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Exchange Rate Pass-through, Firm Heterogeneity and Product Quality: A Theoretical Analysis*

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Abstract

This paper theoretically explores how exchange rate pass-through depends on firm heterogeneity in productivity and product differentiation in quality. Using an extended version of the Melitz and Ottaviano (2008) model, I show that exporting firms absorb exchange rate changes by adjusting both their markups and product quality, which leads to an incomplete exchange rate pass-through. Moreover, the absolute value of exchange rate absorption elasticity (the percentage change in the export prices denominated in the currency of the exporting country in response to a one percent change in the exchange rate rate) negatively depends on firm productivity for products with high scope for quality differentiation, but positively depends on firm productivity for products with low scope for quality differentiation.

JEL codes: F1, D2, L1

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1. Introduction

This paper theoretically investigates how exchange rate pass-through depends on firm heterogeneity in productivity and product differentiation in quality.

The paper derives its motivation mainly from the literature in two areas: the incompleteness of exchange rate pass-through, and the heterogeneous firm models of international trade. The incompleteness of exchange rate pass-through says that when the currency of an exporting country ("exporting currency" hereafter) appreciates against the currency of an importing country ("importing currency" hereafter), the exporting country may absorb part of the exchange rate change by lowering the export price denominated in the exporting currency. Thus the consumer price denominated in the importing currency increases by a magnitude less than the appreciation of the exporting currency, and the impact of exchange rate change on market demand is mitigated. [1] Hence the incompleteness of exchange rate pass-through to consumers in the importing country is equivalent to an exchange rate absorption by the exporting country. The incompleteness of exchange rate pass-through is also called "Pricing-to-Market (PTM)" in the literature.

There have been tons of empirical studies on the incompleteness of exchange rate pass-through. For example, Dornbusch (1987), Giovannini (1988), Krugman and Baldwin (1987), and Feenstra (1989) find that U.S. import prices failed to fall by as much as the value of foreign currencies during the 1979-1985 dollar appreciation period. Goldberg and Knetter (1997) conduct a literature review on incompleteness of exchange rate pass-through (pricing-to-market). More recently, Vigfusson, Sheets and Gagnon (2007) also find that exchange rate pass-through to import price in the U.S. market is relatively low. Most studies show that exchange rate pass-through varies across products and countries. Some other studies explore the determinants of incompleteness of exchange rate pass-through and its variation across products and countries. Menon (1996) finds that most of variation in exchange rate pass-through across products is explained by the presence of multinational corporations and non-tariff barriers. Barhoumi (2006) finds tha most

[1] Similarly, a depreciation of the exporting currency leads to an increase of the export price denominated in the exporting currency and, in turn, a decrease of the consumer price denominated in the importing currency that is less than the depreciation of the exporting currency.

of the differences across countries in exchange rate pass-through into import prices of developing countries are due to exchange rate regimes, trade barriers and inflation regimes. Bergin and Feenstra (2008) find how a rise in the share of U.S. imports from China, or countries with a fixed ER, could lower exchange rate pass-through to U.S. import prices. Coulibaly and Kempf (2011) find that inflation targeting in emerging countries contributed to a reduction in the pass-through to various price indexes. However, these studies on exchange rate pass-through have been done at the industry level. That is, they study how the average price of all firms in an industry responds to a exchange rate change[2]. In these studies, it was not clear whether the industry-level price response to exchange rate change is caused by the intra-industry reallocation between firms with different prices, or the firm-level price change due to cost change or markup adjustment.

Thanks to the availability of micro-level data, some recent studies explore exchange rate pass-through at the firm-product level. Gopinath and Rigobon (2008) use U.S. firm-product level export price data and show that firm-level exchange rate pass-through is indeed incomplete. Using the same data, Gopinath and Itskhoki (2010) show that goods with a high frequency of price adjustment have a higher long-run exchange rate pass-through than low-frequency adjusters; Gopinath, Itskhoki and Rigobon (2010) find that there is a large difference in the exchange rate pass-through of the average good priced in dollars (25 percent) versus nondollars (95 percent), and currency choice is endogenous. Martin and Rodriguez (2004) use Spanish firm-product level data and find that firms raise their markups in response to a depreciation. Goldberg and Hellerstein (2008) use a structual approach and firm-product level data in the U.S beer industy, and find that on average 54.1 percent of the incomplete exchange rate pass-through is due to local non-traded costs, 33.7 percentto markup adjustment, and 12.2 percent to price adjustment costs. However, these studies do not analyze the firm-level determinants of exchange rate pass-through and the role of firm heterogeneity in exchange rate pass-through, which is the focus of this paper.

