Government RD Subsidies and International Competitiveness of Labor-managed Firms

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Abstract

The literature postulates that government subsidization of strategic R&D activities of profit maximising firms (PMFs) increases their shares in international markets. Will this also hold for labor-managed firms (LMFs) which are owned by employees and aim to maximize the profit per labor? This paper provides a theoretical model that examines how such governmental interventions can help LMFs in their home countries to compete better with PMFs in international markets. Our model shows that in most, but not all cases, investing more in R&D activities benefits LMFs by increasing their shares in international markets and decreasing the market share of their competitors. The optimal government R&D subsidy or tax for LMFs depends on the R&D elasticity of LMFs as well as how their competitors react to R&D investment. In contrast, the optimal government R&D subsidy for PMFs depends solely on the slope of the R&D reaction curve of PMFs competitors. Our results present useful policy implications for those governments that seek ways to support LMFs - or more broadly cooperatives - to attain more sustained growth given their advantages over PMFs in the context of sustainable development.

JEL classification: A1; F1

Keywords: duopoly; cooperatives; labor-managed firms; profit-maximizing firm; R&D subsidy

1. Introduction

One common policy instrument used by governments in many countries is the granting of subsidies, especially subsidies on research and development (R&D) activities, to assist exporting companies gain market power in international markets. One reason for this strategy is that while export subsidization is impermissible, R&D subsidization is a more appealing policy tool for a government because it faces less WTO reinforcement.

A firm's investment in R&D activities plays a critical role in enhancing its competitive power in the global market. In an imperfectly competitive market in which both profit-maximizing firms (henceforth PMFs, or PM firms) use R&D investments strategically, Brander and Spencer (1983) show that firms tend to overinvest in R&D activities to gain higher market shares despite total costs not being minimized for the output produced. In another paper, they develop a model which describes the role of government intervention – e.g. R&D or export subsidies - for two PM firms competing in imperfectly competitive international markets. Their model shows that the government has an incentive to tax R&D to eliminate the domestic firm's overuse of R&D (Spencer and Brander, 1983).

Despite classical economics assuming that typical firms aim at maximizing profits, the literature also acknowledges that some firms, instead of exclusively pursuing profits, strive to maximize income per labor and/or employment opportunities, also known as labor-managed firms (LMFs).[1] Historically, the dominant view has been that a LMF produces a smaller output than does a PMF (Ward, 1958; Domar, 1966 ; Vanek, 1970; Meade, 1972). However, recent studies show that LMFs could be as efficient and financially viable as PM firms, depending on management and market structures (Chen *et al.* 2016; Mikami 2018). In fact, LMFs present some advantages over the PMFs in some special contexts. For example, Monteiro and Stewart (2015) using data from Portugal show that high levels of market concentration and low entry costs are conducive to cooperatives which, on average, have more a productive labor force and higher probability of survival. There is also empirical evidence suggesting that cooperatives are to be preferred during economic downturns as membership in worker-owned firms provides more benefits than conventional employment (Monteleone & Reito 2017).

[1] There are differing ways to classify differences between PMFs (conventional firms) and LMFs (worker cooperatives). See Groot and van Der Linde (2017) for a more comprehensive review of these issues. The International Cooperative Alliance (ICA) defines cooperatives as being "people-centred enterprises owned, controlled and run by and for their members to realise their common economic, social, and cultural needs and aspirations" (https://www.ica.coop/en/cooperatives/what-is-a-cooperative). According to this definition, LMFs and cooperatives are quite similar.

It is noted that LM firms exist not only in socialist economies but also in capitalist economies. Surprisingly, EURICSE and COOP (2020) report that China has only one LM firm in the list of top global 300 cooperatives in terms of their turn-over with the majority of these top cooperates located in capitalist economies such as USA (85 cooperatives), France (38), Germany (30), Japan and Netherland (18). In a capitalist economy, LM firms exist in various forms such as cooperatives and stock cooperative enterprises and operate in different sectors including agriculture, insurance and retail. Globally, it is estimated that at least 12% of the global working population are members of around 3 million cooperatives (EURICSE & COOP 2020). Typically, in LM firms' individual workers hold property rights in their enterprise's assets through partnership deeds, individual capital accounts or hold a relatively high portion of shares.

In terms of the coexistence of LM firms and PM firms in the market, Mai and Hwang (1989) pioneered the investigation of the influence of government export subsidization or taxation on an LMF and a PMF operating in an international duopoly market. They find that an export tax rather than a subsidy should be adopted by the government of the LMF to assist the firm to expand its market share in a third country. Extending Mai and Hwang (1989), Okuguchi (1991) finds the same result based on an assumption that both firms produce differentiated goods. Lambertini and Rossini (1998) assess the effect of strategic R&D investments of a LMF and a PMF in a Cournot duopoly model. They show that a LMF always over-invests while a PMF always under-invests. Luo (2013) shows how R&D spillovers differently influence R&D investments of a LMF and a PMF in a duopoly market and which depend on the firm's absorptive capacity effect[2].

To our knowledge, there is a lack of literature which focuses on the role of government R&D subsidization in the context of competition between an LM and a PM firm in a mixed duopoly international market. A typical example observed recently is the intensive R&D subsidization programs for solar PV equipment manufacturing by differing countries in global competitive markets. Historically, China came late to PV production compared with other capitalist economies such as the US, Germany and Japan (Gang 2015). Those capitalist economies provided a range of subsidies, especially in R&D, to their domestic firms which mainly behave like PMFs. Similarly, Chinese governments at both central and local levels have subsidized R&D investment in state-owned and collective firms (Ball *et al.* 2017). Note that literature has reported that regardless differences in ownership, state-owned and collective

[2] Absorptive capacity refers to the degree to which a firm can benefit from other firms' R&D activities when it also enhances its innovative ability.

firms these behave like labor-managed firms (Xin & Frances 1998). Due to subsidies, the solar panel manufacturing capacity of China quadrupled between 2009 and 2011. These factual observations provide a best case for our theoretical investigation on how government subsidisation on R&D in a transition economy can help their LMFs to gain international competitive advantages over PMFs in capitalist countries. Specifically, we present a theory that explains the role of R&D rivalry between a LMF and a PMF in an imperfectly competitive market. In this setting, this paper also derives the optimal R&D subsidy or tax of each government under the assumption of maximizing domestic welfare being the government's objective.

