions of the home j and foreign firm j to quantities produced by other firms. Combining (7) and (9) and imposing symmetry among all home firms and symmetry among all foreign firms, we have the equilibrium relation between outputs of home and foreign firms

$$x^j_{ift} = \frac{n_i c_h - (n_i - 1)e_t\tau_i c_f}{n_i e_t\tau_i c_f - (n_i - 1)c_h} x^j_{iht} = \alpha_1(t, i)x^j_{iht} \tag{10}$$

where $\alpha_1(t,i) = \frac{n_i c_h - (n_i-1)e_t\tau_i c_f}{n_i e_t \tau_i c_f - (n_i-1)c_h}$. A careful examination of (7) suggests that if c_h is large, then the home firms will produce zero quantities, and foreign firms will produce large quantities. This is because foreign firms know that given the quantities they produced, home firms' the marginal revenue in the home market (the first term in (7)) is always less than the marginal cost for all $x^j_{iht} \geq 0$, leading the home firms to optimally choose zero quantities. In this case, the denominator of α_1 will be negative and (10) will no longer describe the relation between home and foreign quantities of output. Similarly when $e_t\tau_i c_f$ is large, foreign firms will produce zero quantities, and the numerator of $\alpha_1(t,i)$ will be negative. It can be shown that the necessary conditions for both home and foreign firms to produce positive quantities in the home market is that both numerator and denominator of $\alpha_1(t,i)$ be positive. These conditions can be expressed as

$$\tau_i > \frac{n_i - 1}{n_i}\frac{1}{e_t}\frac{c_h}{c_f}$$
$$\tau_i < \frac{n_i}{n_i - 1}\frac{1}{e_t}\frac{c_h}{c_f} \tag{11}$$

If (11) is satisfied, we can substitute the last expression into (7) and (9) and solve for x^j_{iht} and x^j_{ift}

$$x^j_{iht} = \frac{n_i - 1 + n_i\alpha_1(t,i)}{(n_i + n_i\alpha_1(t,i))^2 c_h} \tag{12}$$
$$x^j_{ift} = \frac{n_i - 1 + n_i/\alpha_1(t,i)}{(n_i + n_i/\alpha_1(t,i))^2 e_t\tau_i c_f} \tag{13}$$

In particular if $n_i = 1$ the solution is

$$x^j_{iht} = \frac{1}{e_t\tau_i c_f(1 + \frac{c_h}{e_t\tau_i c_f})^2} \tag{14}$$
$$x^j_{ift} = \frac{1}{c_h(1 + \frac{e_t\tau_i c_f}{c_h})^2} \tag{15}$$

If we substitute (12) and (13) into (6) and (8), we have

$$\pi^j_{iht} = \frac{1}{(n_i + n_i\alpha_1(t,i))^2} \tag{16}$$
$$\pi^j_{ift} = \frac{1}{(n_i + n_i/\alpha_1(t,i))^2} \tag{17}$$

Thus for industry i we have a unique symmetric equilibrium in the home market under (11).

Similarly the home firm's and foreign firm's profit functions in the foreign market, denoted in foreign currency, are

$$\pi^*_{iht} = (P^*_{it} - \frac{\tau_i c_h}{e_t})x^{j*}_{iht} = (\frac{1}{\sum_{k=1}^{n_i} x^{k*}_{iht} + \sum_{k=1}^{n_i} x^{k*}_{ift}} - \frac{\tau_i c_h}{e_t})x^{j*}_{iht}$$
$$\pi^{j*}_{ift} = (P^*_{it} - c_f)x^{j*}_{ift} = (\frac{1}{\sum_{k=1}^{n_i} x^{k*}_{iht} + \sum_{k=1}^{n_i} x^{k*}_{ift}} - c_f)x^{j*}_{ift}$$

In a symmetric equilibrium in which firms of both countries produce positive quantities, the equilibrium output and profits are given by

$$x^{j*}_{iht} = \frac{n_i - 1 + n_i\alpha_2(t,i)}{(n_i + n_i\alpha_2(t,i))^2 c_h} \tag{18}$$
$$x^*_{ift} = \frac{n_i - 1 + n_i/\alpha_2(t,i)}{(n_i + n_i/\alpha_2(t,i))^2 e_t\tau_i c_f} \tag{19}$$
$$\pi^*_{iht} = \frac{1}{(n_i + n_i\alpha_2(t,i))^2} \tag{20}$$
$$\pi^*_{ift} = \frac{1}{(n_i + n_i/\alpha_2(t,i))^2} \tag{21}$$

where $\alpha_2(t,i) = \frac{n_i\tau_i c_h - (n_i-1)e_t c_f}{n_i e_t c_f - (n_i-1)\tau_i c_h}$. The necessary condition for both home and foreign firms to produce positive quantities in the foreign market is

$$\begin{aligned} \tau_i &< \frac{n_i}{n_i - 1} e_t \frac{c_f}{c_h} \\ \tau_i &> \frac{n_i - 1}{n_i} e_t \frac{c_f}{c_h} \end{aligned} \tag{22}$$

Given c_h, c_f and e_t, (11) and (22) imply that in industries in the set

$$\begin{aligned} \Theta(e_t) = \{(n_i, \tau_i) \in [1, 2, \cdots, \overline{n}] \times [1, \infty) : \\ \tau_i > \frac{n_i - 1}{n_i}\frac{1}{e_t}\frac{c_h}{c_f},\ \tau_i < \frac{n_i}{n_i - 1}\frac{1}{e_t}\frac{c_h}{c_f}, \\ \tau_i > \frac{n_i - 1}{n_i} e_t \frac{c_f}{c_h},\ \tau_i < \frac{n_i}{n_i - 1} e_t \frac{c_f}{c_h} \Big\}, \end{aligned} \tag{23}$$

both home and foreign firms will produce positive quantities in both markets at time t. I use the notation $\Theta(e_t)$ to emphasize the set depends on e_t. Empirically, an industry in $\Theta(e_t)$ is one that has both positive import and export. For these industries, total profits for home and foreign firms are given by

$$\begin{aligned}\Pi^j_{ih} =& \frac{1}{(n_i + n_i\alpha_1(t=1,i))^2} + \frac{e_1}{(n_i + n_i\alpha_2(t=1,i))^2} \\ &+ \frac{\beta}{(n_i + n_i\alpha_1(t=2,i))^2} + \frac{\beta e_2}{(n_i + n_i\alpha_2(t=2,i))^2} \\ \Pi^j_{if} =& \frac{1}{e_1(n_i + n_i/\alpha_1(t=1,i))^2} + \frac{1}{(n_i + n_i/\alpha_2(t=1,i))^2} \\ &+ \frac{\beta}{e_2(n_i + n_i/\alpha_1(t=2,i))^2} + \frac{\beta}{(n_i + n_i/\alpha_2(t=2,i))^2}. \end{aligned} \tag{24}$$

Proposition 1. *(a) For industries in the set $\Theta(e_t)$, the period t profit of home firm j in industry i is a decreasing function of c_h and an increasing function of exchange rate e_t. (b) For industries with the same τ_i in the set $\Theta(e_t)$, the period t profit for home firms j is decreasing in n_i. (c) For industries with the same τ_i and in which only home firms are producing positive quantities, the period t profit for home firms j is decreasing in n_i.*

Proof:

(a) From (16) and (21), we can see the period t profit of home firm j in industry i is decreasing in α_1 and α_2. Since both α_1 and α_2 are increasing in c_h and decreasing in e_t, the conclusion follows.

(b) For industries in $\Theta(e_t)$, the period t profit for home firm j in the home market is given by

$$\pi^j_{iht} = \frac{1}{(n_i + n_i\alpha_1(t,i))^2} \qquad (16).$$

If $c_h > e_t\tau_i c_f$, then $\alpha_1(t,i) = \frac{n_i c_h - (n_i-1)e_t\tau_i c_f}{n_i e_t\tau_i c_f - (n_i-1)c_h} = \frac{c_h - (n_i-1)(c_h - e_t\tau_i c_f)}{e_t\tau_i c_f - (n_i-1)(e_t\tau_i c_f - c_h)}$ is increasing in n_i. Thus π^j_{iht} is decreasing in n_i. If $c_h = e_t\tau_i c_f$, then $\alpha_1(t,i) = 1$ so $\pi^j_{iht} = \frac{1}{(n_i+n_i\alpha_1(t,i))^2}$ is decreasing in n_i. Lastly, when $c_h < e_t\tau_i c_f$, we can prove π^j_{iht} is decreasing in n_i by showing the derivative of the numerator of (16) with respect to n_i is positive:

$$\frac{\partial}{\partial n_i}(n_i + n_i\alpha_1(t,i))^2 = \frac{\partial}{\partial n_i}(n_i + \frac{n_i\frac{c_h}{e_t\tau_i c_f - c_h} - n_i^2 + n_i}{\frac{e_t\tau_i c_f}{e_t\tau_i c_f - c_h} + n_i - 1})^2$$

$$= 2\frac{\frac{c_h(e_t\tau_i c_f + c_h)}{(e_t\tau_i c_f - c_h)^2}}{(\frac{e_t\tau_i c_f}{e_t\tau_i c_f - c_h} + n_i - 1)^2} > 0.$$

Therefore, we have shown that π_{iht}^j is always decreasing in n_i. Similarly, we can show the period t profit of home firm j in the foreign market is decreasing in n_i.

(c) For industries in which only home firms are producing positive quantities for both markets, it is easy to verify that the period t profit for firm j is

$$\frac{n_i - 1}{n_i^2} + e_t\frac{n_i - 1}{n_i^2} \tag{25}$$

which is decreasing in n_i. ■

The proposition confirms the intuition that an appreciation of home currency erodes the profit of home firms and validates the usual Cournot competition result that profit dissipates with the number of firms.

3 Exchange Appreciation and Investment Decision

In this section I introduce the possibility of cost-saving technology. The term technology is defined as in Jones (2001), as ways to transform factors into output. In general, they can be product innovations, but in this paper I refer to a cost-saving process innovation. For example the innovation could be an improvement in labor practice as emphasized in Baily, Gersbach, Scherer and Lichtenberg (1995), and Schmitz (2005).

