Domestic R&D, Foreign Direct Investment, and Welfare*

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Abstract

This paper examines the two-way relationship between domestic research and development (R&D) and foreign direct investment (FDI), as well as their impacts on domestic welfare in which domestic R&D decisions are endogenized. Our results are as follows. We show that domestic R&D investment may either increase or decrease a foreign firm’s FDI incentives. Further, domestic R&D incentives can always increase regardless of the effects of domestic R&D investment on the foreign firm’s FDI decision. Finally, we find that domestic welfare improves under domestic cost reduction if the slope of the marginal cost of domestic firms’ R&D investment is sufficiently small.

JEL classification: F23; L13; O31.

Keywords: FDI; Domestic R&D; Domestic welfare

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1 Introduction

Foreign direct investment (FDI) has been one of the most important ways for globalization of production in the last few decades, and it plays a crucial role in the volume of international trade and multinational activities in both developed and developing economies.\(^1\) Moreover, it is commonly observed that firms in an FDI-receiving domestic market also undertake innovations by investing in research and development (R&D), which is considered as one major approach for countries to improve technology and promote economic growth. For example, China has attracted the largest share of global investment inflows since 2010. The magnitude of these investment inflows increased from 243,703 million USD in 2010 to 258,200 million USD in 2013, which contributed to over 16% of the total world’s FDI inflows and approximately equaled those in the European Union (EU) (OECD (2013)). Meanwhile, the levels for R&D investment and innovative activities by China’s domestic enterprises have also been increasing since the mid-1990s (Jefferson, Bai, Guan, and Yu (2006)). In particular, according to a recent study by Wu (2012), the R&D investment in China grew at an average rate of 17.8% per annum during the period 2001–2011, and the R&D intensity relative to GDP rose considerably from 0.9% in 2000 to 1.83% in 2011. Since many developing countries like China are opening up their economies for international competition and encouraging expenditures on domestic innovations through R&D simultaneously, it is worth analyzing how the decision of foreign firms to conduct FDI is interrelated with the decision of domestic firms to invest in R&D, in addition to the welfare implication induced by this interplay.

Existing empirical studies have devoted efforts to examine the two-way relation between domestic innovative activities and FDI inflows. On the one hand, for example, Kogut and Chang (1991) find that in the case of Japanese FDI into the US, the R&D efforts by domestic firms are a critical determinant of FDI inflows. Neven and Siotis (1996) also show a similar result in the case of the US and Japanese FDI into the EU. More precisely, Driffield and Munday (2000) and Love (2003) reported that there could exist a positive or negative influence of domestic R&D on FDI.\(^2\) On the other hand, controlling for firm-level heterogeneity, Girma, Gong, and Görg (2009) find a positive effect of sector-level FDI on domestic innovations and R&D for Chinese state-owned enterprises (SOEs) during 1999–2005. Bitzer and Kerekes (2008) also provide evidence in which FDI has a significantly positive impact on domestic R&D capital stock in 10 manufacturing sectors of 17 OECD countries during the period 1973–2000. Consequently, it is shown that there does exist a strong empirical connection between domestic firms’ R&D investment and a foreign firm’s FDI decision.

The abovementioned empirical studies are usually based on the theoretical background of

\(^1\)See Mukherjee and Sinha (2007) and Beladi and Mukherjee (2012) for more details regarding the significance of FDI in recent international trade.

\(^2\)See Beladi, Firoozi, and Co (2008) for a recent survey on the mixed empirical effects of domestic R&D on FDI inflows.
spillovers and technology sourcing to explain the association between domestic R&D and FDI; domestic firms’ R&D increases since they expect to receive technological spillovers from the entry of multinational firms in product competition. The incentive of multinational firms to undertake FDI also becomes higher because it is partially motivated by the spillovers stemming from domestic firms’ R&D. However, some previous studies show that this explanation may be limited and incomplete.3 As for the effect of domestic R&D investment on FDI, Beladi, Firoozi, and Co (2008) indicate that the spillovers argument fails to illustrate the reliance of Japanese multinational enterprises (MNEs) on their own technology in the home country. This argument also appears inappropriate because apart from FDI, there are other direct entry modes (e.g., joint ventures and mergers) available for multinational firms. In contrast, with regard to the effect of inward FDI on domestic R&D investment, the spillovers-and-sourcing explanation seems weak for potential diffusion of knowledge. Dunning (1994) argues that inward FDI may not necessarily raise the host country’s innovative capacities via spillovers. Therefore, it could generate no effect or even a negative effect on indigenous productivity. This paradigm is confirmed by Van Pottelsbergh De La Potterie and Lichtenberg (2001), who claim that “inward FDI does not induce substantial technology transfer from the home country to the host country...the MNEs’ aim when establishing subsidiaries abroad is certainly not to diffuse their own technological advantages towards the host country’s domestic firms, but rather to exploit more fully their own technological innovations.” This result is inconsistent with the positive correlation observed by Bitzer and Kerekes (2008), even though both studies use similar empirical sources and estimation techniques. Hence, our study attempts to seek another channel that enables the investigation of the theoretical two-way interplay between FDI and domestic R&D investment as well as the resulting impacts on domestic welfare.

In this paper, we consider an international Cournot oligopoly with homogeneous products; this setup is similar to Beladi and Mukherjee (2012), whose emphasis is on merger and FDI, while ours is on domestic R&D investment and FDI. We assume that a foreign firm can choose its production strategy by either exporting or FDI and that domestic firms have symmetric constant-returns-to-scale technologies. As for efficiency improvement in terms of cost reduction, domestic firms perform costly R&D activities, whereas the foreign firm undertakes FDI. Both these strategies reduce firms’ marginal costs in production and thus serve a similar role as process innovations. Accordingly, to investigate the link between domestic R&D and FDI, our analysis focuses on how oligopolistic competition affects the use of innovations and firms’ production efficiency comparison. Therefore, our arguments differ from research that addresses the same issue in the existing empirical literature

3Nevertheless, Girma, Gong, and Görg (2009) mention two ways in which FDI affects Chinese SOEs (e.g., domestic firms in the host country). First, at the firm level, injections of foreign capital either bring transfer of knowledge to local firms or reduce their financial constraints, both of which stimulate domestic innovative activities. Second, at the industry level, FDI can influence domestic companies’ innovation activities through potential competition and knowledge spillovers. Specifically, the former (competition) effect could be positive or negative, which will be discussed in Section 4, while the latter (spillovers) effect is positive.
using spillovers and technology sourcing (e.g., Branstetter (2006)).