Our model treats the governments and firms as players in a three-stage game. The government is assumed to be the first player which can commit itself to R&D subsidies before the firms make their R&D decisions. Following Brander and Spencer (1983), our model assumes that the firms have equal opportunity in setting their R&D levels. In the second stage of the game, the firms adopt R&D as a "commitment" or "credible threat" before output is produced. The cost-reducing R&D is viewed as a strategic investment that leads to greater market power in the international market due to lower marginal costs. This second stage R&D strategy is the result of a Nash equilibrium, which is made known to both firms. Following Dixit (1980), we assume the firms can correctly "see through" to the third-stage output levels as a result of a Nash equilibrium. The equilibrium is referred to as a "subgame perfect equilibrium" characterizing that the expectations of firms are confirmed in equilibrium.

Our theoretical model produces several findings which deliver important policy implications for government policies. While the governments of LMFs can expect their strategic R&D subsidising activities to increase LMFs market share in international competition dominated by PMFs, the attainment of such a desirable outcome depends not only on the R&D elasticity of their LMFS but also on the R&D reaction curve of rival PMFs. This means that the governments of the LMFs need to consider their decisions in a more complex manner. Nevertheless, our results highlight the possibility of using governmental R&D subsidies to support the sustained growth of LMFs. That is, this can be viewed as a positive development given the decreasing trend of R&D subsidies being observed over the last few decades around the world.

The main contribution of this paper to the literature in the area of LMF is extending the duopoly model of international trade between labor-managed and profit-maximizing firms by considering the impacts of R&D subsidy on the firms' R&D investments, labor employments, exports to a third country, and the optimal R&D subsidy of each government. First, previous studies have either focused on the effects of a change in *export* subsidy on international duopoly between a LMF and a PMF (Mai & Hwang 1989; Ohnishi 2008) or the effects of a change in R&D subsidy between two *PMFs* (Spencer & Brander 1983). We fill the gap of the literature by considering the role of *R&D* subsidy in the imperfectly competitive world where a *LMF* and a PMF coexist. The investigation of the effects of R&D subsidy on firms' behavior is important especially when direct export subsidy is restricted or violates trade rules. Second, our analysis focuses on LMF because LMF may allocate resources more efficiently than PMF (Groot & van Der Linde 2017) and there still exist some firms in Yugoslavia, America, England, France, Germany, China, and Italy, etc. (Luo 2013). Our analysis of LMF provides guidance to the government of LMF on how to make the best use of R&D subsidy to promote labor-managed firms to compete with traditional profit-maximizing firms in an international market. An understanding of government intervention is vital as a major difference between a LMF and a PMF is a higher demand reduces labor employment in the LMF and boosts employment in the PMF (Groot & van Der Linde 2017). Effective government intervention via R&D subsidy can prevent the disappearance of LMFs in a country. Lastly, the emphasis of our paper on R&D activities becomes more important nowadays as the world has been experiencing a substantial decline in research productivity during the last 40 years. Recent studies document empirical evidence that diminishing returns in idea production are a global phenomenon, including the global technology leader—the U.S. economy—as well as China and Germany (Bloom *et al.* 2020; Boeing & Hünermund 2020). Therefore, our paper offers governments some insights into the development of designing appropriate R&D subsidy policies to tackle the problem.

This paper proceeds as follows. Section 2 sets out the basic model. Section 3 analyses the implications of government R&D subsidies for LMFs and measures the optimal R&D subsidy. Section 4 investigates the impact of the PMF's government R&D subsidy and assess what is the optimal R&D policy. Section 5 discusses how the equilibrium will be affected by a change in the shape of the demand curve. Section 6 concludes the paper.

2. The Basic model

Consider a two-stage game played by two competing firms: a LMF and a PMF. Both firms compete in a duopoly market in a third country by exporting their products to this market. In the first stage, the firms choose R&D levels, and in the second stage, the labor inputs and output levels. We derive the equilibrium labor inputs and outputs by assuming R&D levels as given by the first stage. The second stage solution allows us to express the payoff function of each firm as a function the R&D levels chosen.

We begin by writing the objectives of the LMF and the PMF as

$$V(L,\hat{L}) = \frac{\pi}{L} = \frac{1}{L}[R\left(y(L),\hat{y}(\hat{L})\right) - C(y(L);X) - vX] \tag{1-1}$$

$$\hat{\pi}(L,\hat{L}) = \hat{R}\left(y(L),\hat{y}(\hat{L})\right) - \hat{C}(\hat{y}(\hat{L});\hat{X}) - \hat{v}\hat{X} \tag{1-2}$$

where symbols with a "^" (hat) denote the variables for the profit-maximization firm, and

$R = P(y, \hat{y})y$	total revenue function
$P(\cdot)$	demand inverse function in the market
$y = y(L)$	production function
$C = wL - U(x,y)$	variable cost (excluding R&D expenditure)
$U(\cdot)$	cost reduction effect of R&D
w	wage rate
L	labor input
y	product output
v	R&D cost per unit
x	R&D level

The model assumes these two firms produce identical goods and use the same type of labor from their domestic labor markets. The output of the two firms hence are substitutes: the output of one good decreases the marginal revenue of the other. Thus:

$$R_{\hat{y}} < 0;\ \ R_{y\hat{y}} < 0;\ \ \hat{R}_y < 0;\ \ \hat{R}_{\hat{y}y} < 0 \tag{2}$$

The variable cost C, reduces as a firm increases its R&D expenditure and the rate of decrease declines as R&D expenditure increases. Using subscripts to denote derivatives, this suggests

$$U_x > 0, \hat{U}_{\hat{x}} > 0;\ \ U_{xx} < 0, \hat{U}_{\hat{x}\hat{x}} < 0 \tag{3-1}$$

$$C_x < 0, \hat{C}_{\hat{x}} < 0;\ \ C_{xx} > 0, \hat{C}_{\hat{x}\hat{x}} > 0; \tag{3-2}$$

$$MC > 0, \widehat{MC} > 0;\ MC_x < 0, \widehat{MC}_{\hat{x}} < 0 \tag{3-3}$$

Note that MC > 0 implies $U_y < \frac{\partial(wL)}{\partial y} = \frac{w}{\frac{\partial y}{\partial L}} = \frac{w}{MP_L}$. An increase in R&D level reduces the marginal cost ($MC_x < 0$), implying $U_{yx} > 0$. The first-order conditions characterizing the Nash equilibrium in labor inputs are

$$V_L = \frac{1}{L}\left[\pi_L - \frac{\pi}{L}\right] = \frac{1}{L}[(P + P_y y)y_L - w + U_y y_L - \frac{\pi(L,\hat{L};x)}{L}] = 0 \tag{4-1}$$

$$\hat{\pi}_{\hat{L}} = (P + P_{\hat{y}}\hat{y})\hat{y}_{\hat{L}} - \hat{w} + \widehat{U}_{\hat{y}}\hat{y}_{\hat{L}} = 0 \tag{4-2}$$