To simplify the problem, I assume all home and foreign firms in each industry are endowed with the same unit cost, $c_h = c = c_f$ for both periods. All home firms have access to technology that reduces the second-period marginal cost from c_h to $\frac{1}{\sigma}c_h$, where σ is the improvement in labor productivity. However the technology is also disruptive in the sense that, if a firm chooses $\sigma > 1$, it raises the first period marginal cost from c_h to γc_h, where γ is a constant greater than 1.[3] Since adoption at time t will raise the cost at that period, no firm would adopt the innovation at $t = 2$. Proposition 1 implies the technology will bring higher profit in the second period but entail a loss of profit in the first. Firms can choose σ in the range $[1, \overline{\sigma})$ but will have to pay a fixed cost $I(\sigma)$. I assume $I(\sigma)$ is strictly convex in σ for all $1 < \sigma < \overline{\sigma}$, $I(\sigma = 1) = 0$, $\lim_{\sigma \to 1} I(\sigma) > 0$, and $\lim_{\sigma \to \overline{\sigma}} I(\sigma) = \infty$. [4]

My assumption regarding new technology follows that of Holmes et al. (2008), which suggests that technology change is disruptive in the sense that there is a costly transition to lower cost of production. Holmes et al. (2008) motivate this assumption by citing a large number of empirical observations. For illustrative purposes consider the following scenario. The implementation of new technology requires a fixed investment in the training of employees and during the transition, as a result, workers are less productive as they are learning to master the new technology. In general, the downward path of cost can arise due to mechanisms such as learning-by-doing and external increasing return to scale. As mentioned in the introduction, Vives (2008) studies a wide variety of industrial organization models and concludes that in general more competition induces a bigger effort to improve productivity. Holmes et al. (2008) obtain similar predictions with the empirically motivated assumption of disruptive technology changes. I follow their assumption to maintain model tractability.

It is clear from the nature of the technology that the trade off between current costs and future gain is crucial for adoption choices. A two-period world is the minimum structure that allows us to study the trade off between the present and the future. Adding more periods simply requires one to replace second-period profits in firms' objective func-

[3]It is possible that firms could improve productivity by adopting other new technologies that are not disruptive and are always profitable to implement. I choose not to model such technology opportunities as they would not interact with exchange rate movements. In the empirical section of the paper, I will try to account for this possibility.

[4]In general γ can be increasing in σ, however, since the assumptions regarding $I(\sigma)$ ensure that the first-period cost of adoption (which equals $I(\sigma)$ plus the profit loss due to a high marginal cost γc_h) is increasing in σ, I do not pursue this complication.

tions with value functions. Both a second-period profit function and a value function should be increasing in productivity, giving rise to a future gain due to a technological upgrade. Since the focus of this paper is on how first-period loss interacts with exchange rate movements, a two-period model is sufficient.

Since the two countries are symmetric, it is reasonable to conjecture that without exogenous shocks, the exchange rate is $e_t = 1$,[5] will hold in both periods. The timing of the game in industry i is the following:

- **Stage 0**, an exogenous shock to exchange rate is realized, firms have perfect foresight that $e_1 < 1$ and $e_2 = 1$;[6]

- **Stage 1**, home firm j determines its choices of σ^j and pay $I(\sigma^j)$, for $j = 1, 2, \cdots, n_i$; foreign firm j determines its choices of σ^{j*} and pay $I(\sigma^{j*})$, for $j = 1, 2, \cdots, n_i$;

- **Stage 2**, the choices of firms in stage 1 are observed by all (so every firm knows the marginal cost of each firm in both periods), and firms play the Cournot game as described in section 2 to determine outputs in each of the four markets (home and foreign markets in period 1 and 2).

The game is solved by standard backward induction. In stage 2, given $\{\sigma^1, \sigma^2, \cdots, \sigma^{n_i}\}$ and $\{\sigma^{1*}, \sigma^{2*}, \cdots, \sigma^{n_i*}\}$ firms play the Cournot game described in section 2 and the payoffs are as derived in section 2. In stage 1, given how the equilibrium profit depends on $\{\sigma^1, \sigma^2, \cdots, \sigma^{n_i}\}$ and $\{\sigma^{1*}, \sigma^{2*}, \cdots, \sigma^{n_i*}\}$, home firm j chooses σ^j, for $j = 1, 2, \cdots, n_i$ and foreign firm j chooses σ^j*, for $j = 1, 2, \cdots, n_i$. Again, I will focus on an equilibrium in which all home firms are symmetric, and all foreign firms are symmetric in stage 1.

[5]In Tang (2008), I close the model and derive the equilibrium exchange rate as a function of firm productivities and shock to currency demand. In a steady state in which the productivities are equal across countries and currency demand shocks equal zero, the equilibrium exchange rate is 1.

[6]As indicated by Rogoff (1996) and references therein, the exchange rate tends to revert to the Purchasing Power Parity (PPP) level in the long run. To simplify the analysis, I assume that the firms know for sure the exchange rate will return to its long run value of 1 for sure.

In stage 2, I focus on the choices of σ for industries in which firms of both countries produce positive quantities in all markets, except that home firms may be forced out of the foreign market during the period 1 appreciation. The game potentially has a large number of equilibrium, so I choose to focus on an intuitive one in which all home firms in industry i choose the same $\sigma > 1$ while all foreign firms choose $\sigma^* = 1$. In such an equilibrium, if it exists and if firms of both countries are producing positive quantities then the total profit of the home firm j before paying $I(\sigma)$ is

$$\begin{aligned}\Pi^j_{ih}(\sigma) = & \frac{1}{(n_i + n_i\frac{n_i\gamma-(n_i-1)e_1\tau_i}{n_ie_1\tau_i-(n_i-1)\gamma})^2} + \frac{e_1}{(n_i + n_i\frac{n_i\tau_i\gamma-(n_i-1)e_1}{n_ie_1-(n_i-1)\tau_i\gamma})^2} \cdot 1(e_1 > \frac{n-1}{n}\tau_i\gamma) \\ & + \frac{\beta}{(n_i + n_i\frac{n_i/\sigma-(n_i-1)e_2\tau_i}{n_ie_2\tau_i-(n_i-1)/\sigma})^2} + \frac{\beta e_2}{(n_i + n_i\frac{n_i\tau_i/\sigma-(n_i-1)e_2}{n_ie_2-(n_i-1)\tau_i/\sigma})^2} \end{aligned} \quad (26)$$

where $1(e_1 > \frac{n-1}{n}\tau_i\gamma)$ is an indicator function. When $e_1 > \frac{n-1}{n}\tau_i\gamma$ fails, the home firms are driven out of the foreign market, and make zero profit. If all home firms choose status quo (sq), i.e. $\sigma = 1$, the total profit is

$$\begin{aligned}\Pi^j_{ih}(sq) = & \frac{1}{(n_i + n_i\frac{n_i-(n_i-1)e_1\tau_i}{n_ie_1\tau_i-(n_i-1)})^2} + \frac{e_1}{(n_i + n_i\frac{n_i\tau_i-(n_i-1)e_1}{n_ie_1-(n_i-1)\tau_i})^2} \cdot 1(e_1 > \frac{n-1}{n}\tau_i) \\ & + \frac{\beta}{(n_i + n_i\frac{n_i-(n_i-1)e_2\tau_i}{n_ie_2\tau_i-(n_i-1)})^2} + \frac{\beta e_2}{(n_i + n_i\frac{n_i\tau_i-(n_i-1)e_2}{n_ie_2-(n_i-1)\tau_i})^2}\end{aligned}$$

I refer to the difference $\Pi^j_{ih}(\sigma) - \Pi^j_{ih}(sq)$ as the benefit of adopting the disruptive technology. Choosing some $\sigma > 1$ dominates $\sigma = 1$, if the associated benefit is greater than the cost $I(\sigma)$. The benefit has two components, the profit loss in the first period

$$\begin{aligned}|L_1| = & \frac{1}{(n_i + n_i\frac{n_i-(n_i-1)e_1\tau_i}{n_ie_1\tau_i-(n_i-1)})^2} + \frac{e_1}{(n_i + n_i\frac{n_i\tau_i-(n_i-1)e_1}{n_ie_1-(n_i-1)\tau_i})^2} \cdot 1(e_1 > \frac{n-1}{n}\tau_i) \\ & - \left(\frac{1}{(n_i + n_i\frac{n_i\gamma-(n_i-1)e_1\tau_i}{n_ie_1\tau_i-(n_i-1)\gamma})^2} + \frac{e_1}{(n_i + n_i\frac{n_i\tau_i\gamma-(n_i-1)e_1}{n_ie_1-(n_i-1)\tau_i\gamma})^2} \right) \cdot 1(e_1 > \frac{n-1}{n}\tau_i) \end{aligned} \quad (27)$$

and the profit gain in the second

$$
\begin{aligned}
G_2 =& \frac{\beta}{(n_i + n_i \frac{n_i/\sigma - (n_i-1)e_2\tau_i}{n_i e_2 \tau_i - (n_i-1)/\sigma})^2} + \frac{\beta e_2}{(n_i + n_i \frac{n_i \tau_i/\sigma - (n_i-1)e_2}{n_i e_2 - (n_i-1)\tau_i/\sigma})^2} \\
& - \left(\frac{\beta}{(n_i + n_i \frac{n_i - (n_i-1)e_2\tau_i}{n_i e_2 \tau_i - (n_i-1)})^2} + \frac{\beta e_2}{(n_i + n_i \frac{n_i \tau_i - (n_i-1)e_2}{n_i e_2 - (n_i-1)\tau_i})^2} \right)
\end{aligned} \tag{28}
$$

Similar to (23), given $e_1 < 1$ and $e_2 = 1$, we can formally define the set of industries with $\{n_i, \tau_i, \sigma_i\}$ such that firms of both countries produce positive quantities for all markets, except that home firms may produce zero for the foreign market during the period 1 due to the appreciation, as

$$
\begin{aligned}
\Theta_\sigma(e_1) =& \{(n_i, \tau_i, \sigma_i) \in [1, 2, \cdots, \overline{n}] \times [1, \infty) \times \sigma_i \in [1, \overline{\sigma}) : \\
& \tau_i < \frac{n_i}{(n_i - 1)e_1\gamma}, \; \tau_i > \frac{(n_i - 1)\gamma}{n_i e_1}, \; \tau_i < \frac{n_i}{(n_i - 1)\sigma_i}, \; \tau_i > \frac{(n_i - 1)\sigma_i}{n_i} \Big\}
\end{aligned} \tag{29}
$$

In terms of import and export, an industry in $\Theta_\sigma(e_1)$ have positive import in both periods, positive export in the second period and possibly positive export in the first period.