To explore the firm-level determinants of exchange rate pass-through and the role of

[2]This is partly due to the data availability constraints faced by the researchers.

firm heterogeneity in exchange rate pass-through, I turn to the second literature relevant to this paper — heterogeneous firm models of international trade. Heterogeneous firm models were spurred by empirical studies, beginning with Bernard and Jensen (1995)[3], which use plant or firm-level data to document that exporting firms are on average larger and more productive than non-exporting firms. These models are characterized by firm heterogeneity in productivity, and focus on the intra-industry reallocation between firms caused by changes in trade environment. The representative models include Melitz (2003) and Bernard, Eaton, Jensen, and Kortum (2003). Melitz (2003) shows the exposure to trade induces the more productive firms to enter the export market, some less productive firms produce only for domestic market, and the least productive firms to exit the market. Thus the exposure to trade leads to inter-firm reallocations towards more productive firms.

None of the heterogeneous firm models focuses directly on how firm heterogeneity impacts exchange rate pass-through, though most of them have some implications for this. The first-generation heterogeneous firm models assume constant marginal cost as well as CES utility, with the latter implying constant markups. With constant marginal cost and markups, firms do not have any room for price adjustment. Thus the firm-level exchange rate pass-through is complete, and the observed incomplete exchange rate pass-through at the industry level must be completely due to the intra-industry reallocation between firms with different prices. For intra-industry reallocation to explain incomplete exchange rate pass-through, it must be that, after the appreciation of the exporting currency, the surviving exporting firms, which are more productive than the exiting firms, should have lower-than-average prices, so that the average industry price after the appreciation of the exporting currency is lower than before. However, this contradicts the prediction of a large body of heterogeneous firm models that incorporate product quality into CES utility, such as Baldwin and Harrigan (2007), Kugler and Verhoogen (2008), Mandel (2008), and Gervais (2009), among others. These models predict that more productive firms could have higher-than-average prices since they produce high quality differentiated goods. The researchers also provide empirical evidence supporting this prediction. Therefore the first-

[3]Others include Roberts and Tybout (1997), Bernard and Jensen (1999), Bernard, Jensen, Redding, and Schott (2007), etc.

generation heterogeneous firm models based on CES utility and constant markups are not very convincing in explaining the incompleteness of exchange rate pass-through.

Given this consideration, I switch to the second-generation heterogeneous firm models, beginning with Melitz and Ottaviano (2008). These models feature linear demand and variable markups. With variable markups, the firm-level exchange rate pass-through could be incomplete, since firms could adjust their markups and hence their exporting prices in response to an exchange rate change, even if they have constant marginal cost. Antoniades (2008) incorporates product quality into the Melitz and Ottaviano (2008) model. Given the empirical evidence supporting heterogeneous firm models with quality dimension, this model is a good starting point for analyzing firm-level exchange rate pass-through.

Our model is similar to Antoniades (2008). The difference is that the quality-upgrading cost in his model only contains a quantity-invariant R&D cost, but in our model I add another type of quality-upgrading cost, the quantity-dependent component-upgrading cost. This extension makes it easier to justify that a firm chooses different quality levels for different markets, which is crucial to guarantee a closed form solution to the model. In our model, exporting firms absorb the exchange rate change not only by adjusting their markups due to the linear demand structure, but also by adjusting the quality of their products. Both these two adjustments lead to an incomplete exchange rate pass-through. Moreover, high productivity firms have high absolute magnitude of quality adjustment and exchange rate absorption. For products with high scope for quality differentiation, the relative exchange rate absorption, i.e., exchange rate absorption elasticity, is lower for high productivity firms, since their initial prices are higher. In contrast, for products with low scope for quality differentiation, the exchange rate absorption elasticity is higher for high productivity firms, since their initial prices are low. In sum, the model predicts that exchange rate pass-through depends on both firm heterogeneity in productivity and product differentiation in quality.

To my knowledge, this is the first paper that investigates, both theoretically and empirically, how exchange rate pass-through depends on firm productivity and product quality. The paper contributes to both the literature on exchange rate pass-through and the literature on heterogeneous firm models in international trade.

This paper is also related to the literature on tariff pass-through. Feenstra (1989) shows the symmetry between tariff and exchange rate pass-through. Following his research, some researchers, including Pompelli and Pick (1990), Rezitis and Brown (1999), and Mallick and Marques (2007), explore exchange rate pass-through and tariff pass-through at the same time. Ludema and Yu (2012) use U.S. transaction-level export data and plant-level manufacturing data and find that tariff pass-through depends on firm productivity and product quality in a way similar to that described in this paper. This paper is a direct extension of that study to exchange rate pass-through.