These two equations are the labor reaction functions of LMF and PMF in implicit form, respectively, implying that a firm's labor employment is determined by both of its own and rival's R&D investments.[3]

The second-order conditions are

$$V_{LL} = \frac{1}{L}[y_L^2(2P_y + P_{yy}y + U_{yy}) + y_{LL}(P + P_y y + U_y)] < 0 \tag{5-1}$$

$$\hat{\pi}_{\hat{L}\hat{L}} = \hat{y}_{\hat{L}}^2(2P_{\hat{y}} + P_{\hat{y}\hat{y}}\hat{y} + \widehat{U}_{\hat{y}\hat{y}}) + \hat{y}_{\hat{L}\hat{L}}(P + P_{\hat{y}}\hat{y} + \widehat{U}_{\hat{y}}) < 0 \tag{5-2}$$

We assume the following set of inequalities which is sufficient for the global stability of the equilibrium

$$A = V_{LL}\hat{\pi}_{\hat{L}\hat{L}} - V_{L\hat{L}}\hat{\pi}_{\hat{L}L} > 0 \tag{6-1}$$

[3] In our theoretical framework, whether the wage of LMF workers differs from the wage for PMF workers can be examined based on the labor reaction functions of the firms. According to the reaction functions, we can derive each firm's wage rate as follows:

LMF: $w = (P + P_y y)y_L + U_y y_L - \frac{\pi(L,\hat{L};x)}{L}$

PMF: $\hat{w} = (P + P_{\hat{y}}\hat{y})\hat{y}_{\hat{L}} + \widehat{U}_{\hat{y}}\hat{y}_{\hat{L}}$

Assuming that the LMF and the PMF produce an identical good and adopt the same technology, in equilibrium, the wage for the LMF workers will be lower than the wage for the PMF workers by the amount of the profit distributed to each worker in the LMF, thus, the bonus equal to $\frac{\pi(L,\hat{L};x)}{L}$. However, taking into account the bonus, the total monetary payoff (i.e., wage plus bonus) each LMF's worker receives is identical to the wage for the PMF.

$$V_{L\hat{L}} = \frac{1}{L}\left(\pi_{L\hat{L}} - \frac{\pi_{\hat{L}}}{L}\right) < 0;\ \hat{\pi}_{\hat{L}L} = (P_y + P_{\hat{y}y}\hat{y})y_L\hat{y}_{\hat{L}} < 0 \tag{6-2}$$

For a given set of x and $\hat{x}$, the slopes of the reaction functions of labor inputs of the firms, respectively - derived from the total derivatives of (4-1) and (4-2) with respect to L and $\hat{L}$ - are

$$\frac{d\hat{L}}{dL}_{LMF} = -\frac{V_{LL}}{V_{L\hat{L}}} < 0 \tag{7-1}$$

$$\frac{d\hat{L}}{dL}_{PMF} = -\frac{\hat{\pi}_{\hat{L}L}}{\hat{\pi}_{\hat{L}\hat{L}}} < 0 \tag{7-2}$$

$$\left(\frac{d\hat{L}}{dL_{LMF}} - \frac{d\hat{L}}{dL_{PMF}}\right) < 0 \tag{7-3}$$

These equations indicate that both firms' reaction curves for labor inputs are downward sloping: however, the labor reaction curve of the LMF has a steeper slope than that of the PMF (See Appendix B). Combining the firms' production functions with the labor reaction curves, we can derive the output reaction curves for both firms. Similarly, the output reaction curve of the LMF is steeper than that of the PMF.

Under the theoretical model specified above, we are now ready to examine the effects of an increase in a firm's R&D expenditure on both firms' labor inputs and outputs.

2.1 The impact of LMF's R&D expenditure on labor inputs and outputs

We first consider the impact of an increase in the R&D expenditure of the LMF on labor inputs and outputs for both firms. Assuming the R&D expenditure of the PMF is fixed, taking the total derivatives of Eqs. (4-1) and (4-2) with respect to $L, \hat{L},$ and x gives

$$\begin{bmatrix} V_{LL} & V_{L\hat{L}} \\ \hat{\pi}_{\hat{L}L} & \hat{\pi}_{\hat{L}\hat{L}} \end{bmatrix} \begin{bmatrix} \frac{dL}{dx} \\ \frac{d\hat{L}}{dx} \end{bmatrix} = \begin{bmatrix} -V_{Lx} \\ 0 \end{bmatrix} \tag{8}$$

Holding the R&D expenditure of the PMF constant, Cramer's rule shows that the impacts of the LMF's R&D expenditure on the labor inputs of both firms are[4]

[4] See Appendix A for a more detailed discussion.

$$L_x \equiv \frac{\partial L}{\partial x} = -\frac{V_{Lx}\hat{\pi}_{\hat{L}\hat{L}}}{A} > 0;\ \hat{L}_x \equiv \frac{\partial \hat{L}}{\partial x} = \frac{V_{Lx}\hat{\pi}_{\hat{L}L}}{A} < 0 \tag{9}$$

where $A = V_{LL}\hat{\pi}_{\hat{L}\hat{L}} - V_{L\hat{L}}\hat{\pi}_{\hat{L}L}$. Eq. (9) suggests that an increase in the R&D expenditure of the LMF has a positive effect on its labor inputs while reduces its competitor's labor inputs. Consequently, the LMF gains a larger market share in the international market by hiring more labor to increase its output while the PMF loses its market share due to a decline in the output production.

2.2 The impact of PMF's R&D expenditure on inputs and outputs

To analyse the impact of changes in the R&D expenditure of the PMF on the labor inputs and outputs of both firms, we assume that the R&D expenditure of the LMF is fixed. Taking the total derivatives of Eqs. (4-1) and (4-2) with respect to $L, \hat{L},$ and $\hat{x}$ leads to

$$\hat{L}_{\hat{x}} \equiv \frac{\partial \hat{L}}{\partial \hat{x}} = -\frac{V_{LL}\hat{\pi}_{\hat{L}\hat{x}}}{A} > 0;\ L_{\hat{x}} \equiv \frac{\partial L}{\partial \hat{x}} = \frac{V_{L\hat{L}}\hat{\pi}_{\hat{L}\hat{x}}}{A} < 0 \tag{10}$$

Eq. (10) shows that when the PMF increases its R&D expenditure, its labor inputs and outputs both, increase. However, it causes reductions in its rival's labor inputs and outputs. The results clearly indicate that, in a duopoly market, an increase in R&D expenditure helps a firm to increase its own labor employment and market share while it has an adverse impact on its competitor's labor employment and market share.