To make it possible for the adoption decision problem to interact with the exchange rate, I assume

- (i) For industries in $\Theta_\sigma(e_1 = 1)$, $\Pi^j_{ih}(\sigma) - \Pi^j_{ih}(sq) < I(\sigma)$ for all $\sigma \in (1, \overline{\sigma})$;
- (ii) If $\tau_i = 1$, for all $n_i \in [1, 2, \cdots, \overline{n}]$ we can find an interval $\Sigma_{n_i} \subset (1, \overline{\sigma})$ such that the second-period profit gain of firms in industry i, given by equation (28), is strictly greater than the cost $I(\sigma)$ for all $\sigma \in \Sigma_{n_i}$.

Assumption (i) implies it is not profitable to choose any $\sigma > 1$ with $e_1 = 1$ although the technology is readily available, and assumption (ii) says that if the first-period profit loss is zero, it will be profitable for home firms of industry i to adopt $\sigma \in \Sigma_{n_i}$.

The following two propositions show how benefits in adopting disruptive new technologies are affected by e_1 and τ_i. Firstly given τ_i and n_i, an exchange appreciation lowers the first period profit loss, so choosing some $\sigma > 1$ can be profitable. Secondly, given e_1 and n_i, a large trade cost τ_i insulates home firms from trade and the influence of exchange rate movements. Home firms will have no incentive to choose $\sigma > 1$, even if they experience an appreciation.

Proposition 2. *Consider industries in $\Theta_\sigma(e_1)$. Given n_i, and τ_i close enough to 1, for all $\sigma \in \Sigma_{n_i}$ there exists an exchange rate threshold such that it is profitable to adopt σ for home firms for all e_1 below the threshold. Meanwhile, all foreign firms choose not to invest, i.e. they choose$\sigma^* = 1$.*

Proof:

The absolute value of the first-period profit loss due to adoption (27) is bounded by the first-period profit in the status quo

$$\frac{1}{(n_i + n_i \frac{n_i-(n_i-1)e_1\tau_i}{n_i e_1 \tau_i-(n_i-1)})^2} + \frac{e_1}{(n_i + n_i \frac{n_i\tau_i-(n_i-1)e_1}{n_i e_1-(n_i-1)\tau_i})^2} \cdot 1(e_1 > \frac{n-1}{n}\tau_i).$$

As e_1 tends to $\frac{n_i-1}{\tau_i n_i}$ from above, the first-period profit will tend to zero and so will the first-period profit loss due to adoption. By assumption (ii), for industries with τ_i, the benefit of adopting $\sigma > 1$ is greater than the cost for all $\sigma \in \Sigma_{n_i}$. Since the profit functions are continuous in τ_i, by assumption (ii) for τ_i close enough to 1, the second-period profit gain of firms in industry i will be strictly greater than $I(\sigma)$, i.e. $G_2 > I(\sigma)$, for all $\sigma \in \Sigma_{n_i}$. Therefore for each $\sigma \in \Sigma_{n_i}$ we can find an $\underline{e}_1$ such that for all $e_1 < \underline{e}_1$, the first period loss $|L_1| < G_2 - I(\sigma)$. Thus for all $e_1 < \underline{e}_1$, adopting $\sigma \in \Sigma_{n_i}$ is profitable since $\Pi_i^j(\sigma) - \Pi_i^j(sq) = G_2 - |L_1| > I(\sigma)$.

Given the optimal choice of home firms, σ, there exists a unique σ^* for foreign firms to maximize profit in period 2. However, because the profit gain in period 2 for foreign firms (G_2^*) is bounded, there exists an $\underline{e}_1^*$ such that the first period profit loss dominates, i.e. $|L_1^*| + I(\sigma^*) > G_2$. Taking the threshold to be $\min\{\underline{e}_1, \underline{e}_1^*\}$, the conclusion follows. ■

Proposition 3. *Given an* $e_1 < 1$*, there exists a threshold* $\hat{\tau}$ *such that adopting the technology of any level* σ *will not profitable for firms in any industry with* $\tau_i \geq \hat{\tau}$*, regardless of the number of firms in the industry.*

Proof:

Consider an industry with n firms. There are two possibilities. Firstly, given e_1 adopting any $\sigma \in (1, \overline{\sigma})$ will not be profitable for all $\tau \in [1, \infty)$. In this case, set the threshold to be $\hat{\tau}_n = 1$.

Secondly, given e_1, adopting some $\sigma \in (1, \overline{\sigma})$ will be profitable for some $\tau \in [1, \infty)$. Fix the new technology at a specific level σ. Either the technology of level σ is not profitable for all τ_i, or it is profitable for some level of τ. In the former case, set the threshold to be $\hat{\tau}_n(\sigma) = 1$. In the latter case, note that as $\tau \to \frac{n_i}{n_i - 1}\frac{1}{e_1}$, home firms operate only in the home market and the foreign firms' market share in the home market tends to zero in both periods.[7] The limit of firm j's total gain (which equals benefit minus cost) from adopting the new technology of level σ is

$$\lim_{\tau \to \frac{n_i}{n_i - 1}\frac{1}{e_1}} \Pi_{ih}^j(\sigma) - \Pi_{ih}^j(sq) - I(\sigma) = -I(\sigma),$$

Set $\hat{\tau}_n(\sigma) = \frac{n_i \sigma}{n_i - 1}$, then all firms in all n-firm industries with $\tau_i \geq \hat{\tau}_n(\sigma)$ will not adopt the technology of the level σ. Now, we allow σ to vary in the range $(1, \overline{\sigma})$. Taking the supremum of $\hat{\tau}_n(\sigma)$ over the range $(1, \overline{\sigma})$, the threshold for the n-firm industries is $\hat{\tau}_n = \sup\{\hat{\tau}_n(\sigma) : \sigma \in (1, \overline{\sigma})\}$.

To find the trade cost threshold for all possible n, we take

$$\hat{\tau} = \max\{\hat{\tau}_n : n = 1, 2, \cdots, \overline{n}\}$$

and the conclusion follows. ■

[7]By condition (11) and (22), if $\tau > \frac{n-1}{n}\frac{1}{e_1}$ and $\tau > \frac{n}{n-1}\frac{1}{e_1}$, then only home firms will sell in the home market. If $\tau > \frac{n}{n-1}e_1$ and $\tau > \frac{n-1}{n}e_1$, then only the foreign firms will sell in the foreign market. Combining the four inequalities implies, if $\tau > \frac{n_i}{n_i-1}\frac{1}{e_1}$, the home and foreign firms will only operate in their native markets in period 1. Since $e_1 < e_2 = 1$ implies $\frac{1}{e_1} > \frac{1}{e_2}$, the condition $\tau > \frac{n_i}{n_i-1}\frac{1}{e_1}$ also ensures the home and foreign firms will only operate in their native markets in period 2.

Proposition 3 implies that given an appreciation of a certain magnitude, $\hat{\tau}$ will partition the industries into two sets. The first set of industries with low τ_i may choose a new technology of level $\sigma > 1$ and the second set of firms will not. The remaining part of the section examines how home firms choose σ. We will see that if the first set contains industries with the same trade cost but the different n_i, then those with low n_i are likely to choose a large σ.

In stage 2 of the game, the first-period profit is not dependent on the choice of σ, and the equilibrium quantities and profits are similar to section 2. The second-period profits for home firm j and foreign firm j in the home market are

$$\pi^j_{ih2} = \left(\frac{1}{\sum_{k=1}^{n_i} x^k_{ih2} + \sum_{k=1}^{n_i} x^k_{if2}} - \frac{c_h}{\sigma^j} \right) x^j_{ih2}$$
$$\pi^j_{if2} = \left(\frac{1}{\sum_{k=1}^{n_i} x^k_{ih2} + \sum_{k=1}^{n_i} x^k_{if2}} - \frac{\tau_i c_f}{e_2} \right) x^j_{if2}$$

and the first order conditions are

$$\frac{\sum_{k\neq j} x^k_{ih2} + \sum_{k=1}^{n_i} x^k_{if2}}{(\sum_{k=1}^{n_i} x^k_{ih2} + \sum_{k=1}^{n_i} x^k_{if2})^2} - \frac{c_h}{\sigma^j} \leq 0$$
$$\frac{\sum_{k=1}^{n_i} x^k_{ih2} + \sum_{k\neq j} x^k_{if2}}{(\sum_{k=1}^{n_i} x^k_{ih2} + \sum_{k=1}^{n_i} x^k_{if2})^2} - \frac{\tau_i c_f}{e_2} \leq 0 \tag{30}$$

The first order conditions implicitly define the optimal output x^j_{ih2} as a function of $\vec{\sigma} = [\sigma^1, \sigma^2, \cdots, \sigma^{n_i}]$. Denote it as $x^j_{ih2}(\vec{\sigma})$. Similarly we define the optimal output function in the foreign market as $x^{j*}_{ih2}(\vec{\sigma})$