The paper is organized as follows. Section 2 presents the demand side of the model. Section 3 describes the supply side. Section 4 analyzes the equilibrium and price structure. Section 5 contains the analysis on how firm productivity and product quality impact exchange rate pass-through. Conclusions are included in section 6.

2. Consumers and Demand

As mentioned in section 1, my model is based on Melitz and Ottaviano (2008) and Antoniades (2008). Consider a world consisting of a Home country (h) and a Foreign country (f), with consumers L^h and L^f in each country. Preferences are defined over a homogeneous good chosen as numeraire, and a continuum of horizontally-differentiated varieties indexed by $i \in \Omega$. Consumers in both countries share the same quasi-linear utility function as in Antoniades (2008):

$$U = q_0^c + \alpha \int_{i\in\Omega} (q_i^c + z_i)di - \frac{1}{2}\gamma \int_{i\in\Omega} (q_i^c - z_i)^2 di - \frac{1}{2}\eta \left(\int_{i\in\Omega} (q_i^c - \frac{1}{2}z_i)di \right)^2, \qquad (1)$$

where q_0^c and q_i^c represent, respectively, the individual consumption levels of the numeraire good and variety i; z_i stands for the quality level of variety i, and thus indexes the vertical differentiation of the variety. If the quality level for all varieties is 0 ($z_i = 0$ for all i), then the utility function boils down to that in Melitz and Ottaviano (2008).

The demand parameters α and η index the substitution pattern between the numeraire and the horizontally-differentiated varieties, while the parameter γ indexes the degree of horizontal differentiation between the varieties. They are all positive.

The utility function implies the following linear market demand for variety i in country $l \in \{h, f\}$:

$$q_i^l \equiv L^l q_i^c = \frac{\alpha L^l}{\eta N^l + \gamma} - \frac{L^l}{\gamma} p_i^l + \frac{\eta N^l L^l}{(\eta N^l + \gamma)\gamma} \bar{p^l} + L^l z_i^l - \frac{1}{2} \frac{\eta N^l L^l}{\eta N^l + \gamma} \bar{z^l}, \tag{2}$$

where p_i^l and z_i^l are, respectively, the price and quality of variety i in country l; N^l is the measure of varieties actually consumed in country l (with $q_i^l > 0$); $\bar{p^l} = \frac{1}{N} \int_{i \in \Omega^l} p_i^l di$ and $\bar{z^l} = \frac{1}{N} \int_{i \in \Omega^l} z_i^l di$ are the average price and quality (across both local and foreign firms selling in country l) of these consumed varieties, where $\Omega^l \subset \Omega$ is the subset of varieties that are consumed. The demand function implies: (1) The demand for variety i is negatively related to its own price but positively related to its own quality; (2) It is positively related to the average price of all varieties and negatively related to the average quality of all varieties, and (3) All these relationships are linear.

3. Firms, Production and Export

Each firm in each country produces a differentiated variety and faces a fixed entry cost f_E, which is common across firms. Subsequent production of firm i incurs the following total cost function:

$$TC_i = c_i q_i + b q_i z_i + \theta (z_i)^2. \tag{3}$$

where q_i and z_i are the quantity and quality of the variety that the firm produces. The first term on the right hand side, $c_i q_i$, depends on the quantity but not the quality of output, and could be interpreted as "processing cost" of a firm. The third term, $\theta(z_i)^2$, depends on the quality level of the output but fixed with respect to the quantity of output, which captures the definition of "R&D cost" for quality upgrading. The second term, $b q_i z_i$, depends on both the quantity and the quality of the output, which captures the definition of "component-upgrading cost" associated with quality upgrading. A firm could choose a component with one quality level for the home market but another component with another quality level for the foreign market.

There are three things worth pointing out. First, both the "processing cost" and the "R&D cost" exist in Antoniades (2008), but the "component-upgrading cost" is what I add to his model. The purpose of this extension is to justify that a firm can choose different product quality levels for different markets, which is crucial to ensure a closed form solution to the model, as will be shown below. Second, c_i is a firm-specific constant which indexes the marginal processing cost; parameters b and θ are product-specific constants which index the "toughness" of quality upgrading for a product, but they are common across all firms producing different varieties of the same product. Third, c_i is the marginal "processing" cost of the firm, and the overall marginal cost of the firm is $MC_i = c_i + bz_i$, where z_i is a function of c_i (as will be shown shortly). $1/c_i$ indexes the processing productivity of the firm, and $1/MC_i$ indexes the overall productivity of the firm.