The main results in this study can be summarized as follows. First, we show that domestic R&D investment, which is endogenously determined by domestic firms, may raise or lower the foreign firm’s incentives for FDI depending on the magnitudes of the domestic firms’ marginal costs and the foreign firm’s marginal cost of exporting. This result is due to the interaction in two opposing effects of competition on innovations, namely, the *Schumpeterian effect* and the *escape-competition effect*. Second, we find that it can be profitable for domestic firms to invest in R&D for cost reduction irrespective of its impact on the foreign firm’s decision of undertaking FDI; investing in R&D reinforces domestic firms’ competitiveness and helps extract sufficient market shares from the foreign firm, which increases domestic firms’ profitability. Finally, the welfare analysis implies that domestic cost reduction may change the foreign firm’s production strategy and in turn affect domestic welfare. If the foreign firm switches from production under FDI to production under exporting, the overall industry cost efficiency could be harmed, followed by welfare losses. However, if the slope of the marginal cost of domestic firms’ R&D investment is not very large, the problem of cost inefficiency becomes less severe, thereby making domestic cost reduction always beneficial to domestic welfare.

This paper is closely relevant for Mukherjee and Sinha (2007) and Beladi, Firoozi, and Co (2008), but there are some differences in the models. First, although these two papers investigate the one-way relation between domestic cost reduction and FDI, Mukherjee and Sinha (2007) and Beladi, Firoozi, and Co (2008) assume a duopoly market structure in the domestic country, while the current study focuses on the two-way relation and oligopolistic competition by including the number of domestic firms. Additionally, domestic cost reduction in Mukherjee and Sinha (2007) is an exogenous process due to potential technology spillovers from the foreign firm. However, in our analysis, domestic firms also have a cost-reducing strategy through endogenizing their own R&D decisions. Given that FDI acts as a cost-reducing strategy for the foreign firm, which is interpreted as an innovating developed-country firm by Beladi and Mukherjee (2012), the focus of this paper is related to the strategic interaction among innovating firms in a technologically follower country and an innovating firm in an advanced country. Finally, unlike Beladi, Firoozi, and Co (2008) where the foreign firm uses FDI as the only production strategy, the foreign firm in our study can choose to enter the domestic product market by either exporting or FDI. Hence, there is a significant difference between Beladi, Firoozi, and Co (2008) and our study in terms of the presence of foreign competition, which enriches the analysis of the foreign firm’s entry mode and the implications on domestic welfare.

The rest of the paper is organized as follows. Section 2 describes the model setup. Section 3 explores the impact of domestic R&D on FDI. Section 4 discusses the changes in the domestic firms’ R&D incentives in the presence of foreign competition. Section 5 takes account of the foreign
firm’s production strategy and examines the effect of domestic cost reduction on domestic welfare. Section 6 concludes this study.

2 The Model

Suppose that there are two countries in this model: a domestic country and a foreign country. In the domestic country, there are \( n \) firms with identical technology who produce homogeneous goods and compete through Cournot oligopoly. Moreover, there is one firm in the foreign country, denoted by \( F \), who can sell goods to serve the domestic market either through FDI or export.

Suppose that the foreign firm’s marginal cost under export is \( c_x \), whereas the marginal cost under FDI is \( c_f \) that is assumed to be zero for simplicity; thus \( c_x > c_f = 0 \). The cost difference between the entry modes of the foreign firm can be considered as the per-unit trade cost (see e.g., Mathew and Mukherjee (2014)). It stems from some exogenous conditions such as logistics and transportation, which are unaffected by the foreign firm’s actions (e.g., foreign innovations and R&D). Hence, in this study, the FDI decision acts as the only cost-reducing strategy of the foreign firm that influences the gain of its total profit when competing with domestic firms. If the foreign firm chooses FDI, it has to incur a fixed cost \( K \).

Assume that the domestic firms’ marginal cost is \( c > 0 \). The domestic firms are located in a country with relatively inferior technology, whereas the foreign firm belongs to a country with more sophisticated technology (e.g., the technology frontier); thus the marginal cost of the domestic firms is larger than the counterpart of the foreign firm under FDI.

The domestic firms have an option to invest in innovations through R&D, which reduce their marginal cost of production by the effect on marginal profits (e.g., d’Aspremont and Jacquemin (1988) and Sacco and Schmutzler (2011)). Specifically, the domestic firms decrease their marginal cost \( c \) by investing in a certain amount of research \( z \). The R&D cost follows the function \( \gamma z^{2/2} \), where \( \gamma \) pins down the convexity of this function and satisfies \( \gamma > \frac{4}{n+2} \) for computational convenience. In this paper, the domestic firms’ cost-reducing strategy is different from that of the foreign firm in domestic competition. The reasons are twofold. First, using an R&D cost function generates an endogenous technology choice for the domestic firms. Second, innovations that advance domestic technology do not originally exist and discovering more of them through R&D is increasingly costly. Further, we assume that both the domestic and foreign firms completely protect their cost-reducing strategies so there are no R&D externalities or spillovers across the firms in our analysis.\(^5\)

\(^4\)See Leahy and Naghavi (2010) and Qiu and Wang (2011) for a similar setup where the fixed cost of FDI is used for establishing a new production plant in the domestic country so that the foreign firm can utilize its existing superior technology. Therefore, as the foreign firm’s cost-reducing strategy, FDI has a similar role as process innovations.

\(^5\)This assumption is consistent with Beladi, Firoozi, and Co (2008), who specify that technology spillovers have failed to explain the mixed empirical results of the effect of domestic R&D on the inflow of FDI. There is also
Suppose that the representative consumer’s utility is \( u(q, m) = aq - \frac{q^2}{2} + m \), where \( a > 0 \) and \( m \) is the numeraire good. This utility function generates the (inverse) demand function in the domestic market, which is given by

\[
P = a - q,
\]

where \( P \) denotes the price and \( q \) is the total output of the firms.

Let us consider a three-stage game. In stage 1, the domestic firms decide whether to invest in R&D or not and choose the subsequent R&D investment if they prefer cost reduction. In stage 2, the foreign firm decides whether it exports or undertakes FDI to enter the domestic market. In stage 3, the firms compete via a Cournot-Nash fashion in the product market. We solve the game by backward induction.