In stage 1, home firm j foresees the equilibrium output functions in the second stage and chooses σ^j to maximize total profit

$$\begin{aligned}
&\Pi^j_{ih}(\sigma^j) - I(\sigma^j) \\
=&\pi^j_{ih1} + e_1\pi^{j*}_{ih1} + \beta\pi^j_{ih2}(\sigma^j) + \beta e_2\pi^{j*}_{ih2}(\sigma^j) - I(\sigma^j) \\
=&\pi^j_{ih1} + e_1\pi^{j*}_{ih1} - I(\sigma^j) \\
&+ \beta\left(\frac{1}{\sum_{k=1}^{n_i} x^k_{ih2}(\vec{\sigma}) + \sum_{k=1}^{n_i} x^k_{if2}(\vec{\sigma})} - \frac{c_h}{\sigma^j}\right) x^j_{ih2}(\vec{\sigma}) \\
&+ \beta e_2\left(\frac{1}{\sum_{k=1}^{n_i} x^{k*}_{ih2}(\vec{\sigma}) + \sum_{k=1}^{n_i} x^{k*}_{if2}(\vec{\sigma})} - \frac{\tau_i c_h}{e_2\sigma^j}\right) x^{j*}_{ih2}(\vec{\sigma}) \qquad (31)
\end{aligned}$$

By the Envelop Theorem, the first order condition for an interior solution is

$$\begin{aligned}
\frac{\partial}{\partial\sigma^j}\Pi^j_{ih}(\sigma^j) = I'(\sigma^j) \quad \Rightarrow \\
\beta\frac{c_h}{(\sigma^j)^2}\left[x^j_{ih2}(\vec{\sigma}) + \tau_i x^{j*}_{ih2}(\vec{\sigma})\right] = I'(\sigma^j) \qquad (32)
\end{aligned}$$

Imposing symmetry among home firms' choices of σ, we have $x^j_{ih2}(\vec{\sigma}) = x^k_{ih2}(\vec{\sigma})$ for all k. Using this knowledge to simplify the (30), we have

$$\begin{aligned}
x^j_{ih2} &= \left(\frac{1}{n_i(1+\alpha_1)} - \frac{1}{n_i^2(1+\alpha_1)^2}\right)\frac{\sigma^j}{c_h} \\
x^j_{ih2} &= \left(\frac{1}{n_i(1+\alpha_2)} - \frac{1}{n_i^2(1+\alpha_2)^2}\right)\frac{\sigma^j}{c_h} \\
x^j_{if2} &= \left(\frac{1}{n_i(1+1/\alpha_1)} - \frac{1}{n_i^2(1+1/\alpha_1)^2}\right)\frac{1}{\tau_i c_f} \\
x^j_{if2} &= \left(\frac{1}{n_i(1+1/\alpha_2)} - \frac{1}{n_i^2(1+1/\alpha_2)^2}\right)\frac{1}{\tau_i c_f} \qquad (33)
\end{aligned}$$

where $\alpha_1 = \frac{n_i - \sigma^j\tau_i(n_i-1)}{n_i\sigma^j\tau_i - n_i + 1}$ and $\alpha_2 = \frac{n_i\tau_i/\sigma^j - n_i + 1}{n_i - (n_i-1)\tau_i/\sigma^j}$. Substituting (33) into (32) we obtain

$$\begin{aligned}
\frac{\beta}{\sigma^j}\left[\left(\frac{1}{n_i(1+\alpha_1)} - \frac{1}{n_i^2(1+\alpha_1)^2}\right) + \tau_i\left(\frac{1}{n_i(1+\alpha_2)} - \frac{1}{n_i^2(1+\alpha_2)^2}\right)\right] \\
= I'(\sigma^j) \qquad (34)
\end{aligned}$$

from which we can solve for the equilibrium σ^j.

Proposition 4. *Let $e_1 < 1$ and consider industries with the same trade cost $\tau < \hat{\tau}$ in $\Theta_\sigma(e_1)$. If all values of σ in some interval in $(1, \overline{\sigma})$ are profitable for firms in industries with different n_i, then the choice of σ is decreasing in n_i for $2 \leq n_i \leq \overline{n}$.*

Proof:

Using the left-hand-side of (34) we have

$$\frac{\partial}{\partial n_i}(\frac{\partial}{\partial \sigma^j}\Pi^j_{ih}(\sigma^j)) =$$

$$\frac{1}{\sigma^j}\left[\frac{(1^j_\sigma \tau_i)(2-n_i-n_i\alpha_1)}{(n_i\tau_i\sigma^j - n_i + 1)n_i^3(1+\alpha_1)^3} + \frac{\tau_i(\tau_i/\sigma^j+1)(\tau_i/\sigma^j)(2-n_i-n_i\alpha_2)}{(n_i-(n_i-1)\tau_i/\sigma^j)^2 n_i^3(1+\alpha^2)^2}\right]$$

which is negative if $n_i \geq 2$. This means the marginal benefit of σ^j is bigger for industries with a smaller n_i, provided $n_i \geq 2$. By the Envelop Theorem again we have

$$\frac{\partial^2}{\partial \sigma^j \partial \sigma^j}\Pi^j_{ih}(\sigma^j) = \beta\frac{-2c_h}{(\sigma^j)^3}\left[x^j_{ih2}(\vec{\sigma}) + \tau_i x^{j*}_{ih2}(\vec{\sigma})\right] < 0$$

Thus $\Pi^j_{ih}(\sigma^j)$ is a strictly concave function.

Let n' and n'' be the number of firms in two industries with the same trade cost $\tau < \tilde{\tau}$ and $2 \leq n' < n'' \leq \overline{n}$. Denote the firms' optimal choices of technology levels as $\sigma_{n'}$ and $\sigma_{n''}$. Suppose $\sigma_{n''} \geq \sigma_{n'}$. Then we have

$$\frac{\partial \Pi^j_{ih}(\sigma^j, n_i = n')}{\partial \sigma^j}\Big|_{\sigma_{n''}} > \frac{\partial \Pi^j_{ih}(\sigma^j, n_i = n'')}{\partial \sigma^j}\Big|_{\sigma_{n''}} = \frac{\partial}{\partial \sigma^j} I(\sigma^j)\Big|_{\sigma_{n''}}$$

which means the profit for firm j in the n'-firm industry, $\Pi^j_{ih}(\sigma^j, n_i = n') - I(\sigma^j)$, is increasing at some level no smaller than $\sigma_{n'}$. This increase contradicts that $\sigma_{n'}$ is the optimal choice for firms in the industry with n_i firms, unless there is another local maximizer σ^* with $\sigma^* > \sigma_{n'}$. However, since $\Pi^j_{ih}(\sigma^j)$ is strictly concave and $I(\sigma)$ is strictly convex, there are no other local maximizers. Thus we conclude that $\sigma_{n''} < \sigma_{n'}$ for all $2 \leq n' \leq n'' \leq \overline{n}$.

■

Note when σ is greater $(1 + \frac{1}{n_i - 1})\frac{1}{\tau_i}$, all foreign firms in industry i are forced out of the home market. Given a τ_i, if $I(\sigma)$ rises fast enough, then it will exceed the benefit of adoption at $\sigma = (1 + \frac{1}{\overline{n}-1})\frac{1}{\tau_i}$, ensuring that all home firms will have interior choices of σ, i.e. the foreign firms will not be out of the home and foreign market. Figure 1 illustrates this point.

The key for the proof is that among industries with the same τ, the profit of firms in industries with lower n_i is more responsive to σ. Thus the marginal profit with respect to σ is equal to the marginal cost $I'(\sigma)$ at a bigger value. Figure 2 demonstrates the argument graphically.

Putting Propositions 2, 3 and 4 together yields the following predictions. First, among industries with trade cost lower than the threshold $\hat{\tau}$ there is negative correlation between the number of firms per industry and the choice of σ if $n_i \geq 2$. Since the concentration level of an industry is inversely related to the number of firms, if we regress σ on concentration for the set of industries with $\hat{\tau}$, OLS is predicted to find a positive relation. Second, industries with trade costs greater than $\hat{\tau}$ will not adopt the disruptive technology. For these industries, a regression of σ on concentration will yield a zero slope coefficient. Figure 3 illustrates the adoption choices for firms in different industries. Overall, if we simply pool all industries together and regress σ on concentration, we are likely to find a positive relation.

Compared to Holmes et al. (2008) and other previous theoretical papers which focus on the question of whether firms will adopt a new technology when there is more competition, this paper studies both the conditions for adoption and the intensity of adoption. The model presented here differentiates between two types of competition, the competitive pressure from appreciations, and market concentration. The competitive pressure from appreciations is predicted to provide an incentive for adopting new technologies, consistent with finding of previous papers. However, firms in highly-concentrated industries, i.e. those subject to less competition in this dimension, are likely to invest more to achieve bigger productivity improvements. Thus, my model illustrates that the effect of competition on adoption of new technologies is subtle.

While the above model focuses on the interaction between exchange rate appreciation and the adoption of a disruptive technology, it should be recognized that an important alternative mechanism can potentially also give rise to similar predictions. That is, when exchange rate appreciates, foreign capital goods that embody better technology will become cheaper. Although there is no explicit role of capital in my model, this idea of cheaper investment goods can be modeled by assuming the home firms purchase the investment $I(\sigma)$ from the foreign country. In this case, the home firm j problem, previously given by equation (31) is modified as

$$\begin{aligned}&\max_{\sigma^j}\ \Pi^j_{ih}(\sigma^j) - e_1 I(\sigma^j)\\ &\quad =\pi^j_{ih1} + e_1\pi^{j*}_{ih1} + \beta\pi^j_{ih2}(\sigma^j) + \beta e_2\pi^{j*}_{ih2}(\sigma^j) - e_1 I(\sigma^j)\end{aligned}$$

It can be showed that Proposition 4 holds under this setup, without making the assumption of disruptive technology. Such a mechanism will predict increase in purchase of foreign capital goods. Without access to detail data on the capital investment and intermediate good trade for Canadian manufacturing industries, I am unable to differentiate between the two hypotheses in the empirical section.

4 Manufacturing Productivities in Canada from 1997 to 2006

When the home country experiences an appreciation, the model developed in sections 2 and 3 offers the following two key predictions. First, in general appreciations provide incentives for firms to improve productivity. Second, among industries with low trade costs, the highly concentrated ones will implement bigger improvements to productivity, as profits of firms with a bigger market share will be more responsive to change in productivity. Industries with high trade costs will have no incentive to improve productivity regardless of the concentration level, as the high trade cost will limit competition from foreign industries.