The timing of firms' decisions is as follows. First, firms learn about product-specific, quality-upgrading costs b and θ, the distribution of firm processing cost $G(c)$, and the fixed entry cost f_E, all of which are common knowledge, and they decide whether to enter the industry or not. Second, after they enter the industry by making the irreversible investment f_E, they learn about their individual processing cost c_i, and decide on the quality and price for the product that they will produce.

Consider a firm in the Home country h with parameter c. The firm faces both domestic and foreign markets. Assume (1) the two markets are segmented, and (2) the firm chooses separate levels of product quality for the two markets. As mentioned above, the validity of the second assumption is based on the "component-upgrading cost" that I add to Antoniades (2008). These two assumptions, together with the assumption of constant marginal "processing cost" c, imply that the firm independently maximizes the profits earned from domestic and export sales:

$$
\begin{aligned}
\pi^{hh} =& p^{hh}q^{hh} - cq^{hh} - bq^{hh}z^{hh} - \theta(z^{hh})^2, \\
\pi^{hf} =& \frac{p^{hf}}{e}q^{hf} - cq^{hf} - bq^{hf}z^{hf} - \theta(z^{hf})^2,
\end{aligned}
\tag{4}
$$

where p^{hh} and p^{hf} denote its prices in the domestic and foreign markets; q^{hh} and q^{hf} stand for the corresponding quantities sold in the two markets; e is the exchange rate denominated in units of foreign currency per unit of home currency (and thus an increase in e means an appreciation of the home currency). Note that the export price of the firm in home currency is $p = p^{hf}/e$.

Solutions to the profit maximization problems are:

$$
\begin{aligned}
p^{hh} =& \frac{1}{2}(c^{hh} + c) + \frac{\gamma + b}{2}z^{hh}, \\
p^{hf} =& \frac{e}{2}(c^{hf} + c) + \frac{\gamma + eb}{2}z^{hf}, \\
z^{hh} =& \lambda^{hh}(c^{hh} - c), \\
z^{hf} =& e\lambda^{hf}(c^{hf} - c),
\end{aligned}
\tag{5}
$$

where $c^{hh} = sup\{c : \pi^{hh} > 0\}$ and $c^{hf} = sup\{c : \pi^{hf} > 0\}$ are cost upper bounds for firms to earn positive profits from domestic and export sales; $\lambda^{hh} = \frac{(\gamma-b)L^h}{4\gamma\theta-(\gamma-b)^2L^h}$ and $\lambda^{hf} = \frac{(\gamma-eb)L^f}{4\gamma\theta e-(\gamma-eb)^2L^f}$. I can show that $c^{hf} = c^{ff}/e$. Assume that $\gamma - b > 0$, $\gamma - eb > 0$, $4\gamma\theta - (\gamma - b)^2L^h > 0$ and $4\gamma\theta e - (\gamma - eb)^2L^f > 0$ to ensure z^{hh} and z^{hf} to be positive.

We can also show that the level of quality upgrading that the firm chooses (z^{hh} or z^{hf}) is increasing in (i) the processing productivity of the firm ($1/c$), (ii) the market size (L^h or L^f), and (iii) the degree of product horizontal differentiation (γ), but it is decreasing in (i) the toughness for quality upgrading (θ and b), and (ii) the exchange rate (e), i.e., the value of home currency comparing to foreign currency. The intuition for these conclusions is straightforward and thus is omitted here.

4. Equilibrium and Price Structure

The free entry condtion implies that the expected profits from domestic and export sales should be equal to the fixed entry cost, f_E, that is,

$$\int_0^{c^{hh}} \pi^{hh} dG(c) + \int_0^{c^{hf}} \pi^{hf} dG(c) = f_E \tag{6}$$

where $G(c)$ is the distribution of the "processing cost" c. Assume that this cost has a Pareto distribution with parameter k and upper bound c_M: $G(c) = (c/c_M)^k$, where $c \in [0, c_M]$. Substituting this and (4)-(5) into (6), doing the same thing for the free-entry condition in the foreign country, and using $c^{hf} = c^{ff}/e$, I get the two cost bounds:

$$\begin{aligned} c^{hh} &= \left[\frac{\gamma\phi}{L^h[1+(\gamma-b)\lambda^{hh}]} \cdot \frac{1-(e)^{-k-1}\sigma^f}{1-\sigma^f\sigma^h} \right]^{\frac{1}{k+2}}, \\ c^{hf} &= \left[\frac{\gamma\phi e^2}{L^f[1+(\gamma-b)\lambda^{ff}]} \cdot \frac{1-(1/e)^{-k-1}\sigma^h}{1-\sigma^h\sigma^f} \right]^{\frac{1}{k+2}} /e, \end{aligned} \tag{7}$$