### 2.1 No R&D Investment in the Domestic Country

Consider the game when the domestic firms do not invest in R&D. In this case, if the foreign firm exports, the \( i \)th domestic firm where \( i = 1, 2, \ldots, n \) and the foreign firm choose their outputs to maximize the profits, respectively, in the following manner:

\[
\max_{q_i} (a - q - c)q_i \quad \text{and} \quad \max_{q_F} (a - q - c_F)q_F; \quad i = 1, 2, \ldots, n.
\]

The equilibrium outputs of the \( i \)th domestic firm and the foreign firm are given by \( q_i^{x*} = \frac{a - 2c + c_F}{n + 2} \) and \( q_F^{x*} = \frac{a + nc - (n + 1)c_F}{n + 2} \). We assume that \( c < \frac{a}{2} \equiv \bar{c} \) and \( c_F < \frac{c}{\gamma(n+1)(n+2)} \equiv c_x \), which ensure that the firms’ equilibrium outputs are positive.\(^6\) Hence, the profits of the \( i \)th domestic firm and the foreign firm are given by

\[
\pi_i^{x*} = \frac{(a - 2c + c_F)^2}{(n + 2)^2} \quad \text{and} \quad \pi_F^{x*} = \frac{(a + nc - (n + 1)c_F)^2}{(n + 2)^2}.
\]

However, if the foreign firm undertakes FDI, then the domestic firms and the foreign firm choose their outputs to maximize the profits, respectively, in the following manner:

\[
\max_{q_i} (a - q - c)q_i \quad \text{and} \quad \max_{q_F} (a - q)q_F - K; \quad i = 1, 2, \ldots, n.
\]

The equilibrium outputs of the \( i \)th domestic firm and the foreign firm are given by \( q_i^{f*} = \frac{a - 2c}{n + 2} \) and \( q_F^{f*} = \frac{a + nc}{n + 2} \), respectively, where \( c < \bar{c} \) ensures that these outputs are positive. Hence, the profits of

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\(^6\)It can be checked that \( c_x \) is less than \( (a + nc) / (n + 1) \) because \( a > c \), so that the foreign firm’s equilibrium output under exporting in the presence of domestic R&D is positive (i.e., \( q_F^{e*} > 0 \)).
the \( i \)th domestic firm and the foreign firm, respectively, are given by
\[
\pi_i^* = \frac{(a - 2c)^2}{(n + 2)^2} \quad \text{and} \quad \pi_F^* = \frac{(a + nc)^2}{(n + 2)^2} - K.
\] (5)

Then, it is straightforward that under no domestic R&D investment, the foreign firm will conduct FDI if
\[
K < \frac{c_x(n + 1)(2a + 2nc - (n + 1)c_x)}{(n + 2)^2} \equiv K^N.
\]

2.2 R&D Investment in the Domestic Country

Consider the game when the domestic firms have incentives for R&D investment. In this case, if the foreign firm exports, then the \( i \)th domestic firm and the foreign firm choose their outputs to maximize their profits in the following manner:
\[
\max_{q_i} (a - q - (c - z_i^x))q_i - \gamma z_i^x \quad \text{and} \quad \max_{q_F} (a - q - c_x)q_F; \quad i = 1, 2, \ldots, n.
\] (6)

Given the domestic R&D investment \( z_i^x \), the equilibrium outputs of the domestic and foreign firms are
\[
q_i^x = \frac{a - 2(c - z_i^x) + c_x}{n + 2} \quad \text{and} \quad q_F^x = \frac{a + n(c - z_i^x) - (n + 1)c_x}{n + 2},
\]
respectively. Given these outputs, the foreign firm's profit under exporting is given by
\[
\pi_F^x = \frac{(a + n(c - z_i^x))^2}{(n + 2)^2}.
\]

However, if the foreign firm undertakes FDI, then the \( i \)th domestic firm and the foreign firm choose their outputs to maximize profits, respectively, in the following manner:
\[
\max_{q_i} (a - q - (c - z_i^f))q_i - \gamma z_i^f \quad \text{and} \quad \max_{q_F} (a - q - c_x)q_F - K; \quad i = 1, 2, \ldots, n.
\] (7)

The equilibrium outputs of the \( i \)th domestic firm and the foreign firm are given by
\[
q_i^f = \frac{a - 2(c - z_i^f)}{n + 2} \quad \text{and} \quad q_F^f = \frac{a + n(c - z_i^f) - (n + 1)c_x}{n + 2},
\]
respectively. Given these outputs, the foreign firm's profit under FDI is given by
\[
\pi_F^f = \frac{(a + n(c - z_i^f))^2}{(n + 2)^2} - K.
\]
Hence, in stage 2, where the levels of domestic R&D investment are given, the foreign firm will undertake FDI if
\[
K < \frac{[a + n(c - z_i^f)]^2 - [a - (n + 1)c_x + n(c - z_i^f)]^2}{(n + 2)^2} \equiv K^f.
\]

Let us move backward to the stage for determining domestic R&D levels. For analytical convenience, this study only focuses on a unique subgame perfect Nash equilibrium in the sense that a firm strictly prefers one cost-reducing strategy.\(^7\) If \( K > K^f \), in which case the foreign firm chooses

\(^7\)This uniqueness ensures that the foreign firm must use one entry mode to serve the domestic market. Hence, the possibility that the foreign firm’s payoffs are equal under exporting and FDI, which may cause multiple equilibria, is eliminated. Technically, if the condition \( K = K^f \) holds, backward induction implies that in the domestic firms’ profit maximization by choosing the R&D levels, the complementary slackness has an equal constraint. This optimization problem significantly complicates the analysis and does not generate new insights into the firms’ choice on their strategies.
exporting, then the profit-maximizing R&D level of the ith domestic firm can be computed by

$$\max_{z_i} \left[ \frac{a - 2(c - z_i) + c_x}{n + 2} \right]^2 - \frac{\gamma}{2} \frac{z_i^2}{n^2}; \quad i = 1, 2, \ldots, n, \quad s.t. \quad K^I < K.$$ 

This profit maximization problem is equivalent to the optimization problem with an inequality constraint. Since the constraint never binds, complementarity implies that the Lagrangian multiplier is zero. Then the domestic R&D levels and the outputs of the ith domestic firm and the foreign firms in equilibrium are given by

$$z_i^* = \frac{4(a - 2c_x)}{\gamma(n + 2)^2 - 8}, \quad q_i^* = \frac{\gamma(n + 2)(a - 2c_x)}{\gamma(n + 2)^2 - 8}, \quad \text{and} \quad q_F^* = \frac{a + n(c - z_i^*) - (n + 1)c_x}{n + 2}.$$ 

Substituting $z_i^*$, $q_i^*$, and $q_F^*$ into (6) yields the equilibrium profits of the ith domestic firm and the foreign firm under exporting, respectively,

$$\pi_i^* = \frac{\gamma(a - 2c + c_x)^2}{\gamma(n + 2)^2 - 8} \quad \text{and} \quad \pi_F^* = \frac{[a(\gamma(n + 2) - 4) + \gamma c n(n + 2) - (\gamma(n + 2)(n + 1) - 4)c_x]^2}{(\gamma(n + 2)^2 - 8)^2}.$$  