In the model I assume that in the country that experiences a depreciation, productivity will not respond to depreciation. The assumption is needed to simplify the analysis when industries in the other country are allowed to choose the level of productivity improvement. If this assumption is a reasonable approximation of firms' behavior during depreciation, we would see the firms' productivity fall relative to their counterparts in the other countries as the latter group of firms have an incentive to improve productivity to counter the movement of the exchange rate.

To test the predictions of the model, I analyze how the productivity of Canadian manufacturing industries responded between 1997 and 2006 to the interactions between exchange rate movements, trade costs, and concentrations. There are a few advantages to using Canadian manufacturing data. First, Canada is a highly open economy, and its manufacturing industries are exposed to a substantial amount of trade. In particular, because of the Free Trade Agreement with the US, Canada's main trading partner, we may consider the trade costs of Canadian industries reflect mostly exogenous factors.

Second, during the sample period the Canadian dollar experienced first a moderate depreciation then a major appreciation. Since there is evidence (see for instance Maier and DePratto (2007)) that the recent exchange movements are partly driven by movements in commodity prices, it is reasonable to suggest the movements are exogenous to manufacturing industries. Although productivity of manufacturing industries may contribute to the movements in exchange rates, such effects are likely to be dominated by the commodity factor.

Third, since both Canada and the US have adopted the North American Industry Classification System (NAICS), I am able to use productivity growth in the US manufacturing industries to control for some of the unobserved industry characteristics. Among others, this would capture technological spillovers from US industries.

4.1 Specification and Data

The sample used in this study involves the annual data of 237 6-digit NAICS Canadian manufacturing industries from 1997 to 2006.[8] The sources of Canadian data are the Annual Survey of Manufacturers (ASM) published by Statistics Canada, the Canadian Socioeconomic Information Management (CANSIM) Database, the Bank of Canada. The US data are obtained from the Annual Survey of Manufactures (ASM) published by the US Census Bureau, and the Basic Economics database (DRI/McGraw-Hill).

The empirical specification is

$$\begin{aligned} & dln(productivity)_{it} = \\ & \quad \beta_0 + \beta_1 \cdot dln(exchange\ rate)_{t-1} + \beta_2 \cdot concentration_{it-1} \\ & \quad + \beta_3 \cdot dln(exchange\ rate)_{t-1} \cdot concentration_{it-1} \\ & \quad + \beta_4 \cdot dln(exchange\ rate)_{t-1} \cdot concentration_{it-1} \cdot Trade\ Dummy_i \\ & \quad + \beta_5 \cdot (other\ controls) + u_i + \epsilon_{it} \end{aligned} \tag{35}$$

where i is the index for the industries and t for year. u_i is the industry specific effect and ϵ_{it} is the error term assumed to be i.i.d. across industries and time.

In the specification, I use last period exchange rate movement as a regressor. In the theoretical model, at the beginning of the first period firms decide whether to improve productivity conditioned on the perfect foresight of an appreciation. While firms in the real world do not possess perfect foresight, they can predict exchange rate by exploiting the fact that the deviation of exchange rate from the PPP value is highly persistent.[9] An appreciation in the last period is a good predictor that the current period exchange rate will stay at an appreciated level. According to my calculation, for the Canadian dollar/US dollar exchange rate, the correlation coefficient between the deviation from PPP and its

[8] The total number of 6-digit NAICS manufacturing industries is 262. 25 industries are missing from the sample due to the lack of data.

[9] See Rogoff (1996) for a discussion of the persistence in deviation from PPP.

one-period lag is 0.887. Hence, I used the last period exchange rate movement to capture the firms' expectation about exchange rate in the current period.

The interaction between exchange rate and concentration corresponds to the model prediction, that in general, there is a positive relation between market concentration and productivity growth during appreciations. The triple interaction term reflects the model prediction that, during an appreciation, market concentration level is positively associated with productivity gain within the group of highly traded industries. Since an appreciation is defined as a decrease in the exchange rate, a negative β_4 would support the prediction.

The traditional measure of productivity, total factor productivity (TFP), is not available for Canadian manufacturing industries as Statistics Canada does not provide data on capital stock or investment necessary for the computation of TFP. Thus I use labor productivity instead, and the main measure is value added per production worker. In robustness checks I also explore manufacturing revenue per production worker as an alternative measure of labor productivity. Value added per production worker is often used to measure labor productivity in the international trade literature, for instance in Bernard and Jensen (1999). Trefler (2004) uses "value added in production activities per hour worked by production workers" as the measure for productivity. While the analysis of Trefler (2004) is based on the 3-digit SIC manufacturing industries, this paper is based on 6-digit NAICS classification of industries. As the hours worked are not reported by Statistics Canada for the 6-digit NAICS industries, it is not possible for this paper to use the same measure.

The measure of exchange rate is the Canadian-dollar effective exchange rate index (CERI) created by the Bank of Canada. It is defined by the Bank of Canada as "a weighted average of bilateral exchange rates for the Canadian dollar against the currencies of Canada's major trading partners"[10]. Since the US dollar carries a weight of 0.7618, the

[10]These currencies are the US dollar, the European Union euro, the Japanese yen, the UK pound, the Chinese yuan, and the Mexican peso. Details can be found at http://www.bank-banque-canada.ca/en/rates/ceri.pdf.

movement of the CERI closely mimics the movement of the Canada/US exchange rate, as shown in Figure 2.5. I deflate the CERI by the inflation rate in Canada and the weighted inflation rate of the major trading partners to obtain movements in real exchange rate. [11]

The concentration of production in each industry is measured by the 4-firm concentration ratio (CR4) reported by Statistics Canada. In the model firms are symmetric, so CR4 has an inverse relation with the number of firms in the industry. In reality firms differ in size so CR4 might be a better measure of concentration compared to the number of firms [12]. Since data on CR4 is not available beyond 2003, I use the 2003 values for the years 2004 and 2005[13].

Trade costs of industries are not observed but in the model they have an inverse relation with the trade to sales ratio. I construct the ratio for an industry as the value of total import plus export divided by the manufacturing revenue of the industries between 1997 and 2006.

Other control variables included in the regressions are growth in energy per production worker, growth in material per production worker, growth in R&D expenditure, average establishment size, productivity growth in corresponding US industry, and GDP growth in Canada and the US. Lastly, industry fixed effects and year effects are also used in most of the regressions.

As mentioned before, there are no direct measures of the capital stock, its utilization variation, and changes in hours worked per worker. Including energy and material use provides a limited remedy. The model in the paper focuses on the adoption of a known

[11] In unreported regressions, I use the Canada/US real exchange rate and find results are not sensitive to this treatment.

[12] CR4 is used by MacDonald (1994) to study how the change in productivity varies with market power after an import surge. This paper is similar in that it also studies how the effect of competition differs with cross section difference in CR4.

[13] Note CR4 enters the regression model with a one-period lag. Using 2003 values for the year of 2004 and 2005 does not have a major impact on the results, since CR4 is stable over time (see Table 1) and most of the variation in CR4 comes from the cross-section. In the robustness check subsection, I show the main results hold even if I use the 1990 CR4 values as the measure for concentration between 1997 and 2006.

technology, and the inclusion of R&D expenditure helps to control for the improvement to productivity due to firms' search for new technologies. However, R&D is available only for 3-digit or 4-digit NAICS industries, at a higher level of aggregation than 6-digit NAICS industries. Average establishment size is computed as the number of production workers per establishment in an industry. It is included to control for return-to-scale effects. Since it is possible for Canadian industries to benefit from technological spillover from foreign industries, especially US industries, I include productivity growth in the corresponding US industry to capture such learning opportunities. Adding real GDP growth rates of Canada and US will control for the effects of macroeconomic productivity and demand shocks.

Before turning to regression results, it is useful to have a brief look at a number of key variables during the depreciation sub-period (1997-2002) and the appreciation sub-period (2002-2006) in Table 1.

We can see that during appreciation export growth and employment of production workers dropped. Meanwhile, Canadian manufacturing labor productivity, measured by both value added per production worker and manufacturing revenue per production worker increased, although it was outpaced by US labor productivity growth. Judging from the means reported, we cannot rule out the possibility that the higher labor productivity growth in Canada had come from spillover from the 5.2% growth in US labor productivity. It could also be the case that higher energy use per production worker contributed to the labor productivity growth. Growth in R&D expenditures and scale effects as measured by establishment sizes, on the other hand, appear to be poor explanations for the higher productivity growth in the appreciation sub-period, as the two variables were lower during the appreciation. Lastly, it's worth noting there was little change in the average concentration ratio.

4.2 Main Results

I estimate all specifications with the linear model with industry fixed effects. The only complication comes from the threshold effect of trade. Conditioned on whether trade exceeds a threshold level, the model predicts different relations between concentration of production and productivity gain during appreciation. The trade threshold is unknown and has to be estimated. The estimation of the threshold follows Hansen (2000), and is based on least-square regressions. I first construct a grid of trade-ratios with the step size being 0.5 of a centile and then search the grid for a threshold at which the effect of concentration-exchange-rate interaction changes significantly. The estimated threshold is located at the 83.5th centile, translating to a trade to revenue ratio of 1.89. There are 39 industries with a trade ratio above the threshold. The 95% confidence interval for the threshold is between the 76th and 92.5th centiles, or $[1.63, 2.80]$ in terms of trade-to-revenue ratio. Using the threshold estimate, I estimate the threshold regression model specified in (35). Standard errors are computed with methods suggested in Hansen (2000).

Though not predicted by the theory, it is plausible that the effect of exchange rate on labor productivity growth may also change with a trade threshold. The application of the threshold estimation method on the interaction between trade and exchange rate movement indicates there is no statistically significant threshold effect[14]. In essence, I have used the method in Hansen (2000) to guide the empirical specification. In one of the robustness checks, the interaction between the trade dummy and exchange rate movement is included to show key results are insensitive to its inclusion.

The first three columns of Table 2 report the benchmark regression results. The specification in column (1) includes year dummies, thus precluding variables that are invariant across the cross-section, in particular the last-period exchange rate movement. Specification (2) and (3) estimate the same specification using only the subsamples.

[14]In unreported regressions, the interaction between trade-to-revenue ratio and other variables, such as the concentration ratio, are also included as regressors. Such interactions are always highly insignificant.