where $\phi = 2(k+1)(k+2)c_M^k f_E$, $\sigma^f = \frac{1+(\gamma-eb)\lambda^{hf}}{1+(\gamma-b)\lambda^{ff}}$, $\sigma^h = \frac{1+(\gamma-b/e)\lambda^{fh}}{1+(\gamma-b)\lambda^{hh}}$, $\lambda^{ff} = \frac{(\gamma-b)L^f}{4\gamma\theta-(\gamma-b)^2L^f}$ and $\lambda^{fh} = \frac{(\gamma-b/e)L^h}{4\gamma\theta/e-(\gamma-b/e)^2L^h}$. Equations (5) and (7) determine the closed form solutions to the model.

It is very helpful to have a careful examination for the structure of the equilibrium export price. As mentioned before, the incompleteness of exchange rate pass-through is equivalent to "exchange rate absorption" of exporting firms, i.e., an adjustment of their export prices in home currency. Here I focus on the export price in home currency:

$$\begin{aligned} p &= \frac{p^{hf}}{e} \\ &= \frac{1}{2}\left(c^{hf}+c\right) + \frac{(\gamma+eb)}{2}\frac{z^{hf}}{e} \\ &\equiv p_q + p_z \\ &= \frac{1}{2}\left(c^{hf}+c\right) + \frac{(\gamma+eb)\lambda^{hf}}{2}\left(c^{hf}-c\right) \\ &= (1-B)c^{hf} + Bc. \end{aligned} \tag{8}$$

where $B = \frac{2\gamma\theta e - \gamma(\gamma - eb)L^f}{4\gamma\theta e - (\gamma - eb)^2 L^f}$, and $1 - B = \frac{2\gamma\theta e + eb(\gamma - eb)L^f}{4\gamma\theta e - (\gamma - eb)^2 L^f} > 0$.

The first equality is the relationship between the export price in home currency and that in foreign currency. The second equality shows that the export price in home currency consists of two components: the first term, $\frac{1}{2}\left(c^{hf} + c\right)$, is derived from the quantity processing; the second term, $\frac{(\gamma + eb)}{2}\frac{z^{hf}}{e}$, is derived from the quality upgrading. I refer to these two terms as the quantity component p_q and the quality component p_z, respectively — as indicated by the third equality (equivalence).

The forth equality shows the relationship between these two components and firm processing productivity. The quantity component, $p_q = \frac{1}{2}\left(c^{hf} + c\right)$, is negatively related to firm processing productivity ($1/c$), i.e.,

$$\frac{\partial p_q}{\partial(\frac{1}{c})} < 0. \tag{9}$$

We refer to this as the "processing effect": the higher is firm processing productivity, the lower is the marginal processing cost, and hence the lower is the unit price. The quality component, $p_z = \frac{(\gamma + eb)\lambda^{hf}}{2}\left(c^{hf} - c\right)$, is positively related to firm productivity ($1/c$), i.e.,

$$\frac{\partial p_z}{\partial(\frac{1}{c})} > 0. \tag{10}$$

We refer to this as the "quality effect": the higher is firm processing productivity, the higher is the product quality level that the firm will choose (as mentioned in section 2.2), and thus the higher is the quality-upgrading cost and the unit price.

The fifth (the last) equality describes the relationship between the overall price and firm processing productivity. From this equality I can get

$$\frac{\partial p}{\partial(\frac{1}{c})} < 0 \qquad \text{if} \qquad B > 0, i.e., \left(\frac{2\theta}{L^f} + b\right) e > \gamma, \tag{11}$$

$$\frac{\partial p}{\partial(\frac{1}{c})} > 0 \qquad \text{if} \qquad B < 0, i.e., \left(\frac{2\theta}{L^f} + b\right) e < \gamma. \tag{12}$$

The intuition is as follows. The condition $\left(\frac{2\theta}{L^f} + b\right) e > \gamma$ implies that (1) the quality-upgrading toughness for the product, θ and b, are relatively high, (2) the value of home currency comparing to foreign currency, e, is high, (3) the market size, L^f, is relatively small, and (4) the product horizontal differentiation γ is relatively low. All these imply that the quality level chosen by all firms (producing different varieties of the same product) is relatively low (as mentioned in section 2.2), and the product has low scope for quality differentiation. As the result, the "processing effect" dominates the "quality effect", and hence the overall price is negatively related to firm processing productivity — I refer to this type of products as "quality homogeneous goods". In contrast, the condition $\left(\frac{2\theta}{L^f} + b\right) e < \gamma$ implies that the opposite is true: the product has high scope for quality differentiation, and the overall price is positively related to firm processing productivity — I refer to this type of products as "quality differentiated goods".