2.3 The determination of R&D expenditures

Our analysis so far has focused on the second-stage Nash equilibrium in labor inputs and outputs under the assumption that the firms' R&D levels are resolved in the first-stage Nash game and made known to each other. We now turn our analysis to how firms determine their own R&D levels.

Eqs. (9) and (10) show that the labor inputs of both firms are influenced by the R&D levels of the firms. Hence, the profit functions described in Eqs. (1-1) and (1-2) can be expressed in the following forms

$$g \equiv V\big(L(x,\hat{x}), \hat{L}(x,\hat{x}); x\big) \tag{11-1}$$

$$\hat{g} \equiv \hat{\pi}\big(L(x,\hat{x}), \hat{L}(x,\hat{x}); \hat{x}\big) \tag{11-2}$$

The first-stage Nash equilibrium in R&D expenditure of the LMF must satisfy

$$g_x = V_L L_x + V_{\hat{L}} \hat{L}_x - \frac{C_x}{L} - \frac{v}{L}$$

Accordingly, Eq. (4-1), this can be expressed as

$$g_x = V_{\hat{L}} \hat{L}_x - \frac{C_x}{L} - \frac{v}{L} = \frac{R_{\hat{L}}}{L} \hat{L}_x - \frac{C_x}{L} - \frac{v}{L} = 0$$

Hence,

$$\frac{R_{\hat{L}}}{L} \hat{L}_x - \frac{C_x}{L} = \frac{v}{L} \tag{12-1}$$

Similarly, the optimal R&D expenditure of the PMF must satisfy

$$\hat{R}_L L_{\hat{x}} - \hat{C}_x = \hat{v} \tag{12-2}$$

The left-hand side of Eqs. (12-1) and (12-2), respectively, is the marginal profit of a firm's R&D expenditure while the right-hand side shows its marginal cost. The results suggest that, if a firm *uses R&D strategically*[5], the optimal R&D expenditure can be determined only when it makes marginal profit equal to marginal cost. The second-order conditions are $g_{xx} < 0$ and $\hat{g}_{\hat{x}\hat{x}} < 0$. We also assume that the own effect of R&D on marginal profit exceeds the cross effect which can be represented as

$$D = g_{xx} \hat{g}_{\hat{x}\hat{x}} - g_{x\hat{x}} \hat{g}_{\hat{x}x} > 0 \tag{12-3}$$

3. Analysis of LMF's government R&D subsidy policy

The previous section does not incorporate the role of government into the model. This section explores the effect of the government R&D subsidy of LMFs on a firms' R&D expenditure, labor inputs, and outputs. We also examine the government's optimal R&D subsidy policy. Our analysis assumes that the government's R&D subsidy directly influences the R&D expenditures of the firms while its impact on labor inputs and outputs are indirectly affected through the R&D-labor inputs and labor inputs-outputs channels.

3.1 Impact of government R&D subsidies on *LMFs*

[5] We also consider a scenario in which firms adopt R&D for cost reduction. Our result shows that firms invest more in R&D activities when they use it strategically compared to when R&D plays no strategic role. Proofs are available upon request.

When only the LMF receives an R&D subsidy from its government, the firms' profit functions become

$$g(x,\hat{x};s) = \frac{1}{L}[R\left(y(L),\hat{y}(\hat{L})\right) - C(y(L);x) - (v-s)x]$$

$$\hat{g}(x,\hat{x}) = \hat{R}\left(y(L),\hat{y}(\hat{L})\right) - \hat{C}(\hat{y}(\hat{L});\hat{x}) - \hat{v}\hat{x} \tag{13}$$

where $L = L(x,\hat{x}), \hat{L} = \hat{L}(x,\hat{x})$, and s denotes the government subsidy for each unit of the R&D investment of the LMF. The first-order condition for the maximization of Eq. (13) is

$$g_x(x,\hat{x};s) = \frac{L\pi_x - \pi L_x}{L^2} = \frac{1}{L}\left(\pi_x - \frac{\pi}{L}L_x\right) = 0$$

$$\hat{g}_{\hat{x}}(x,\hat{x}) = 0 \tag{14}$$

where $\pi = R\left(y(L),\hat{y}(\hat{L})\right) - C(y(L);x) - (v-s)x$. The total differentiation of Eq. (14) yields

$$g_{xx}dx + g_{x\hat{x}}d\hat{x} + g_{xs}ds = 0$$

$$\hat{g}_{\hat{x}x}dx + \hat{g}_{\hat{x}\hat{x}}d\hat{x} = 0$$

where $g_{xs} = \frac{1}{L}\left(1 - \frac{L_x}{L}x\right) = \frac{1}{L}(1-\eta)$. η measures the sensitivity of labor input to changes of R&D level (i.e., the R&D elasticity) for the LMF. The sign of g_{xs} relies on the value of η relative to 1. Expressing the total differential above in matrix form and applying Cramer's rule show

$$x_s \equiv \frac{dx}{ds} = \frac{-\hat{g}_{\hat{x}\hat{x}}g_{xs}}{g_{xx}\hat{g}_{\hat{x}\hat{x}} - g_{x\hat{x}}\hat{g}_{\hat{x}x}} = \frac{-\hat{g}_{\hat{x}\hat{x}}g_{xs}}{D}$$

$$\hat{x}_s \equiv \frac{d\hat{x}}{ds} = \frac{\hat{g}_{\hat{x}x}g_{xs}}{g_{xx}\hat{g}_{\hat{x}\hat{x}} - g_{x\hat{x}}\hat{g}_{\hat{x}x}} = \frac{\hat{g}_{\hat{x}x}g_{xs}}{D} \tag{15}$$

As discussed in the previous section, since $D > 0$ and $\hat{g}_{\hat{x}\hat{x}} < 0$, the impact of the government's R&D subsidy on the R&D investment of the LMF depends on whether the sign of $g_{xs}(= \frac{1}{L}(1-\eta))$. This suggests that the LMF would increase its R&D expenditure if the sensitivity of labor employment to changes of R&D level is less than 1 (i.e., $\eta < 1$) while its investment in R&D reduces when the R&D elasticity is greater than 1.