In column (1) of Table 2, the level of concentration ratio is not significant, consistent with the theory prediction that it should not matter independent of the exchange rate. The interaction between concentration and exchange rate is negative and significant, with a coefficient of -0.009. This estimate implies that during a 5% appreciation[15] an industry with a 20% higher concentration ratio will experience labor productivity growth that is 0.9% higher. Since the average labor productivity growth rate between 1997 and 2006 was 1.4%, and that the standard deviation of the concentration ratio was 24%, we can say this is an economically significant effect. Meanwhile, the coefficient on the triple interaction of exchange rate, concentration and trade dummy is -0.005, which is economically large but not statistically significant.

The growth rate in R&D expenditure appears to have had no effect on labor productivity growth. While the establishment size did have an impact on labor productivity growth, the magnitude was not big as a coefficient of 0.004 meant that an increase of establishment size by 100 workers only raised labor productivity growth by 0.04.%[16] The coefficient on the energy and material variables suggest that the energy and material elasticity of productivity are 0.199 and 0.250 respectively. Both are highly significant. Lastly, the labor productivity growth in Canadian industries was positively correlated with the growth in US. A 1% increase in productivity in a US industry is associated with a 0.159% increase in the corresponding Canadian industry.

Column (2) is estimated with the subsample between 2002 and 2006, i.e. the appreciation period, while column (3) is estimated with the subsample of the depreciation period. The discussion will be focused on the interaction terms, as estimates of other coefficients are similar to column (1). In column (2), the interaction between concentration and exchange rate becomes insignificant while the triple interaction term becomes significant. A coefficient of -0.011 on the triple interaction term implies that during a 5%

[15]Note again, appreciation is defined as decrease in the exchange rate.

[16]The unit of measurement for establishment is scaled up to 10 workers to facilitate the presentation of results, i.e. to avoid many fractions with four digits after the decimal point.

appreciation an industry with a 20% higher concentration ratio will experience a labor productivity growth that is 1.1% higher. The estimates are in line with the predictions of the theory, i.e. we expect to see a positive correlation between concentration and labor productivity growth *only* for the high-trade industries.[17] On the other hand, the estimation on the depreciation subsample indicates no threshold effect and the effect of concentration-exchange-rate interaction is large but not statistically significant.[18]

It is worth noting that most of the variation in concentration ratio comes from the cross-section, rather than variation in the time dimension. Over the sample period, 98% of the variance in concentration is accounted for by the variance in the industry average concentration ratio. Namely, within most industries, the concentration levels had experienced very little change. Therefore, in interpreting the results, we can roughly view the concentration level as fixed over time and regard the regression coefficients on the concentration-exchange-rate interactions as reflection of the different effects of exchange rates movements on industries with different pre-determined concentration levels.

4.3 Robustness Checks

In this subsection, I conduct several robustness checks. Table 3 reports the results with alternative dependent variables. The dependent variable in columns (1) through (3) is the difference between Canadian and US labor productivity growth rates. Adopting this dependent variable is equivalent to imposing the restriction that the coefficient on US productivity growth is 1 in the regressions in Table 2. Careful comparison between the first three columns of Table 3 and Table 2 suggests they are very similar. In the last

[17] Fernandes (2007) finds that when faced with the competitive presure of trade liberalization, there were bigger productivity gains for plants in less competitive Colombian manufacturing industries. While working on a different type of competitive pressure, my findings about productivity and market power are consistent with hers.

[18] In Fung and Liu (2009), the authors find that productivity of Taiwanese firms actually increased during the depreciation of the New Taiwan dollar in late the 1990s. They suggest the increase may be due to the larger scale of production after depreciation. Both my theoretical and empirical results do not add new evidence on the relation between depreciation and productivity.

three columns, the dependent variable is manufacturing revenue per production worker, arguably a poorer measure for labor productivity not accounting for costs of other inputs. Although the overall fit of the three regressions are much better, we can only find a weak relation between concentration and labor productivity growth and there is no evidence of a threshold effect.

In the baseline estimations, I look at the effect of exchange rate change between year $t-1$ and t on productivity growth between t and $t+1$. Since in their decision-making, firms may look into exchange rate change over a longer period in the past, and the change in productivity may realize over a longer period too, I also estimate equations with alternative assumption about the length of periods. In Table 4, the first three columns present effects of exchange rate change between $t-2$ and t on productivity between t and $t+2$. The last three columns are effects of exchange rate change between $t-3$ and t on productivity between t and $t+1$. While there are some changes in parameter estimates, the coefficients on the triple interaction term for the appreciation period are very similar to the benchmarks in 2.

After a major appreciation, productivity can improve due to firms upgrading their technologies, as suggested in this paper. However, productivity increase can also result from exits of less efficient firms. In Table 5, I present results from specifications augmented by change in the number of establishments. We can see the coefficients on the interaction terms are similar to the benchmarks. However, adding change in the number of establishments is a crude way to control for the effect of entries and exits. Ideally one should control for the size of entrants and exiting firms, but these data have not been available.

In columns (1) and (2) of Table 6, I allow for an interaction between the trade dummy and exchange rate movement, with the triple interaction absent in column (1). This interaction is not always significant. In column (1) we see a significant effect of the concentration-exchange-rate interaction, and in column (2) there is a threshold effect, significant at the 10% level.

Lastly, it is reasonable to suspect the concentration ratio may affect labor productivity growth one period later via channels other than its interaction with the exchange rate, for example, the consolidation of firms in the current period can raise concentration and the resulting synergy can lead to productivity gains in the future periods. To show that this suspicion is unlikely, I use CR4 in 1990 to interact with exchange rate movements and trade between 1997 and 2006. In this case, only the lagged cross-section variation in CR4 is used in estimation. The results are reported in column (3) of Table 6. We can still see a positive relation between concentration and labor productivity growth, and a trade threshold effect, although the interaction terms are only significant at the 10% level.

On the balance, the evidence suggest the appreciation provided incentive for Canadian manufacturing industries to improve productivity. In particular, highly-concentrated industries experienced higher labor productivity growth during an appreciation. On the other hand, the theoretical model does not offer a direct prediction for periods of depreciation, and the evidence during the 1997-2002 sub-period is inconclusive. Lack of productivity responses during the depreciation sub-period could be due to that the depreciation between 1997 and 2002 was too moderate to trigger responses from competitors of Canadian firms.

5 Conclusion

This paper is motivated by the question of how productivity responds to major real exchange rate movements. Drawing on observations of disruptive technological changes documented in Holmes et al. (2008), I have built a partial equilibrium model to clarify how productivity responses of industries vary with trade costs and market concentration during an appreciation. Similar to results in previous literature, I find that competitive pressure resulting from appreciations increases incentives to improve productivity, as the appreciation lowers the profit loss during costly transitions. Meanwhile, higher trade costs reduce the incentives by diminishing the competitive pressure of appreciations. In addition, this paper contributes to the theoretical literature by studying the intensity of technology adoption, suggesting a positive relation between market concentration and the intensity of adoption. It is firms in highly concentrated industries that will invest more in productivity improvements, as their marginal benefits from adopting better technologies are greater.

Empirical analysis of 237 6-digit Canadian manufacturing industries between 1997 and 2006 supports the theoretical model's predictions. During the appreciation period between 2002 and 2006, labor productivity growth was on average higher after controlling for industry fixed effects, and growth in all of energy use, material use, R&D expenditure, and productivity in corresponding US industries. Highly concentrated industries experienced high productivity growth, conditional on their exposure to a substantial amount of trade. The theoretical model does not offer predictions for productivity response to depreciations, and during the depreciation period between 1997 and 2002, there is little empirical evidence that labor productivity growth had been correlated with exchange rate movements or concentration. The empirical analysis adds to the evidence of a positive relationship between competitive pressure and productivity improvement.

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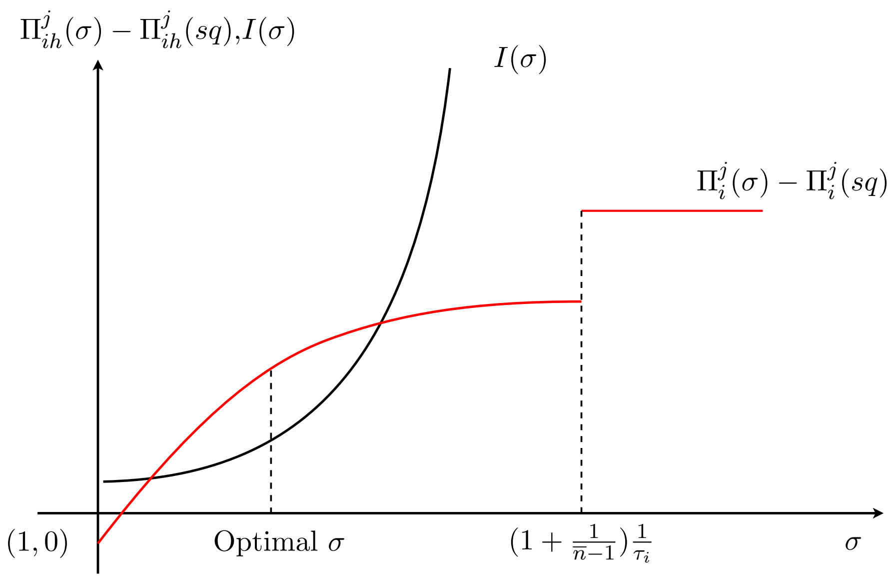
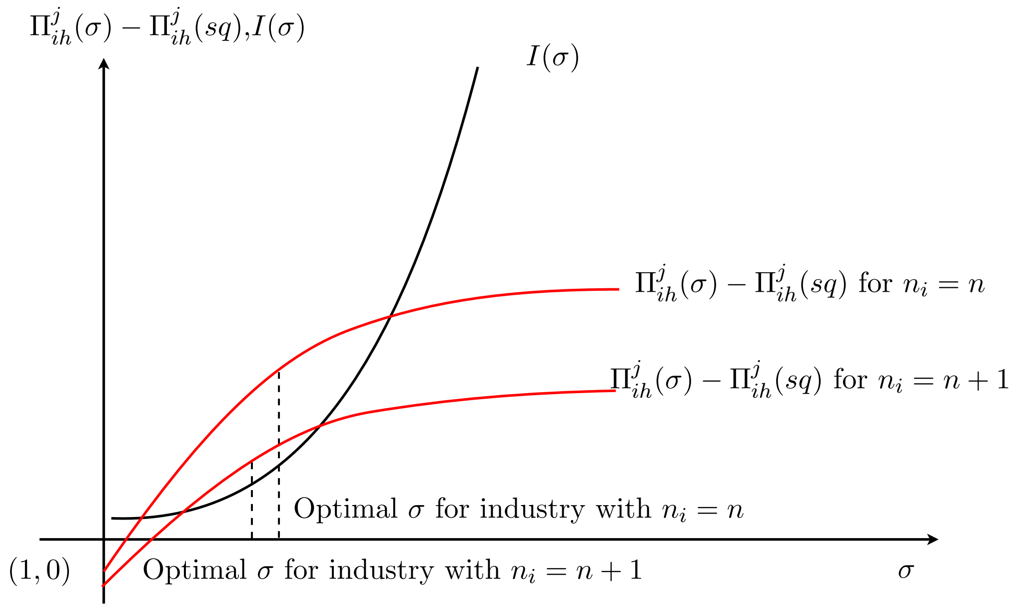