However, if $K < K^I$, in which case the foreign firm chooses FDI, then the profit-maximizing R&D level of the ith domestic firm can be computed by

$$\max_{z_i} \left[ \frac{a - 2(c - z_i)}{n + 2} \right]^2 - \frac{\gamma}{2} \frac{z_i^2}{n^2}; \quad i = 1, 2, \ldots, n, \quad s.t. \quad K < K^I.$$ 

Hence, by the same logic as previously, we derive the equilibrium R&D levels and outputs of the ith domestic firm and the foreign firm as follows:

$$z_i^* = \frac{4(a - 2c)}{\gamma(n + 2)^2 - 8}, \quad q_i^* = \frac{\gamma(n + 2)(a - 2c)}{\gamma(n + 2)^2 - 8} \quad \text{and} \quad q_F^* = \frac{a(\gamma(n + 2) - 4) + \gamma c n(n + 2)}{\gamma(n + 2)^2 - 8},$$

which are positive given that $c < c_x$, $c_x < c_x^*$, and $\gamma > 4/(n + 2)$. Consequently, combining $z_i^*$, $q_i^*$, $q_F^*$ and (8), the equilibrium profits for the ith domestic firm and the foreign firm, respectively, are given by

$$\pi_i^* = \frac{\gamma(a - 2c)^2}{\gamma(n + 2)^2 - 8} \quad \text{and} \quad \pi_F^* = \frac{[a(\gamma(n + 2) - 4) + \gamma c n(n + 2)]^2}{(\gamma(n + 2)^2 - 8)^2} - K.$$  

Then, it is obvious that the threshold of the fixed cost for the foreign firm to conduct FDI under domestic R&D investment becomes

$$K^I = \frac{c_x(\gamma(n + 1)(n + 2) - 4)[2a(\gamma(n + 2) - 4) + 2\gamma(n + 2)c_x - (\gamma(n + 1)(n + 2) - 4)c_x]}{(\gamma(n + 2)^2 - 8)^2}.$$  

### 3 The Effect of Domestic R&D on FDI

In this section, we investigate the first way of the interplay between the cost-reducing strategies of domestic and foreign firms. We analyze how the domestic firms’ R&D investment impacts the

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\[ \gamma > \frac{4}{n+2} \] satisfies the second-order condition and ensures that the domestic R&D levels and the firms’ outputs are positive along with $n \geq 1$, $c < c_x$, and $c_x < c_x^*$. In addition, we assume that $c > \frac{4a(2n+3)}{(n+1)(n+2)}$ that yields $\gamma > \frac{4a(2n+3)}{c(n+1)(n+2)}$ by $\gamma > \frac{4}{n+2}$, which sufficiently ensures $z_x^* < \frac{c_x(n+2)^2 - 4a}{4}$; thus $c > z_x^*$.  

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foreign firm’s incentives for FDI into the domestic market.

Let us denote $c^*_x \equiv -\frac{an(-4+\gamma(n+2)^2)+\gamma(3n+2)(n+2)^2}{-8-6n+\gamma(n+1)(n+2)^2}$, so that if $c_x > (\lhd) c^*_x$, then $K^N > (\lhd) K^I$. Moreover, it is known that $c^*_x \geq 0$ if $c \geq \frac{an(-4+\gamma(n+2)^2)}{-16(n+1)+\gamma(3n+2)(n+2)^2} \equiv \zeta > 0$. To make the lower bound of $c$ always compatible with the positive marginal costs of domestic firms after R&D investment, we assume that there exist a sufficiently large number of domestic firms in the market.\footnote{In the Appendix, we show that with $\gamma > 4/(n + 2)$, this assumption satisfies $\zeta > \frac{2n+3}{2(n+1)(n+2)}$ if $n \geq 6$.}

Note that $c^*_x < c_x$ if $c < \frac{aA}{2B} \equiv c^*$, where $A \equiv \gamma^2(1+n)^2(n+2)^3 + 8(5n+4) - 2\gamma(n+2)(3n(2n+5)+8) > 0$, $B \equiv 32(n + 1) + \gamma(n + 2)(-16 + g(n + 1)^2(n + 2)^2 - n(11n + 28)) > 0$, and $A < B$. Accordingly, we know $c^* \in (\zeta, c)$.

Then, comparing $K^N$ and $K^I$ yields the following result.

**Proposition 1.** (I) If either $c > c^*$ and $c_x < c^*_x$, or $c < c^*$ and $c_x < c^*_x$, then $K^I > K^N$ such that domestic R&D investment increases the foreign firm’s FDI incentives; (II) If $c < c^*$ and $c_x > c^*_x$, then $K^I < K^N$ such that domestic R&D investment decreases the foreign firm’s FDI incentives.

Proposition 1 provides an explanation for the mixed (i.e., positive and negative) correlations between domestic R&D and FDI inflows without technology sourcing and spillovers, as specified by Beladi, Firoozi, and Co (2008). R&D investment enhances the domestic firms’ competitiveness in the product market by reducing their marginal costs. Given the level of domestic R&D investment, the degree of competition faced by the foreign firm tends to increase since its equilibrium output and profit decline. Therefore, provided that FDI plays a similar role as process innovations for the foreign firm, the effect of domestic R&D investment on the FDI decision leads to the discussion on the relationship between competition and innovations in existing literature.

First, domestic R&D investment intensifies product market competition between the domestic firms and the foreign firm. This is likely to decrease the foreign firm’s incentives for adopting the cost-reducing strategy (i.e., FDI), because as a result of domestic cost reduction, the residual demand that the foreign firm could capture by undertaking FDI is very limited. Hence, this creates the “Schumpeterian effect,” which implies that higher market competition discourages firms’ incentives for innovations by reducing potential post-innovation rents (Schumpeter (1943)).\footnote{The decreasing relation between competition and innovations is shared by models of monopolistic competition and product differentiation (e.g., Dixit and Stiglitz (1977) and Salop (1977)) in addition to models of endogenous Schumpeterian growth (e.g., Grossman and Helpman (1991) and Aghion and Howitt (1992)).} \footnote{This argument is similar to the positive effect of merger on innovations (i.e., FDI) that is specified in Beladi and Mukherjee (2012).}

Second, domestic R&D investment increases the foreign firm’s incentives for FDI. Cost reduction induces the domestic firms to steal market shares from the foreign firm. If the foreign firm does not undertake FDI, its competitiveness and residual demand in the market would decline further. This generates the “escape-competition effect,” thereby implying that higher market competition

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\footnote{In the Appendix, we show that with $\gamma > 4/(n + 2)$, this assumption satisfies $\zeta > \frac{2n+3}{2(n+1)(n+2)}$ if $n \geq 6$.}
causes firms to innovate, since with higher competition firms’ pre-innovation rents decrease more than their post-innovation rents (Aghion, Bloom, Blundell, Griffith, and Howitt (2005)).