In contrast, the impact of the LMF's government R&D subsidy on its rival's R&D investment is more complicated because it involves the relationship of the slopes of the reaction curves of both firms. The slopes of the reaction curves of the firms can be derived from the total differential of Eq. (14). Rearranging the results, we obtain their slopes as

$$LMF\colon \frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}}$$

$$PMF\colon \frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} \tag{16}$$

The second-order conditions state that both g_{xx} and $\hat{g}_{\hat{x}\hat{x}}$ are negative. Consequently, the relationship between the slopes of these two firms can be established based on the signs of $g_{x\hat{x}}$ and $\hat{g}_{\hat{x}x}$. One thing that is worth noting is that the LMF's R&D reaction curve moves to the right as the LMF's government R&D subsidy increases if $\eta < 1$ (i.e., $g_{xs} > 0$) while it moves to the left if $\eta > 1$ (i.e., $g_{xs} < 0$) (See Appendix C). The following shows the cases according to the various relationships between the R&D reaction curves of both firms.

Case I: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} > 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} < 0$ if $g_{x\hat{x}} > 0$ and $\hat{g}_{\hat{x}x} < 0$.

For $\eta < 1$, the signs of x_s and $\hat{x}_s$ in Eq. (15) are

$$x_s \equiv \frac{dx}{ds} = \frac{-\hat{g}_{\hat{x}\hat{x}} g_{xs}}{D} > 0$$

$$\hat{x}_s \equiv \frac{d\hat{x}}{ds} = \frac{\hat{g}_{\hat{x}x} g_{xs}}{D} < 0$$

The result that the LMF's R&D investment increases while its rival's R&D investment decreases as the government of the LMF increases its R&D subsidy can be depicted in Figure 1. When η<1, Figure 1 shows that an increase in the government R&D subsidy of the LMF shifts LMF's R&D reaction curve to the right. Consequently, it increases the R&D investment of the LMF but decreases its rival's R&D investment.

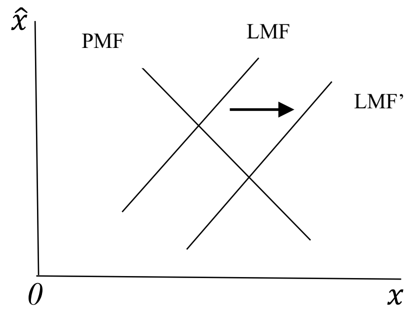

Figure 1: Shifts in LMF reaction curve due to LMF's government R&D subsidy

Case II: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} < 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} < 0$[6] if $g_{x\hat{x}} < 0$ and $\hat{g}_{\hat{x}x} < 0$.

For $\eta < 1$, $x_s \equiv \frac{dx}{ds} = \frac{-\hat{g}_{\hat{x}\hat{x}} g_{xs}}{D} > 0$ and $\hat{x}_s \equiv \frac{d\hat{x}}{ds} = \frac{\hat{g}_{\hat{x}x} g_{xs}}{D} < 0$

The graph of the reaction curves for both firms also confirms the results that the LMF's R&D investment increases but the R&D investment of its rival decreases as the government R&D subsidy of the LMF increases.[7]

Case III: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} > 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} > 0$ if $g_{x\hat{x}} > 0$ and $\hat{g}_{\hat{x}x} > 0$.

For $\eta < 1$, $x_s \equiv \frac{dx}{ds} = \frac{-\hat{g}_{\hat{x}\hat{x}} g_{xs}}{D} > 0$ and $\hat{x}_s \equiv \frac{d\hat{x}}{ds} = \frac{\hat{g}_{\hat{x}x} g_{xs}}{D} > 0$

In this case, both R&D reaction curves have positive slopes but the reaction curve of the LMF is steeper. When the government of the LMF increases its R&D subsidy, it causes both firms to increase their R&D investments.

Case IV: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} < 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} > 0$ if $g_{x\hat{x}} < 0$ and $\hat{g}_{\hat{x}x} > 0$.

For $\eta < 1$, $x_s \equiv \frac{dx}{ds} = \frac{-\hat{g}_{\hat{x}\hat{x}} g_{xs}}{D} > 0$ and $\hat{x}_s \equiv \frac{d\hat{x}}{ds} = \frac{\hat{g}_{\hat{x}x} g_{xs}}{D} > 0$

The corresponding R&D reaction curve of the LMF is negative while the R&D reaction curve of the PMF is positive. As in case III, an increase in the LMF's government R&D subsidy creates a positive impact on the R&D investments of both firms.

[6] Similar to the labor reaction curves, the R&D reaction curve of the LMF is steeper than that of the PMF.
[7] To save space, we do not depict the figure here.

Overall, the analysis above shows that when $\eta < 1$ ($\eta > 1$), an increase in the government R&D subsidy of the LMF always leads to increases (decreases) in the R&D expenses for the LMF. However, its impact on the R&D expenses of the PMF is conditional on the slope of PMF's R&D reaction curve. Combining Eqs. (15) and (16) shows that there exists a special relation between x_s and $\hat{x}_s$ as

$$\hat{x}_s = -x_s \frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} = x_s \times (Slope\ of\ PMF's\ R\&D\ reaction\ curve) \tag{17}$$

Eq. (17) provides a detailed explanation about how increases in the government R&D subsidy for the LMF influence the R&D investment of the PMF. Specifically, the magnitude of the impact is determined by two components. The first component is the degree to which the LMF's R&D investment responds to its government's R&D subsidy policy (x_s). A stronger response leads to a greater impact on the R&D investment of the PMF. The second component is the sign of the slope of the R&D reaction curve of the PMF. An upward-sloping (or downward-sloping) reaction curve implies that the PMF would increase (decrease) its R&D investment.

3.2 Optimal LMF's government R&D subsidy

Our analysis shows that the LMF's government R&D subsidy has various impacts on the R&D investment decisions of both firms. The next question that is natural to ask is "What is the optimal level of government R&D subsidization of the LMF?"