An interesting observation here is that the horizontal differentiation of a product γ is related to the vertical differentiation or quality scope of the product. A product with low horizontal differentiation γ is also likely to have low vertical differentiation or quality scope, and thus is likely to be a quality homogeneous good. A product with high horizontal differentiation γ is also likely to have high vertical differentiation or quality scope, and thus is likely to be a quality differentiated good.

5. Exchange Rate Absorption, Firm Productivity and Product Quality

Now I shall turn to explore how an exchange rate change impacts the export price in home currency, p. From (8) I can derive that the absolute magnitude of this impact is

$$\begin{aligned}\frac{\partial p}{\partial e} =& -\frac{\partial B}{\partial e}(c^{hf} - c) + (1 - B)\frac{\partial c^{hf}}{\partial e} \\ <& 0.\end{aligned} \tag{13}$$

The last inequality holds since I can show that $\frac{\partial B}{\partial e} > 0$, $1 - B > 0$, and $\frac{\partial c^{hf}}{\partial e} < 0$, and $c^{hf} - c > 0$ by definition of cost bound. The relative magnitude of the impact is

$$\begin{aligned}
\Theta \equiv & \frac{\partial p}{\partial e}\frac{e}{p} \\
= & \left[-\frac{\partial B}{\partial e}(c^{hf} - c) + (1 - B)\frac{\partial c^{hf}}{\partial e} \right] \frac{e}{(1 - B)c^{hf} + Bc} \\
< & 0.
\end{aligned} \tag{14}$$

The negative signs of the absolute and relative price changes in response to an exchange rate change imply the incompleteness of exchange rate pass-through, i.e., "exchange rate absorption": the export price in home currency decreases in response to an appreciation of the home currency. Θ is the exchange rate absorption elasticity: the percentage decrease in the export price in home currency in response to a one percent appreciation of the home currency.

There are three things worth pointing out. First, I can verify that both the quantity component and the quality component of the export price in home currency decrease in response to an appreciation of the home currency, that is, $\frac{\partial p_q}{\partial e} < 0$ and $\frac{\partial p_z}{\partial e} < 0$. The decrease of the quantity component of the price is essentially a decrease in its markup, i.e., $\frac{\partial u_q}{\partial e} < 0$, where $u_q = p_q - c = \frac{1}{2}(c^{hf} - c)$, since the processing cost c is fixed. This markup adjustment is possible because of the linearity of the demand structure. The decrease of the quality component of the price is caused by the quality downgrading of the product in response to the appreciation of the home currency, that is, $\frac{\partial z^{hf}}{\partial e} < 0$.[4] In sum, when exporting firms face an appreciation of the home currency, they will not only reduce their markups due to the linear demand structure, but also downgrade the quality level of their products. That is, they will transfer the increased export cost due to home currency appreciation to lower markups and quality. Thus the model shows that both markup adjustment and quality adjustment are sources of firm-level exchange rate absorption.

[4] We can also show the following. (1) The decrease of the quality component of the price caused by the quality downgrading is due to the decrease of quality-upgrading cost, i.e., $\frac{\partial c_z}{\partial e} < 0$, where $c_z = [bq^{hf}z^{hf} + \theta(z^{hf})^2]/q^{hf}$ is the unit quality-upgrading cost. (2) However, the sign of the markup change associated with quality-downgrading, $\frac{\partial u_z}{\partial e}$, is ambiguous, where $u_z = p_z - c_z$.

Second, I can show that the absolute magnitude of exchange rate absorption, in terms of its absolute value, positively depends on firm processing productivity, i.e.,

$$\frac{\partial|\partial p/\partial e|}{\partial(\frac{1}{c})} > 0. \tag{15}$$

We can also verify that, the absolute decrease of the quantity component of the export price in home currency in response to an appreciation of the home currency is independent of firm processing productivity, that is, $\frac{\partial|\partial p_q/\partial e|}{\partial(\frac{1}{c})} = 0$.[5] However, the absolute decrease of the quality component of the export price in response to an appreciation of the home currency is positively related to firm processing productivity, that is, $\frac{\partial|\partial p_z/\partial e|}{\partial(\frac{1}{c})} > 0$; this is because firms with high processing productivity will downgrade their product quality more than firms with low processing productivity, i.e., $\frac{\partial|\partial z^{hf}/\partial e|}{\partial(\frac{1}{c})} > 0$, since their initial quality level is high and thus have more room for quality adjustment.