Consequently, the coexistence of these two conflicting forces explains the mixed effects of domestic R&D investment on FDI incentives. When the foreign firm’s marginal cost of exporting is relatively small, the foreign firm under exporting either enjoys a cost advantage over the domestic firms or firms might compete in a “neck-and-neck” industry (i.e., Proposition 2 (I)). If the domestic firms invest in R&D, compared to the situation of no R&D investment, the foreign firm’s residual demand becomes smaller. Then, using FDI can counteract this impact by improving the foreign firm’s competitiveness and making the market competition more severe. In this case, the foreign firm’s pre-innovation rents decrease so significantly by domestic R&D that the escape-competition effect dominates the Schumpeterian effect; thus, the foreign firm’s incentives for FDI become higher with domestic R&D than without domestic R&D. However, when the domestic firms’ marginal costs are low and the foreign firm’s counterpart of exporting is large, R&D investment already helps the domestic firms capture large market shares, which mainly affect the foreign firm’s post-innovation rents (i.e., Proposition 2 (II)). Therefore, undertaking FDI, which changes the degree of competition, cannot generate much gain for the foreign firm by increasing its residual demand that is essentially small. This means that domestic R&D does not implies a significant decrease in the foreign firm’s pre-innovation rents, such that the Schumpeterian effect dominates the escape-competition effect. Hence, the foreign firm’s incentives for FDI become lower with domestic R&D than without domestic R&D.

4 Changes in Domestic R&D Incentives

In this section, we reverse our viewpoint by examining how the presence of the foreign firm’s FDI decision may influence the domestic firms’ incentives to invest in R&D in terms of ex-post profits. The analysis in the previous section indicates that it is possible that $K^N \geq K^I$, depending on the domestic firms’ marginal costs and the foreign firm’s marginal cost of exporting. Solving the game backward to the R&D stage and comparing the domestic firms’ profits in different subgames, we obtain the following proposition.

**Proposition 2.** Domestic R&D incentives may increase irrespective of the effects of the domestic firms’ R&D investment on the foreign firm’s decision to undertake FDI.

Beladi and Mukherjee (2012) refer to the increasing relation between competition and innovations as Arrow’s “replacement effect” (Arrow (1962)). However, the escape-competition effect in ABBGH (2005) is more appropriate for this model since it involves two types of competing firms with actions in process innovations (i.e., cost-reducing strategies), which feature changes in the degree of market competition induced by the rivals’ innovations. In fact, the escape-competition effect in this analysis can also be interpreted as Arrow’s replacement effect as follows. Investing in domestic R&D decreases the residual demand and the pre-innovation rents of the foreign firm and implies a higher competition in the product market. Nevertheless, the existing profits that the foreign firm can replace by its innovations (namely, FDI) also decrease, which creates a higher incentive for FDI.
Proof. Given the production strategy of the foreign firm, we compare the domestic firms’ profits in the following cases.

**Case 4.1.** Suppose that the foreign firm undertakes either exporting or FDI regardless of domestic R&D investment, namely, $K > \max \{K^N, K^I\}$ or $K < \min \{K^N, K^I\}$. Then, comparing (3) and (8) in Section 2.1, and (5) and (9) in Section 2.2, we know that each domestic firm’s profit becomes higher with R&D investment than without R&D investment, which implies that domestic R&D incentives always increase in this case.

**Case 4.2.** Suppose that domestic R&D investment prevents the foreign firm from undertaking FDI, namely, $K \in (K^I, K^N)$ for $c < c^*$ and $c_x > c^*_x$. Then, comparing (5) and (8) reveals that the profit of each domestic firm with R&D investment when the foreign firm exports is greater than the counterpart without R&D investment when the foreign firm undertakes FDI, which implies that domestic R&D incentives always increase in this case.

**Case 4.3.** To investigate how domestic R&D incentives change when the foreign firm’s incentives for FDI rise under domestic R&D investment— that is $K \in (K^N, K^I)$ for either $c > c^*$ and $c_x < \bar{c}_x < c^*_x$, or $c < c^*$ and $c_x < c^*_x$, we denote $c^{**}_x \equiv (a - 2c) \left[ \frac{\sqrt{\gamma(n+2)}}{\sqrt{\gamma(n+2)^2 - 8}} - 1 \right]$ and $\bar{c} \equiv (\{an(\gamma(n+2)^2 - 4) + a(\gamma(n+2)^2(n+1) - 6n - 8)\}/(\sqrt{\gamma(n+2)^2 - 8}) - 1)/([16(n+1) + \gamma(n+2)^2(3n+2) + 2(\gamma(n+2)^2(n+1) - 6n - 8)])/(\sqrt{\gamma(n+2)^2 - 8}))$. Accordingly, we compare the profit of each domestic firm with R&D investment under FDI by the foreign firm (i.e., $(\gamma/a - 2c^2)/(\gamma(n+2)^2 - 8)$) and the counterpart without R&D investment under exporting by the foreign firm (i.e., $(a - 2c + c_x^2)/(n+2)^2$). This comparison shows that domestic firms prefer to invest in R&D that attracts FDI by the foreign firm if $c_x < c^{**}_x$. Further, to be consistent with the conditions in Proposition 1, we consider the following two situations:

If $c \in (c^*, \bar{c})$, then FDI-attracting domestic R&D investment (i.e., $K \in (K^N, K^I)$) implies that $c_x < \bar{c}_x < c^*_x$ and $c^{**}_x < \bar{c}_x$. Therefore, domestic R&D incentives increase when $c_x < c^{**}_x$.

If $c \in (\bar{c}, c^*)$, then FDI-attracting domestic R&D investment (i.e., $K \in (K^N, K^I)$) implies $c_x < c^*_x$. Given that $\partial(c_x - c^*_x)/\partial c > 0$, $c^*_x < c^{**}_x$ for $c = \bar{c}$ and $c^*_x > c^{**}_x$ for $c = c^*$, there exists a threshold $\bar{c} \in (\bar{c}, c^*)$ such that $c^{**}_x < c^*_x$ if $c > \bar{c}$. Therefore, domestic R&D incentives increase when $c_x < \min \{c^*_x, c^{**}_x\}$.

Hence, we can conclude that when domestic R&D investment attracts the foreign firms to undertake FDI— that is $K \in (K^N, K^I)$ for $c \in (\bar{c}, \bar{c})$, domestic R&D incentives always increase if $c_x < \min \{c^*_x, c^{**}_x\}$.