To answer this question, we assume that the objective of the government is to maximize the social welfare of its own country when determining the optimal government R&D policy. We define the social welfare measure as the firm's profit in excess of the total R&D subsidy:

$$W(s) = \pi(x, \hat{x}; s) - sx \tag{18}$$

where $\pi = R(y, \hat{y}) - C(y; x) - (v - s)x$. Differentiating Eq. (18) with respect to s shows

$$\frac{dW}{ds} = (\pi_x - s)x_s + \pi_{\hat{x}}\hat{x}_s$$

According to Eqs. (14) and (17), the first-order condition can be expressed as

$$\frac{dW}{ds} = \left[\frac{WL_x}{L} + (\frac{xL_x}{L} - 1)s + \pi_{\hat{x}} \frac{d\hat{x}}{dx_{PMF}}\right] x_s = 0$$

Hence, the optimal LMF's government R&D subsidy is

$$s = \frac{1}{1-\eta}\left(\frac{WL_x}{L} + \pi_{\hat{x}} \frac{d\hat{x}}{dx_{PMF}}\right) \tag{19}$$

where $\eta = \frac{L_x}{L} x > 0$ and $\pi_{\hat{x}} < 0$ (See Appendix D).

According to Eq. (19), we present the optimal R&D subsidy or tax policy of LMF's government in Table 1.

Table 1: Optimal R&D Policy of LMF Government

LMF's R&D Elasticity	Tax	Subsidy
$\eta < 1$	$\frac{d\hat{x}}{dx_{PMF}} \leq -\frac{WL_x}{L\pi_{\hat{x}}}$	$-\frac{WL_x}{L\pi_{\hat{x}}} \leq \frac{d\hat{x}}{dx_{PMF}}$
$\eta > 1$	$-\frac{WL_x}{L\pi_{\hat{x}}} \leq \frac{d\hat{x}}{dx_{PMF}}$	$\frac{d\hat{x}}{dx_{PMF}} \leq -\frac{WL_x}{L\pi_{\hat{x}}}$

To maximize its social welfare, Table 1 shows that the government of the LMF can either tax or subsidize the firm's R&D investment, depending on whether the response of the firm's R&D investment to the government's subsidy is elastic or inelastic[8], and the slope of the PMF's R&D reaction curve. Interestingly, our results regarding the government's optimal R&D subsidy policy is different from that of Brander and Spencer (1983) who suggest that it is desirable for the government to subsidize its own firm when both firms are PMFs competing in a duopoly international market. In contrast, in the context of a LMF and a PMF competing in an international market, our model show that it is only socially optimal for the LMF's government to subsidize their firm's R&D expenditure in the case that the PMF is highly responsive to the level of R&D of the LMF and its government's subsidy. Therefore, the slope of the PMF's R&D reaction curve is greater than the turning point (i.e. $-\frac{WL_x}{L\pi_{\hat{x}}}$) in the case of $\eta < 1$. If the slope of PMF's R&D reaction curve is smaller than the turning point, the subsidy policy is not justified from the viewpoint of maximising social welfare. If $\eta > 1$, a subsidy policy is recommended as long as the slope of PMF's R&D reaction curve is smaller than the turning point.

On the other hand, taxing LMF's R&D activities may be considered if the PMF's reaction is not responsive and LMF's employment and market share are highly and positively responsive to its R&D activities. This sounds reasonable as there is no reason why an LMF's government should promote further R&D given its firms are performing well on their own. This is particularly clear in the case of $\eta < 1$. However, when $\eta > 1$, the decision to tax its

[8] When η=1, LMF's government R&D subsidy policy has no impact on the R&D investments of both firms because $g_{xs} = 0$.

firm for the LMF's government gets more complicated given uncertainty over the net responsiveness of PMFs' with respect to both taxation policy and changes in the R&D level of the LMF.

4. Analysis of PMFs' government R&D subsidy policy

In this section, we turn our analysis to the implications of government R&D subsidies for the PMF.

4.1 Impact of government R&D subsidies for PMFs

When the PMF's government subsidizes the R&D activities of its firm, the profit functions of both firms become

$$g(x,\hat{x}) = \frac{1}{L}[R\left(y(L),\hat{y}(\hat{L})\right) - C(y(L);x) - vx]$$

$$\hat{g}(x,\hat{x};\hat{s}) = \hat{R}\left(y(L),\hat{y}(\hat{L})\right) - \hat{C}(\hat{y}(\hat{L});\hat{x}) - (\hat{v}-\hat{s})\hat{x} \tag{20}$$

where $\hat{s}$ denotes the PMF's government R&D subsidy. Following the analysis described in Section 3.1 for the LMF, we obtain the impact of such a subsidy on both firms as

$$x_{\hat{s}} = \frac{g_{x\hat{x}}}{D}$$

$$\hat{x}_{\hat{s}} = -\frac{g_{xx}}{D} \tag{21}$$

From the second-order condition ($g_{xx} < 0$) and $D > 0$, Eq. (21) suggests that an increase in the PMF's government R&D subsidy has a positive impact on the PMF's R&D investment ($\hat{x}_{\hat{s}} > 0$). However, its impact on the R&D investment of its competitor is determined by $g_{x\hat{x}}$. Since the slopes of the R&D reaction curves of these firms are also associated with $g_{x\hat{x}}$ and $\hat{g}_{\hat{x}x}$, we examine the impacts of the PMF's R&D subsidy on both firms based on the relationship of $g_{x\hat{x}}$ and $\hat{g}_{\hat{x}x}$ below.

Case I: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} > 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} < 0$ if $g_{x\hat{x}} > 0$ and $\hat{g}_{\hat{x}x} < 0$.

In this case, the R&D reaction curve of the LMF is upward-sloping while the slope for the PMF is downward-sloping. An increase in the R&D subsidy for the PMF shifts its reaction curve to the right (See Appendix E). The mathematical expressions below are consistent with the graphical results.[9]

$$x_{\hat{s}} = \frac{g_{x\hat{x}}}{D} > 0$$

$$\hat{x}_{\hat{s}} = -\frac{g_{xx}}{D} > 0$$

Case II: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} < 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} < 0$ if $g_{x\hat{x}} < 0$ and $\hat{g}_{\hat{x}x} < 0$.

The R&D reaction curves of both firms are downward sloping the steeper one being for the LMF. When the PMF's government increases its R&D subsidy for the PMF, it encourages the firm to invest more in its R&D activities but discourages its rival's R&D investment. Thus, $x_{\hat{s}} < 0$ and $\hat{x}_{\hat{s}} > 0$.

Case III: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} > 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} > 0$ if $g_{x\hat{x}} > 0$ and $\hat{g}_{\hat{x}x} > 0$.