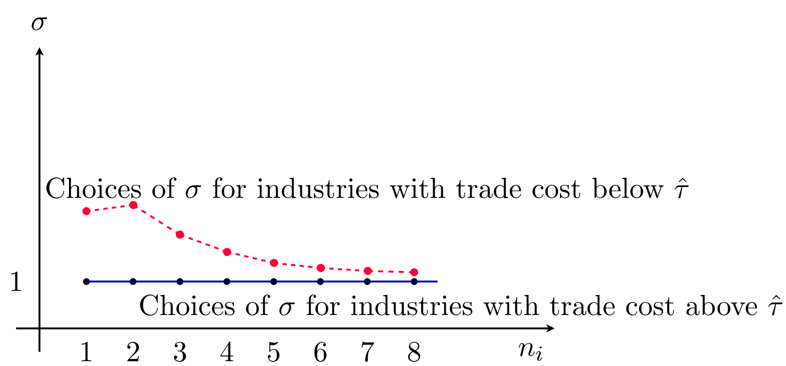
$\Pi^j_i(\sigma) - \Pi^j_i(sq)$ is the benefit of adopting technology of level σ and $I(\sigma)$ is the fixed cost. For a given τ_i, when improvement in home productivity σ is larger than $(1 + \frac{1}{\overline{n}-1})\frac{1}{\tau_i}$, foreign firms in industries with $\overline{n}$ firms begin to drop out of the market and home firms has a jump in profit as they are competing only against each other. When $I(\sigma)$ rises fast enough, choosing $\sigma > (1 + \frac{1}{\overline{n}-1})\frac{1}{\tau_i}$ is not optimal and home firms will choose an interior σ. For industries with $n_i < \overline{n}$, their jump points in profits are bigger than $(1 + \frac{1}{\overline{n}-1})\frac{1}{\tau_i}$. Firms in these industries will choose interior σ as well as long as this is the case in the $\overline{n}$-firm industry.

Figure 1: The Benefit and Cost of Adopting the Disruptive Technology



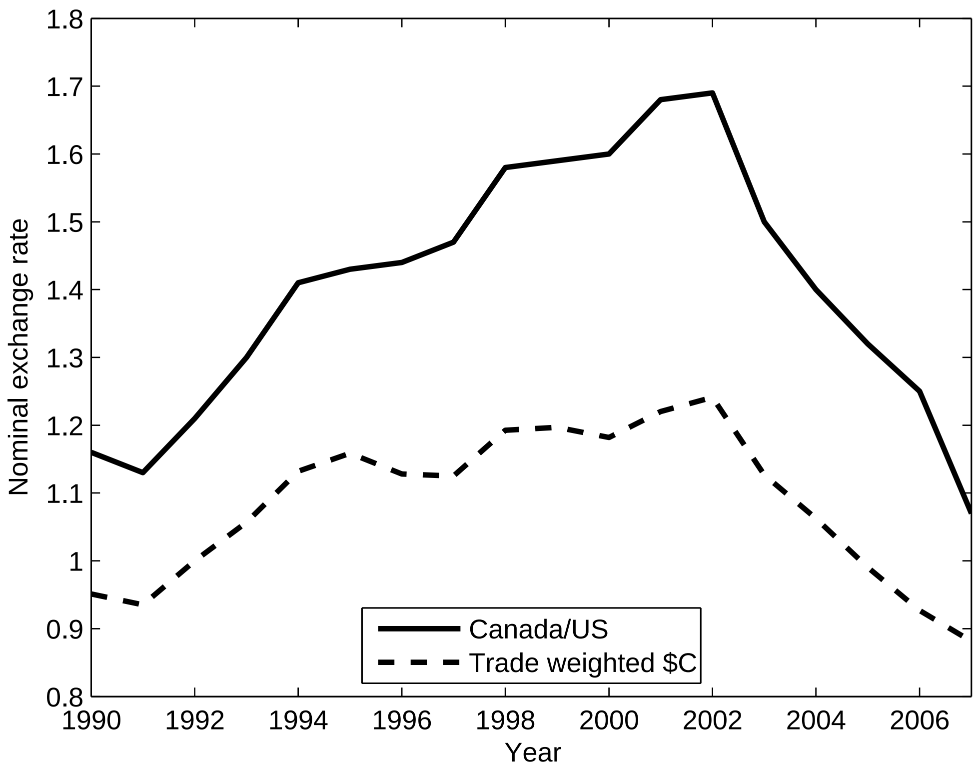
$\Pi^j_{ih}(\sigma) - \Pi^j_{ih}(sq)$ is the benefit of adopting technology of level σ and $I(\sigma)$ is the fixed cost. Proposition 4 shows, the benefit of adoption for industries with n firms is increasing faster in σ than industries with $n+1$ firms. Given the same fixed cost $I(\sigma)$, the optimal choice of σ for firms in industries with fewer firms is larger.

Figure 2: Illustration of The Relation between n_i and Choice of σ



The model suggests, 1) for industries with trade cost lower than $\hat{\tau}$ the choice of productivity improvement σ is negatively correlated with the number of firms per industry n_i , and 2) industries with trade cost greater than $\hat{\tau}$ will not adopt the disruptive technology (denoted as choosing $\sigma = 1$ in the figure).

Figure 3: Level of Technology Adoption and Number of Firms in the Industry



The solid line is the Canada/US nominal exchange rate and the dashed line is the Canadian-dollar effective exchange rate (CERI). Both are measured at annual frequency. Note the original CERI has a base value of 100 and is defined as the price of Canadian dollar in terms of the basket of foreign currencies. To make it compatible with the definition in the paper, I divide the original CERI by 100 and take the inverse. The dashed line plots the edited CERI series.

Figure 4: Movements of Canadian Dollar Exchange Rate Since 1990

Table 1: Means of Key Variables between 1997 and 2006

	Whole period	Depr(1997-2002)	Appr(2002-2006)
dln(value added per production worker), CND	1.4% (0.39%)	1.0% (0.53%)	2.0% (0.56%)
dln(value added per production worker), US	3.0% (0.31%)	1.3% (0.42%)	5.2% (0.42%)
dln(revenue per production worker), CND	1.5% (0.29%)	0.6% (0.02%)	2.5% (0.39%)
dln(effective exchange rate)	-1.4% (4.9%)	1.6% (2.6%)	-5.6% (4.4%)
trade to revenue ratio	1.39 (0.04)	1.36 (0.05)	1.43 (0.05)
4-firm concentration ratio	48.3% (0.52%)	48.3% (0.69%)	48.0% (0.80%)
dln(manufacturing revenue)	0.8% (0.31%)	2.3% (0.45%)	-1.1% (0.43%)
dln(value of export)	0.9% (0.48%)	4.0% (0.73%)	-3.0% (0.57%)
dln(value of import)	2.8% (0.44%)	4.2% (0.68%)	1.1% (0.49%)
dln(number of production workers)	-0.7% (0.33%)	1.7% (0.43%)	-3.7% (0.48%)
dln(R&D expenditure)	7.9% (0.36%)	12.3% (0.54%)	2.5% (0.79%)
dln(energy per production worker)	5.2% (0.37%)	2.7% (0.49%)	8.2% (0.55%)
dln(material per production worker)	1.5% (0.34%)	1.5% (0.45%)	1.6% (0.51%)
establishment size	60 (2.53)	66 (3.90)	52 (2.89)

Notes: 1) The numbers are the means of 237 6-digit NAICS industries over the time period indicated, except for the case of R&D expenditure where the means are calculated from 4-digit NAICS industries. 2) "dln" denotes first differences in log, as approximations for growth rates. 3) The numbers in the parentheses are standard errors.

Table 2: Benchmark Fixed Effect Estimations

Dependent variable dln(productivity)	Full sample 1997-2006	Appr. 2002-2006	Depr. 1997-2002
$CR4$	-0.001	-0.003	-0.001
	(0.006)	(0.003)	(0.001)
$dln(RER) \cdot CR4$	-0.009**	-0.005	-0.013
	(0.003)	(0.004)	(0.010)
$dln(RER) \cdot CR4 \cdot TradeD$	-0.005	-0.011**	0.001
	(0.003)	(0.004)	(0.009)
$dln(R\&D)$	0.002	-0.013	-0.018
	(0.027)	(0.046)	(0.044)
$Estab\ size$	0.004***	0.001	0.001**
	(0.001)	(0.001)	(0.0002)
$dln(Energy)$	0.199***	0.106**	0.326**
	(0.028)	(0.040)	(0.049)
$dln(Material)$	0.250**	0.207**	0.276**
	(0.028)	(0.039)	(0.050)
$dln(Productivity\ US)$	0.159**	0.223*	0.165
	(0.074)	(0.098)	(0.151)
year dummies	included	included	included
industry fixed effects	included	included	included
R^2	0.11	0.09	0.10
Observations	2068	906	1162
Industries	237	231	237

Notes: 1) ***, ** and * indicate significance levels of 1%, 5% and 10%.
2)"dln" denotes first differences in log, as approximations for growth rates.
3) The dependent variable is labor productivity, measured as value added per production worker. *RER*, *CR4*, *TradeD*, *R*&D, *Estab size*, *Energy*, *Material*, and *Productivity US* denote respectively real exchange rate, 4-firm concentration ratio, a dummy variable for highly-trade industries, R&D expenditure, average establishment size, energy used per production worker, material used per production worker, growth in value added per production worker in the corresponding US industry.