The intuition of the above result can be described as follows. First, if domestic R&D investment does not affect the foreign firm’s decision to undertake FDI, in the absence of spillovers, cost
reduction enhances the domestic firms’ production efficiency to capture more market shares when the foreign firm’s marginal cost is given. Then, investing in R&D must be the dominant strategy for the domestic firms to increase profits. This is just a special case of innovating firms in d’Aspremont and Jacquemin (1988), with neither spillovers nor R&D cooperation.

Second, when the domestic firms’ marginal costs are sufficiently small \( (c < c^*) \) and the trade cost of exporting is sufficiently high \( (c_x > c^*_x) \), domestic R&D investment prevents FDI. This prevention excludes the possibility for the foreign firm to lower its marginal cost, while cost reduction induces the domestic firms to further steal market shares from the foreign firm. Consequently, cost reduction strengthens the domestic firms’ competitiveness to a great extent in the product market and, thus, generates incentives for them to undertake R&D investment.\(^{14}\)

Finally, when the domestic firms’ marginal costs are not close to the foreign firm’s marginal cost under FDI (which is zero) and the trade cost of exporting is sufficiently small \( (e.g., c_x < c^{**}_x < c^*_x) \), domestic R&D investment attracts FDI. This attraction reduces the foreign firm’s marginal cost and thus reinforces its competitiveness in the product market, which will harm the profitability of the domestic firms if they do not invest in R&D. Hence, cost reduction improves the domestic firms’ production efficiency by decreasing their marginal costs and leaving the smallest proportion of market shares for the foreign firms. This effect becomes stronger if the trade cost of exporting is small, yielding incentives for the domestic firms to invest in R&D that minimizes the impact of FDI.\(^{15}\) Of course, if the trade cost of exporting is relatively large \( (e.g., c_x \in (c^{**}_x, c^*_x)) \), then the above scenario reverses such that the incentives for the domestic firms to undertake R&D decrease. These results could alternatively explain the opposite empirical effect of FDI on domestic R&D in Van Pottelsberghe De La Potterie and Lichtenberg (2001) and Bitzer and Kerekes (2008).

5 Comparison of Domestic Welfare

Mukherjee and Sinha (2007) argue that if the foreign firm’s production strategy is altered from FDI to exporting by a domestic firm’s cost reduction, then the level of domestic welfare may reduce because a large cost inefficiency is caused in the overall industry. Hence, this section analyzes the implications of domestic cost reduction through R&D investment on domestic welfare when the foreign firm’s production strategy is also taken into account. We show that domestic cost reduction can be always beneficial to domestic welfare if the domestic firms’ R&D decisions are endogenized and the R&D cost function is properly adjusted.

First, if domestic cost reduction does not affect the foreign firm’s production strategy, then the

\(^{14}\)In this case, domestic R&D investment yields a similar effect on the foreign firm as a profitable domestic merger in Beladi and Mukherjee (2012).

\(^{15}\)See Cheung and Lin (2004) and AlAzzawi (2012) for the positive effects of FDI on domestic innovations via technology transfer and spillovers in the case of China.
analysis of domestic welfare is presented by the following two cases.

**Case 5.1.** Assume that the foreign firm always chooses exporting regardless of domestic cost reduction, namely, $K > \max \{K^N, K^I\}$ for $c_x \in (0, \overline{c}_x)$ and $c \in (c, \overline{c})$. Therefore, the domestic welfare under no domestic R&D investment is given by

$$W^{x*}_N = \frac{[a(n+1) - 2c_x - cn]^2 + 2n(a - 2c + c_x)^2}{2(n+2)^2},$$

(10)

whereas the domestic welfare under domestic R&D investment is

$$W^{x*}_I = \left[\frac{2n\gamma(n+2)^2 - 8)(a - 2c + c_x)^2}{(4c_x - \gamma(n+2)(c_x + cn) + a(\gamma(n+1)(n+2) - 4))^2}\right] / \left[2(\gamma(n+2)^2 - 8)^2\right].$$

(11)

Denote $H_1 = W^{x*}_I - W^{x*}_N$. It can be shown that for $c \in (c, \overline{c})$, $H_1$ is concave in $c_x$, $H_1|_{c_x = 0} > 0$ and $H_1|_{c_x = \overline{c}_x} > 0$. Hence, the level of domestic welfare becomes higher under domestic R&D investment as compared to under no domestic R&D investment.

**Case 5.2.** Assume that the foreign firm always undertakes FDI regardless of domestic cost reduction, namely, $K < \min \{K^N, K^I\}$ for $c_x \in (0, \overline{c}_x)$ and $c \in (c, \overline{c})$. Therefore, the domestic welfare under no domestic R&D investment is given by

$$W^{f*}_N = \frac{2n(a - 2c)^2 + [a(n+1) - cn]^2}{2(n+2)^2},$$

(12)

whereas the domestic welfare under domestic R&D investment is

$$W^{f*}_I = \frac{2n\gamma(n+2)^2 - 8)(a - 2c)^2 + [cn\gamma(n+2) - a(\gamma(n+1)(n+2) - 4)]^2}{2(\gamma(n+2)^2 - 8)^2}.$$ 

(13)

Denote $H_2 = W^{f*}_I - W^{f*}_N$. It can be shown that for $c \in (c, \overline{c})$, $H_2$ is convex in $c$, and $H_2$ reaches the minimum level at $c^{\text{min}}_I = \frac{a\gamma(n+2)^2(3n+10) - 16(n+5)}{4(\gamma(n+2)^2(n+4) - 4(n+8))}$, which is greater than $\overline{c}$. Moreover, $H_2|_{c = \overline{c}} > 0$ and $H_2|_{c = c} = 0$. Hence, the level of domestic welfare becomes higher under domestic R&D investment as compared to under no domestic R&D investment.

Next, let us suppose that domestic cost reduction changes the foreign firm’s production strategy. Then, the analysis of domestic welfare is given by the following two cases.

**Case 5.3.** Assume that the foreign firm chooses exporting under no domestic R&D, while it changes to undertake FDI under domestic R&D. According to Case 4.3, we have $K^N < K < K^I$ for $c_x \in (0, \min \{c^*_x, c^{**}_x\})$ and $c \in (c, \overline{c})$ in this case. Therefore, we compare the domestic welfare between under “domestic R&D and FDI by the foreign firm” and under “no domestic R&D and exporting by the foreign firm,” namely, (13) and (10). Denote $H_3 = W^{f*}_I - W^{x*}_N$. It can be shown
that for \( c \in (c, \bar{c}) \), \( H_3 \) is concave in \( c \). In addition, \( H_3|_{c=c}=0 > 0, H_3|_{c=c^*} > 0 \), and \( H_3|_{c=c^{**}} > 0 \). Hence, the level of domestic welfare becomes higher under domestic R&D investment as compared to under no domestic R&D investment.