The slopes of the R&D reaction curves of the firms are both positive, and the LMF has a steeper curve than does the PMF. In this case, both firms would increase their R&D investments in response to an increase in the R&D subsidy for PMF. Thus, both $x_{\hat{s}}$ and $\hat{x}_{\hat{s}}$ are positive.

Case IV: LMF: $\frac{d\hat{x}}{dx} = -\frac{g_{xx}}{g_{x\hat{x}}} < 0$ and PMF: $\frac{d\hat{x}}{dx} = -\frac{\hat{g}_{\hat{x}x}}{\hat{g}_{\hat{x}\hat{x}}} > 0$ if $g_{x\hat{x}} < 0$ and $\hat{g}_{\hat{x}x} > 0$.

As in Case III, the R&D reaction curve of the PMF is upward sloping. An increase in the government R&D subsidy for the PMF causes the firm's reaction curve to shift to the left. Together with a downward-sloping reaction curve of the LMF, the left shift of the PMF's reaction curve due to the R&D subsidy leads to a result identical to the one in Case II (i.e., $x_{\hat{s}} < 0$ and $\hat{x}_{\hat{s}} > 0$).

Our analysis of the government R&D subsidy for the PMF shows that the subsidy always increases the R&D investment of the PMF. In contrast, the impact on its rival's R&D expenditure is conditional on the slope of LMF's R&D reaction curve – a higher (lower) level of R&D investment for the LMF for an upward-sloping (a downward-sloping) reaction curve.

4.2 Optimal PMFs' government R&D subsidy

[9] We do not present the figure to save space; however, the graphical analysis is similar to Figure 1 except for the shift is for PMF's reaction curve in this case.

To determine the optimal R&D subsidy policy for its firm, we again assume that the PMF's government pursues to maximize its social welfare measure. This can be represented as

$$\widehat{W}(\hat{s}) = \hat{g}(x, \hat{x}; \hat{s}) - \hat{s}\hat{x} = \hat{\pi}(x, \hat{x}; \hat{s}) - \hat{s}\hat{x} \tag{22}$$

The differentiation of Eq. (22) with respect to $\hat{s}$ yields

$$\frac{d\widehat{W}}{d\hat{s}} = \hat{\pi}_x x_{\hat{s}} - \hat{s}\hat{x}_{\hat{s}}$$

According to Eq. (21), $x_{\hat{s}} = \frac{g_{x\hat{x}}}{D} = -\frac{g_{xx}}{D}\left(-\frac{g_{x\hat{x}}}{g_{xx}}\right) = \hat{x}_{\hat{s}} \frac{dx}{d\hat{x}_{LMF}}$, the first-order condition can be expressed as

$$\frac{d\widehat{W}}{d\hat{s}} = (\hat{\pi}_x \frac{dx}{d\hat{x}_{LMF}} - \hat{s})\hat{x}_{\hat{s}} = 0$$

Hence, the optimal PMF's government R&D subsidy is

$$\hat{s} = \hat{\pi}_x \frac{dx}{d\hat{x}_{LMF}} \tag{23}$$

Since $\hat{\pi}_x$ is negative (See Appendix F), the sign of the R&D reaction curve of the LMF plays a critical role in determining whether $\hat{s}$ is positive or negative. Specifically, the government of the PMF should subsidize its firm's investment in R&D activities if the R&D reaction curve of LMF is downward-sloping while it should tax its firm's R&D investment when the reaction curve of the LMF is upward-sloping.

Unlike the determination of the optimal R&D subsidy policy for the government of the LMF, which needs to consider both its rival's R&D reaction curve and the elasticity of the LMF's R&D response to the subsidy, the PMF's government needs to consider the slope of the reaction curve of its rival only to determine whether to subsidize or tax its firm. LMFs tend to over-invest in R&D so governments of LMFs tax them to maximize the social welfare.

5. The role of the shape of the demand function

The shape of the demand curve, whether the curve is convex, concave, or linear, often plays a vital role in the analysis of Cournot competition.[10] In this section, we discuss the role it plays in our model. We start with our discussion about its impact on the LMF by showing that the shape of the demand curve will affect the slope of the firm's labor reaction curve. Combining Eqs. (5-1) and (7-1), the slope of LMF's labor reaction curve can be expressed as:

[10] We thank the reviewer for raising this issue.

$$\frac{d\hat{L}}{dL_{LMF}} = -\frac{V_{LL}}{V_{L\hat{L}}} = -\frac{y_L^2(2P_y + P_{yy}y + U_{yy}) + y_{LL}(P + P_y y + U_y)}{LV_{L\hat{L}}} < 0 \tag{24}$$

Note that the slope is negative because both V_{LL} and $V_{L\hat{L}}$ are negative. When the demand curve is convex (concave/linear), the second-order derivative of the price inverse function with respect to the product output, P_{yy}, is positive (negative/zero). A positive (negative) P_{yy} makes V_{LL} less (more) negative. Therefore, the labor reaction curve derived based on a convex demand curve is flatter than the one derived based on a linear demand curve. The labor reaction curve is steeper when the demand curve is concave.

We now consider the impact of the shape of the demand curve on the PMF. Combining Eqs. (5-2) and (7-2), the slope of the firm's labor reaction curve can be expressed as:

$$\frac{d\hat{L}}{dL_{PMF}} = -\frac{\hat{\pi}_{\hat{L}L}}{\hat{\pi}_{\hat{L}\hat{L}}} = \frac{\hat{\pi}_{\hat{L}L}}{\hat{y}_{\hat{L}}^2(2P_{\hat{y}} + P_{\hat{y}\hat{y}}\hat{y} + \hat{U}_{\hat{y}\hat{y}}) + \hat{y}_{\hat{L}\hat{L}}(P + P_{\hat{y}}\hat{y} + \hat{U}_{\hat{y}})} < 0 \tag{25}$$

The slope is negative because both $\hat{\pi}_{\hat{L}L}$ and $\hat{\pi}_{\hat{L}\hat{L}}$ are negative. Eq. (25) shows that the shape of the demand curve, $P_{\hat{y}\hat{y}}$, can affect the slope of the firm's labor reaction curve. Compared to the labor reaction curve derived when the demand function is linear ($P_{\hat{y}\hat{y}} = 0$), the corresponding labor reaction curve is steeper when the demand function is convex ($P_{\hat{y}\hat{y}} > 0$) and flatter when the demand function is concave $\left(P_{\hat{y}\hat{y}} < 0\right)$.