Table 3: Alternative Dependent Variables

	Full sample 1997-2006	Appr. 2002-2006	Depr. 1997-2002	Full sample 1997-2006	Appr. 2002-2006	Depr. 1997-2002
	(1)	(2)	(3)	(4)	(5)	(6)
$CR4$	-0.001	-0.002	-0.001	-0.001**	-0.001	-0.001
	(0.001)	(0.003)	(0.001)	(0.0003)	(0.001)	(0.001)
$dln(RER) \cdot CR4$	-0.006*	-0.002	-0.014	-0.003*	-0.002	-0.002
	(0.004)	(0.003)	(0.011)	(0.002)	(0.003)	(0.007)
$dln(RER) \cdot CR4 \cdot TradeD$	-0.006*	-0.013***	-0.001	-0.001	-0.002	0.003
	(0.004)	(0.005)	(0.010)	(0.002)	(0.002)	(0.006)
$dln(R\&D)$	0.056**	0.073	0.020	0.002	0.040**	-0.043
	(0.027)	(0.047)	(0.044)	(0.015)	(0.019)	(0.029)
$Estab\ size$	0.005***	0.003	0.008***	0.001*	0.002	0.002*
	(0.001)	(0.003)	(0.002)	(0.0001)	(0.002)	(0.001)
$dln(Energy)$	0.207***	0.092**	0.352***	0.118***	0.139***	0.102***
	(0.029)	(0.042)	(0.050)	(0.015)	(0.017)	(0.032)
$dln(Material)$	0.238***	0.211***	0.252***	0.584***	0.536***	0.637***
	(0.029)	(0.040)	(0.050)	(0.079)	(0.016)	(0.032)
$dln(Productivity\ US)$	-	-	-	0.079*	0.165***	-0.015
				(0.041)	(0.041)	(0.099)
year dummies	included	included	included	included	included	included
industry fixed effects	included	included	included	included	included	included
R^2	0.09	0.06	0.09	0.05	0.06	0.04
Observations	2068	906	1162	2068	906	1162
Industries	237	231	237	237	231	237

Notes:
1) ***, ** and * indicate significance levels of 1%, 5% and 10%.
2) "dln" denotes first differences in log, as approximations for growth rates.
3) The dependent variable in the first three columns is the growth rates difference in Canada and US value added per production worker.
4) The dependent variable in column (4) through (6) is manufacturing revenue per production worker.
5) *RER*, *CR4*, *TradeD*, R&D, *Estab size*, *Energy*, *Material*, and *Productivity US* denote respectively real exchange rate, 4-firm concentration ratio, a dummy variable for highly-trade industries, R&D expenditure, average establishment size, energy used per production worker, material used per production worker, growth in value added per production worker in the corresponding US industry.

Table 4: Alternative Specification of Lags

Dependent variable dln(productivity)	Full sample 1997-2006	Appr. 2002-2006	Depr. 1997-2002	Full sample 1997-2006	Appr. 2002-2006	Depr. 1997-2002
	(1)	(2)	(3)	(4)	(5)	(6)
$CR4$	-0.001	-0.007*	-0.001	-0.001	-0.003	-0.001
	(0.001)	(0.004)	(0.001)	(0.001)	(0.003)	(0.001)
$dln(RER) \cdot CR4$	-0.005	0.002	-0.011	0.001	0.002	-0.005
	(0.003)	(0.004)	(0.009)	(0.002)	(0.002)	(0.014)
$dln(RER) \cdot CR4 \cdot TradeD$	-0.005	-0.011***	0.013	-0.004**	-0.008***	0.019*
	(0.003)	(0.004)	(0.008)	(0.002)	(0.002)	(0.013)
$dln(R\&D)$	0.003	0.073	-0.038	0.008	-0.015	0.023
	(0.024)	(0.042)	(0.043)	(0.017)	(0.028)	(0.041)
$Estab\ size$	0.001***	0.002**	0.001***	0.003**	-0.001	0.001***
	(0.0002)	(0.001)	(0.0002)	(0.0001)	(0.001)	(0.0002)
$dln(Energy)$	-0.022	-0.014	-0.067	0.057***	0.037	0.161***
	(0.031)	(0.046)	(0.054)	(0.022)	(0.030)	(0.049)
$dln(Material)$	0.103***	-0.033	0.191***	0.089***	0.010	0.197***
	(0.031)	(0.047)	(0.053)	(0.021)	(0.031)	(0.048)
$dln(Productivity\ US)$	0.299***	0.408***	0.441**	0.188**	0.253***	0.200
	(0.097)	(0.125)		(0.076)	(0.097)	(0.160)
year dummies	included	included	included	included	included	included
industry fixed effects	included	included	included	included	included	included
R^2	0.05	0.06	0.09	0.06	0.09	0.04
Observations	1818	903	915	2048	906	1162
Industries	237	233	235	239	231	237

Notes:
1) ***, ** and * indicate significance levels of 1%, 5% and 10%.
2) "dln" denotes first differences in log, as approximations for growth rates.
3) The dependent variable in the first three columns is productivity growth rate in Canada between year t and $t+2$. All independent variables are also measured between t and $t+2$, except for that RER measures the exchange rate change between $t-2$ and t.
4) In column (4) through (6) is manufacturing revenue per production worker, the dependent variable and all independent variables are measured between year t and $t+1$, except for that RER measures the exchange rate change between $t-3$ and t.
5) *RER*, *CR4*, *TradeD*, R&D, *Estab size*, *Energy*, *Material*, and *Productivity US* denote respectively real exchange rate, 4-firm concentration ratio, a dummy variable for highly-trade industries, R&D expenditure, average establishment size, energy used per production worker, material used per production worker, growth in value added per production worker in the corresponding US industry.

Table 5: Effects of Entry and Exit of Establishments

Dependent variable dln(labor productivity)	Whole sample 1997-2006	Appr. 2002-2006	Depr. 1997-2002
	(1)	(2)	(3)
$CR4$	-0.001	-0.003	-0.001
	(0.001)	(0.003)	(0.001)
$dln(RER) \cdot CR4$	0.005	-0.006	-0.012
	(0.003)	(0.004)	(0.010)
$dln(RER) \cdot CR4 \cdot TradeD$	-0.005	-0.011***	-0.005
	(0.003)	(0.004)	(0.009)
$dln(R\&D)$	0.011	-0.012	0.002
	(0.027)	(0.046)	(0.043)
$Estab\ size$	0.001***	0.001	0.001***
	(0.0001)	(0.001)	(0.002)
$dln(Energy)$	0.197***	0.100**	0.319***
	(0.028)	(0.040)	(0.048)
$dln(Material)$	0.242***	0.216***	0.244***
	(0.028)*	(0.039)	(0.049)
$dln(Productivity,\ US)$	-0.854***	-0.785***	-0.812***
	(0.075)	(0.093)	(0.156)
$dln(Establishments)$	-0.005	0.062**	-0.107***
	(0.020)	(0.025)	(0.039)
year dummies	excluded	excluded	included
industry fixed effects	included	included	included
R^2	0.16	0.15	0.13
Observations	2068	906	1162
Industries	237	231	237

Notes:
1) ***, ** and * indicate significance levels of 1%, 5% and 10%.
2) "dln" denotes first differences in log, as approximations for growth rates.
3) The dependent variable is labor productivity, measured as value added per production worker. *RER*, *CR4*, *TradeD*, *R*&D, *Estab size*, *Energy*, *Material*, *Productivity US*, *Establishments* denote respectively real exchange rate, 4-firm concentration ratio, a dummy variable for highly-trade industries, R&D expenditure, average establishment size, energy used per production worker, material used per production worker, growth in value added per production worker in the corresponding US industry, and the number of establishments.

Table 6: Other Robustness Checks

Dependent variable dln(labor productivity)	Whole sample 1997-2006 (1)	Whole sample 1997-2006 (2)	Whole sample 1997-2006 (3)
$CR4$	-0.001	-0.001	-
	(0.001)	(0.001)	
$dln(RER) \cdot CR4$	-0.010***	-0.006	-0.007*
	(0.003)	(0.004)	(0.004)
$dln(RER) \cdot TradeD$	-0.153	0.555	-
	(0.191)	(0.444)	
$dln(RER) \cdot CR4 \cdot TradeD$	-	-0.014*	-0.006*
		(0.008)	(0.003)
$dln(R\&D)$	0.002	0.002	-0.009
	(0.027)	(0.027)	(0.028)
$Estab\ size$	0.004***	0.004***	0.004***
	(0.001)	(0.001)	(0.001)
$dln(Energy)$	0.200***	0.198***	0.167***
	(0.028)	(0.028)	(0.028)
$dln(Material)$	0.250***	0.250***	0.269***
	(0.028)*	(0.028)	(0.030)
$dln(Productivity,\ US)$	0.158**	0.157**	0.162**
	(0.074)	(0.074)	(0.076)
year dummies	excluded	excluded	included
industry fixed effects	included	included	included
R^2	0.11	0.11	0.10
Observations	2068	2068	1987
Industries	237	237	224

Notes:
1) ***, ** and * indicate significance levels of 1%, 5% and 10%.
2) "dln" denotes first differences in log, as approximations for growth rates.
3) The dependent variable is labor productivity, measured as value added per production worker. *RER*, *CR4*, *TradeD*, R&D, *Estab size*, *Energy*, *Material*, and *Productivity US* denote respectively real exchange rate, 4-firm concentration ratio, a dummy variable for highly-trade industries, R&D expenditure, average establishment size, energy used per production worker, material used per production worker, and growth in value added per production worker in the corresponding US industry.