**Case 5.4.** Assume that the foreign firm undertakes FDI under no domestic R&D, whereas it chooses exporting under domestic R&D. According to Case 3.2, we have \( K \in (K, K^N) \) for \( c \in (c, c^*) \) and \( c_x > c^*_x \) in this case. Therefore, we compare the domestic welfare between under “domestic R&D and exporting by the foreign firm” and under “no domestic R&D and FDI by the foreign firm,” that is (11) and (12). Denote \( H_4 = W_xI - W_fN \). It can be shown that for \( c \in (c, \bar{c}) \), \( H_4 \) is convex in \( c_x \), and \( H_4 \) reaches the minimum level at \( c_x \) where \( c_x < c^* \). Denote the roots for \( H_4(c)|_{c_x=c_x^{min}} = 0 \) as \( c_x^{min} \) and \( c_x^{max} \) where \( c_x^{min} < c_x^{max} \). Since \( H_4(c)|_{c_x=c_x^{min}} \) is concave in \( c \), if \( \gamma \in \left( \frac{4}{n+2}, \bar{\gamma} \right) \), then we find that \( c_x^{min} \leq c \leq c^* \leq c_x^{max} \) so that \( H(c)|_{c_x=c_x^{min}} > 0 \). Accordingly, given the condition on \( \gamma \), the level of domestic welfare becomes higher under domestic R&D investment as compared to under no domestic R&D investment.

To summarize, we obtain the following result.

**Proposition 3.** Domestic welfare always improves with domestic cost reduction if the slope of the marginal cost of domestic firms’ R&D investment is sufficiently small, i.e., \( \gamma \in \left( \frac{4}{n+2}, \bar{\gamma} \right) \).

Intuitively, the effect of domestic cost reduction on domestic welfare depends on whether the foreign firm’s production strategy is altered since it affects the domestic firms’ profits and the underlying consumer surplus. First, if the foreign firm’s production strategy does not change irrespective of domestic cost reduction (i.e., Cases 4.1 and 4.2), it can be shown that domestic firms’ R&D investment increases consumer surplus since cost reduction strengthens domestic firms’ production efficiency and more equilibrium outputs are expected. Moreover, given that the foreign firm’s cost efficiency does not change in this circumstance, each domestic firm’s profit increases by investing in R&D for cost reduction. Consequently, domestic welfare rises unambiguously with domestic cost reduction.

Second, if domestic cost reduction changes the foreign firm’s production strategy from exporting to FDI (i.e., Case 4.3), it can be shown that domestic firms’ R&D investment raises consumer surplus since both domestic R&D investment and FDI tend to increase the total industry outputs. Additionally, given that the trade cost of exporting is relatively small (i.e., \( c_x < \min\{c^*_x, c^{**}_x\} \)), the improvement in cost efficiency of the foreign firm by undertaking FDI is not significant, so that cost reduction still helps each domestic firm extract sufficiently large market shares from the foreign firm, which increase the domestic firms’ profits. Thus, in this case, domestic welfare rises unambiguously with domestic cost reduction as well.

\(^{16}\)See the Appendix for the proof of \( c_x^{min}, c_x^{max}, \) and \( \bar{\gamma} \).
Finally, if domestic cost reduction changes the foreign firm’s production strategy from FDI to exporting (i.e., Case 4.4), it can be shown that with R&D investment, each domestic firm’s profit becomes larger due to its own cost reduction and the foreign firm’s relative cost inefficiency (because the marginal cost of exporting is higher than that of FDI), but the change in consumer surplus is indeterminate. On the one hand, suppose that consumer surplus increases. Then, domestic welfare rises unambiguously with domestic cost reduction. On the other hand, suppose that consumer surplus decreases. As $\gamma$ increases, both the total cost and the marginal cost of domestic R&D investment would rise, which tend to decrease the equilibrium outputs and domestic firms’ profits. This implies that there exists an upper bound of $\gamma$ that generates a sufficiently large effect of domestic cost reduction, by which the domestic firms’ profits are increased to just compensate for the potential loss of consumer surplus, thereby yielding a rise in domestic welfare.$^{17}$ Hence, under this circumstance, domestic welfare becomes greater with domestic cost reduction than without it.

The above result demonstrates that domestic cost reduction through R&D investment could always be welfare-improving for the domestic country, even if the foreign firm switches its production strategy from FDI to exporting as a consequence. This is due to the fact that if the slope of the marginal cost of domestic firms’ R&D investment is not very large, cost reduction via R&D investment increases domestic firms’ production efficiency, which would adequately cover the market cost inefficiency generated by the shift of the foreign firm’s production strategy. In contrast to Mukherjee and Sinha (2007), endogenizing the domestic R&D decisions in this study helps prevent the overall industry inefficiency from being significant, thereby raising the level of domestic welfare. Accordingly, this result suggests that countries that are behind the technology frontier need appropriate policies (e.g., education and research support) to adjust the (marginal) cost of domestic firms’ R&D by affecting $\gamma$, while these countries stimulate domestic innovations and engage in foreign competition simultaneously.

6 Conclusion

In this paper, we explore the relationship between a foreign firm’s decision on FDI and domestic firms’ decisions on cost reduction through R&D, as well as the influence on domestic welfare. We first provide a rationale through oligopolistic competition and innovations to explain the mixed empirical effects of domestic R&D investment on the foreign firm’s incentives for FDI. In addition, we show that depending on the foreign firm’s marginal cost of exporting, domestic R&D incentives may rise regardless of whether domestic firms’ R&D investment prevents FDI. Finally, domestic firms’ investment in R&D may change the foreign firm’s entry mode from FDI to exporting, which causes cost inefficiency in production. Nevertheless, when the slope of marginal cost of domestic

$^{17}$Notice that the condition $\gamma > 4/(n + 2)$ in Proposition 3 is used to satisfy the second order condition.
firms’ R&D investment is relatively small, domestic firms’ decisions on cost reduction can counteract the impact of the industry cost inefficiency and always enhance domestic welfare. Thus, this result has the following welfare implication for countries: when countries encourage both domestic innovations and participation in foreign competition, policies must be designed wisely to ameliorate the research environment for domestic firms in order to reduce their marginal cost of R&D investment.