Third, the relative magnitude of exchange rate absorption, i.e., the exchange rate absorption elasticity, depends on firm processing productivity in the following way:

$$\frac{\partial|\Theta|}{\partial(\frac{1}{c})} > 0 \qquad \text{if} \qquad B > 0, i.e., \left(\frac{2\theta}{L^f} + b\right) e > \gamma, \tag{16}$$

$$\frac{\partial|\Theta|}{\partial(\frac{1}{c})} \sim 0 \qquad \text{if} \qquad B < 0, i.e., \left(\frac{2\theta}{L^f} + b\right) e < \gamma, \tag{17}$$

$$\frac{\partial|\Theta|}{\partial(\frac{1}{c})} < 0 \qquad \text{if} \qquad B \ll 0, i.e., \left(\frac{2\theta}{L^f} + b\right) e \ll \gamma, \tag{18}$$

where the notation "$\sim$" in (17) denotes "greater than, equal to, or less than", and "$\ll$" in (18) denotes "far less than". Notice that the condition $\frac{2\theta}{L^f} + b > \gamma$ implies that the product is a quality homogeneous good, $\frac{2\theta}{L^f} + b < \gamma$ implies that the product is a quality differentiated good, and $\frac{2\theta}{L^f} + b \ll \gamma$ implies that the product is a quality differentiated good and the scope for quality differentiation is very high.

These results could be explained by the impacts of firm processing productivity $(1/c)$

[5] This is due to the following reason. From equation (8) I can see that p_q consists of two additive components (which is determined by the linear demand function): the first component (c^{hf}) depends on exchange rate but not firm processing productivity, and the second component (c) depends on firm processing productivity but not exchange rate. When exchange rate changes, only the first component changes, which does not depend on firm processing productivity.

on both the numeraire and the denominator of the exchange rate absorption elasticity ($\Theta \equiv \frac{\partial p/\partial e}{p/e}$). As for the numeraire ($\partial p/\partial e$), I have seen that the absolute magnitude of exchange rate absorption, in terms of its absolute value, positively depends on firm processing productivity, as indicated in (15). As for the denominator (p, the initial export price), its relationship with firm processing productivity is determined by product quality scope. For quality homogenous goods, the initial export price is negatively related to firm processing productivity, as indicated in (11). Thus the exchange rate absorption elasticity, in terms of its absolute value, is positively related to firm processing productivity ($1/c$), as indicated in (16). In contrast, for a quality differentiated good, the initial export price is positively related to firm processing productivity, as indicated in (12). Thus the relationship between the exchange rate absorption elasticity, in terms of its absolute value, and firm processing productivity is ambiguous (as indicated in (17)), depending on whether the numeraire or the denominator effect is dominant. If the product quality scope is sufficiently high, then the denominator effect dominates the numeraire effect, and thus the exchange rate absorption elasticity (in terms of its absolute value) is negatively related to firm processing productivity, as indicated in (18).[6]

These results could also be explained in another way. I can verify that, the relative decrease of the quantity component of the export price in home currency in response to an appreciation of the home currency is positively related to firm processing productivity, that is, $\frac{\partial|\Theta_{p_q}|}{\partial(\frac{1}{c})} > 0$, where $\Theta_{p_q} \equiv \frac{\partial p_q}{\partial e}\frac{e}{p_q} < 0$. [7] I can also refer to this as "processing effect", as our interpretation for (9). However, the relative decrease of the quality component of the export price in home currency in response to an appreciation of the home currency is negatively related to firm processing productivity, that is, $\frac{\partial|\Theta_{p_z}|}{\partial(\frac{1}{c})} < 0$, where $\Theta_{p_z} \equiv \frac{\partial p_z}{\partial e}\frac{e}{p_z} < 0$; this is because that firms with high processing productivity will downgrade their product quality by a less percentage, i.e., $\frac{\partial|\Theta_{z^{hf}}|}{\partial(\frac{1}{c})} < 0$, where $\Theta_{z^{hf}} \equiv \frac{\partial z^{hf}}{\partial e}\frac{e}{z^{hf}} < 0$, since their initial quality level is already high. I can also refer to this as "quality effect", as our interpretation for (10). For quality homogenous goods, the "processing effect" dominates

[6]We can also show with numerical examples that there indeed exist model parameters that make this case possible.