It is important to note that our result applies to industries in which domestic firms can only invest in R&D by themselves. We implicitly exclude the possibility that domestic firms could cooperate in R&D activities as an option to affect foreign firms’ FDI decisions. Under the regime of (domestic) cooperative R&D, if across-firms spillovers are present and the degree is high, according to d’Aspremont and Jacquemin (1988) and Kamien, Muller, and Zang (1992), the total domestic R&D investment will increase and the domestic firms’ production efficiency will be strengthened. These outcomes considerably intensify the market competition faced by foreign firms, leaving even smaller residual demand for them to capture by cost reduction. Therefore, their post-innovation rents tend to reduce significantly, thereby making the Schumpeterian effect dominate the escape-competition effect and thus lowering the FDI incentives. Moreover, the domestic firms’ profits will be larger because of higher R&D incentives. Finally, the change in domestic welfare may be indeterminate because it depends on whether the benefits of R&D cooperation in terms of increasing domestic firms’ profits compensate for the cost inefficiency induced by the decrease in FDI. However, the consideration of R&D cooperation, spillovers, and their effects on FDI incentives and domestic welfare are beyond the scope of this study, and we will leave it as a potential direction for future research.

Appendix

In this appendix, we first show that with a sufficiently large number of firms, $c$ is always greater than the assumption $c > \frac{a(2n+3)}{(n+1)(n+2)}$ in Footnote 9. Second, we derive the boundaries for the slope of the marginal cost of domestic R&D investment (i.e., $\gamma$) in Case 5.4, so that domestic welfare always increases with domestic cost reduction when the foreign firm’s production strategy is changed from FDI to exporting.

Derivation for $c > \frac{a(2n+3)}{(n+1)(n+2)}$

First, we show how the assumption $c > \frac{a(2n+3)}{(n+1)(n+2)}$ is obtained. We have to ensure that $c > z_i^{x^*}$, so that we always have $c > z_i^{x^*}$. Thus, this condition is satisfied if $4c\gamma(n+2) + 4a\gamma(n+2) < c\gamma^2(n+1)(n+2)^3 - 4c\gamma(n+2)^2 - 4a\gamma(n+1)(n+2)$. This inequality
can be simplified to
\[ 8c\gamma(n + 1) + 4a\gamma(n + 2) < c\gamma^2(n + 1)(n + 2)^2. \tag{A.1} \]

Since we assume that \( c < a/2 \), then (A.1) is satisfied if \( 4a(2n + 3) < c\gamma(n + 1)(n + 2)^2 \). Therefore, with \( \gamma > 4/(n + 2) \), the assumption \( c > \frac{a(2n+3)}{(n+1)(n+2)} \) is imposed.

Second, we need to ensure that \( c \) always satisfies the above assumption on \( c \), which implies that we have \( \xi = \frac{an(\gamma(n+2)^2-4)}{\gamma(3n+2)(n+2)^2-16(n+1)} > \frac{a(2n+3)}{(n+1)(n+2)} \). This condition is sufficiently satisfied if \( n(n + 1)(n + 2)(\gamma(n + 2)^2 - 4) > 2(n + 2)(\gamma^3(3n + 2)(n + 2)^2 - 16(n + 1)) \). Further simplification yields
\[ \gamma(n + 2)^2(n^2 - 5n - 4) > 4(n + 1)(n - 8). \tag{A.2} \]

Then with \( \gamma > 4/(n + 2) \), (A.2) is obtained if \( (n + 2)(n^2 - 5n - 4) > (n + 1)(n - 8) \), which can be satisfied by \( n^2 - 6n + 4 > 0 \) or \( n > 3 + \sqrt{5} \). Finally, a relatively large number of firms, namely \( n \geq 6 \), suffices the above condition. Notice that \( n \geq 6 \) also ensures that \( \frac{a(2n+3)}{(n+1)(n+2)} < \xi < c < \frac{a}{2} \), which is required in the first part of this derivation.

**Derivation for Case 5.4**

In Case 4.2, we know that the foreign firm undertakes FDI under no domestic R&D, while it chooses exporting under domestic R&D if \( K \in (K^I, K^N) \) for \( c \in (\xi, c^*) \) and \( c_x > c_x^* \). Denoting the domestic welfare difference between these two situations as \( H_4 = W_{I}^{f^*} - W_{N}^{f^*} \), we obtain that \( H_4 \) is convex in \( c_x \) for \( c \in (\xi, c^*) \) and that \( H_4 \) reaches the minimum level at \( c_x^{\min} \). In this case, we only need to solve for the conditions that guarantee \( H_4|_{c_x=c_x^{\min}} > 0 \) for \( c \in (\xi, c^*) \) and \( c_x > c_x^* \), then domestic cost reduction always raises domestic welfare.

Substituting \( c_x^{\min} \) into \( H_4 \) gives a quadratic function of \( c \). Consequently, we find that there exist two roots for \( H_4|_{c_x=c_x^{\min}} = 0 \), which are denoted by \( c^{\min} \) and \( c^{\max} \) where \( c^{\min} < c^{\max} \). Specifically, \( c^{\min} = (M - \mathcal{N}) / \mathcal{D} \) and \( c^{\max} = (M + \mathcal{N}) / \mathcal{D} \), where \( M = an(3\gamma^2(n - 1)(n + 2)^2 + 16(n + 5) - 8\gamma(n(n + 9) + 2)) \), \( \mathcal{N} = 4\sqrt{a^2n(n + 2)^2(\gamma + \gamma n - 2)(16 + \gamma^2(n + 2)^2(2n + 1) - 8\gamma(3n^2 + 2))} \), and \( \mathcal{D} = n(9\gamma^2(n + 2)^2 + 16(n + 8) - 8\gamma(n(n + 18) + 8)) \). Moreover, \( H_4|_{c_x=c_x^{\min}} \) is concave in \( c \). Thus, we need to check if \( H_4|_{c_x=c_x^{\min}} > 0 \) is an empty set when \( (\xi, c^*) \) is within \( (c^{\min}, c^{\max}) \).

Given that \( \gamma > 4/(n + 2) \) and \( n \geq 6 \), we always have \( c^{\min} < \xi < c^* \). Then the remaining task is to see if it is possible that \( c^* < c^{\max} \). Under the same conditions, it can be also shown that \( c^* \) is increasing in \( \gamma \) and that \( c^{\max} \) is decreasing in \( \gamma \). Further, when \( \gamma \to 4/(n + 2) \), \( c^* < c^{\max} \), implying that there must exist a threshold level \( \overline{\gamma} \) such that \( c^* = c^{\max} \). Hence, \( c^* < c^{\max} \) for \( \gamma < \overline{\gamma} \). Finally, if the condition that \( \gamma \in \left( \frac{4}{n+2}, \overline{\gamma} \right) \) holds, then \( (\xi, c^*) \) is within \( (c^{\min}, c^{\max}) \), so that \( H_4|_{c_x=c_x^{\min}} \) is always positive.

\[ ^{18}\text{The proof of the above arguments can be seen in the complementary Mathematica files.} \]
References