[7]This is due to two facts: $\frac{\partial|\partial p_q/\partial e|}{\partial(\frac{1}{c})} = 0$ and $\frac{\partial p_q}{\partial(\frac{1}{c})} < 0$.

the "quality effect", and thus I see a positive relationship between the overall exchange rate absorption elasticity ($|\Theta|$) and firm processing productivity ($1/c$), as indicated in (16). For quality differentiated goods with high scope for quality differentiation, the "processing effect" is dominated by the "quality effect", and thus I see a negative relationship between the overall exchange rate absorption elasticity ($|\Theta|$) and firm processing productivity ($1/c$), as indicated in (18). For quality differentiated goods with medium scope for quality differentiation, it is not quite clear which effect is dominant, and thus I end up with an ambiguous relationship between the overall exchange rate absorption elasticity ($|\Theta|$) and firm processing productivity ($1/c$), as indicated in (17).

The table attached summarizes the model predictions for comparative statics regarding (i) price and productivity, (ii) exchange rate absorption, (iii) absolute exchange rate absorption and productivity, as well as (iv) relative exchange rate absorption and productivity.

Notice that in (11)-(12) and (15)-(18), I focus on the relationship between export price or exchange rate absorption and firm "processing" productivity ($1/c$). It is easy to show that, for exported goods, the overall marginal cost is $MC = \partial TC^{hf}/\partial q^{hf} = c + bz^{hf} = c + b\lambda(c^{hf} - c) = b\lambda c^{hf} + (1 - b\lambda)c$. Under the condition $1 - b\lambda > 0$ (which I assume is true), the overall marginal cost MC and the marginal "processing" cost (c) are positively correlated. Then all the relationships mentioned above ((11)-(12) and (15)-(18)) could be re-written and re-interpreted in terms of firm overall productivity ($1/MC$).

6. Conclusions

This paper theoretically explores how exchange rate pass-through depends on firm heterogeneity in productivity and product differentiation in quality. I use an extended version of the Melitz and Ottaviano (2008) model and show that, when exporting firms face an exchange rate change, they will absorb part of the exchange rate change by adjusting both their markups and their product quality, which leads to an incomplete exchange rate pass-through. Moreover, exchange rate absorption elasticity (in terms of its absolute value) and firm productivity are negatively correlated for products with high scope for quality differentiation, but positively correlated for quality homogeneous goods.

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Table. Summary of Model Predictions for Comparative Statics: Products with Different Scopes for Quality Differentiation

Item	Comparative Statics	Low Scope $\left(\frac{2\theta}{L^f}+b\right)e>\gamma$	Medium Scope $\left(\frac{2\theta}{L^f}+b\right)e<\gamma$	High Scope $\left(\frac{2\theta}{L^f}+b\right)e\ll\gamma$
Price and	$\partial p/\partial(\frac{1}{c})$	$-$	$+$	$+$
	$\partial p_q/\partial(\frac{1}{c})$	$-$	$-$	$-$
Productivity	$\partial p_z/\partial(\frac{1}{c})$	$+$	$+$	$+$
Absolute Exchange	$\partial p/\partial e$		$-$	
Rate Absorption	$\partial p_q/\partial e$		$-$	
	$\partial p_z/\partial e$		$-$	
Relative Exchange	$\Theta \equiv \frac{\partial p}{\partial e}\frac{e}{p}$		$-$	
Rate Absorption	$\Theta_{p_q} \equiv \frac{\partial p_q}{\partial e}\frac{e}{p_q}$		$-$	
	$\Theta_{p_z} \equiv \frac{\partial p}{\partial e}\frac{e}{p_z}$		$-$	
Absolute Exchange	$\frac{\partial\lvert\partial p/\partial e\rvert}{\partial(\frac{1}{c})}$		$+$	
Rate Absorption and	$\frac{\partial\lvert\partial p_q/\partial e\rvert}{\partial(\frac{1}{c})}$		0	
Productivity	$\frac{\partial\lvert\partial p_z/\partial e\rvert}{\partial(\frac{1}{c})}$		$+$	
Relative Exchange	$\frac{\partial\lvert\Theta\rvert}{\partial(\frac{1}{c})}$	$+$	$\pm$	$-$
Rate Absorption and	$\frac{\partial\lvert\Theta_{p_q}\rvert}{\partial(\frac{1}{c})}$	$+$	$+$	$+$
Productivity	$\frac{\partial\lvert\Theta_{p_z}\rvert}{\partial(\frac{1}{c})}$	$-$	$-$	$-$