Our analysis so far has shown that the shape of the demand function can change the slopes of the labor reaction curves of the firms. Will the shape of the demand curve affect the labor employments of the firms in equilibrium? The answer is no because the equilibrium labor employments are determined by the firms' reaction functions as formulated in Eqs (4-1) and (4-2). A closer look at the two equations reveals that neither P_{yy} nor $P_{\hat{y}\hat{y}}$ plays any role in the solution to the equation system, suggesting the shape of the demand curve has no impact on the firms' labor employments and, hence, market shares in equilibrium.

Similarly, we can investigate the influence of the shape of the demand curve on the findings discussed in the remaining sections of our paper. For example, to explore whether the shape of the demand curve may change the impacts of the LMF's R&D expenditure on the labor employments of both firms, we can examine the role of P_{yy} and/or $P_{\hat{y}\hat{y}}$ in Eq. (9). It is not difficult to see that changing the shape of the demand curve does not change the *direction* of the impacts of the LMF's R&D expenditure on the labor inputs of both firms. The magnitudes of the impacts on labor employments may slightly differ for different shapes of the demand curve, the results will be qualitatively the same regardless of the shape of the demand curve assumed in the model.

6. Conclusions

Using a simple three-stage Nash duopoly model, this paper examines the effect of R&D rivalry between a labor managed firm and a profit maximising firm in an international market and the optimal level of government R&D subsidization. Our model yields three important results.

Firstly, when a firm adopts R&D as a strategic investment, the strategic R&D expenditure is higher than the R&D expenditure that minimizes total costs. When a firm increases such R&D investment, it increases its own market share in an international market due to the positive impact of R&D on labor inputs; however, such a strategy reduces its rival's labor employment as well as market share.

Secondly, we find that the influence of the LMF's government R&D subsidy on R&D expenditure, labor input, and output of the LMF depends on the firm's R&D elasticity. The R&D subsidy impact on its rival's R&D investment also relies on the slope of its rival's R&D reaction curve. The R&D elasticity of the LMF and the slope of the R&D reaction curve of the PMF both play a critical role in determining whether the government of the LMF should subsidize or tax its firm's R&D investment.

Thirdly, for the PMF, there is a positive relationship between the R&D subsidy received from its government and its R&D expenditure, labor input, and output. In contrast, whether such an R&D subsidy increases the relevant variables of its rival depends on the slope of the R&D reaction curve of the PMF. Compared to its counterpart, there is a less sophisticated procedure for the government of PMFs government in determining its optimal R&D subsidy/tax policy. The only factor that affects the PMF's government policy is the slope of its competitor's R&D reaction curve.

We should emphasize that our analysis in the present paper does not imply in any sense a recommendation that R&D subsidisation policies be implemented. As stated in Spencer and Brander (1983), any policy advocating subsidies should be viewed with suspicion due to the uncertainty in the possibility that welfare gains are greater than opportunity costs of subsidies. In addition, governmental subsidies are also likely to trigger tensions between governments as observed in the case of solar PV manufacturing reported in Ball *et al.* (2017). It is also noted that trade tensions often harm firms and consumers not only in countries directly involved in the rivalry but also in other countries. However, where there are opportunities that do not impose any crowding out effects, then R&D subsidies could well be beneficial. For example, start-up technologies with clear potential benefits to society which would otherwise have struggled to establish. A pertinent example is that of the widely recognised dynamic ride sharing systems (DRS) which has the potential to bring about fundamental changes to vehicular transport which in particular could provide more cost-effective and convenient individualised forms of transport (Gecchelin and Webb, 2019). Such subsidies in the past have also helped certain industries to catch-up, for example, in the case of China entering PV production (Gang, 2015). As Groot and van der Linde (2017) point out such subsidies need not be permanent, but prevail only to provide start-up support and to help gain a strong footing.

Appendix A

Eq. (9) shows A, $\hat{\pi}_{\hat{L}\hat{L}}$, $\hat{\pi}_{\hat{L}L}$, and V_{Lx} all jointly determine the direction of the impact of the LMF R&D expenditures on the labor inputs for firms. We show that the sign of V_{Lx} is positive. According to Eq. (4-1), V_L can also be expressed as

$$V_L = \frac{1}{L}[(P + P_y y)y_L - w + U_y y_L - \frac{1}{L}(R - C - vx)]$$

Hence,

$$V_{Lx} \equiv \frac{\partial V_L}{\partial x} = \frac{1}{L}(U_{yx} y_L + \frac{1}{L}(C_x + v)]$$

$U_{yx} > 0$ (as discussed earlier), if $(C_x + v) > 0$ then $V_{Lx} > 0$.

Appendix B

Eq. (7-3) implies that the LMF's labor reaction curve is steeper than the PMF's labor reaction curve. Below is our proof of Eq. (7-3):

$$\frac{d\hat{L}}{dL_{LMF}} - \frac{d\hat{L}}{dL_{PMF}}$$

$$= -\frac{V_{LL}}{V_{L\hat{L}}} - \left(-\frac{\hat{\pi}_{\hat{L}L}}{\hat{\pi}_{\hat{L}\hat{L}}}\right)$$

$$= -\frac{(V_{LL}\hat{\pi}_{\hat{L}\hat{L}} - V_{L\hat{L}}\hat{\pi}_{\hat{L}L})}{V_{L\hat{L}}\hat{\pi}_{\hat{L}\hat{L}}}$$

The sign of the result can be determined based on Eqs (6-1), (6-2), and (5-2). In particular, Eq. (6-1) shows that $(V_{LL}\hat{\pi}_{\hat{L}\hat{L}} - V_{L\hat{L}}\hat{\pi}_{\hat{L}L})$ is positive; Eq. (6-2) shows that $V_{L\hat{L}}$ is negative; and Eq. (5-2) shows that $\hat{\pi}_{\hat{L}\hat{L}}$ is negative. Therefore, the overall result is negative. Since both reaction curves are down-ward sloping, this suggests that the reaction curve of LMF is steeper than that of PMF.

Appendix C

Regardless of the signs of the slops of the R&D reaction curves of the firms, the stability condition $D > 0$ implies a greater absolute value of the slope of LMF's R&D reaction curve than that of PMF's R&D reaction curve. This suggests that LMF's R&D reaction curve is steeper than PMF's R&D reaction curve.

Taking the total differential of $g_x(x, \hat{x}; s)$ in Eq. (14) with respect to $x, \hat{x}$ and s, because $g_{xx} < 0$, we show that when $g_{xs} = -g_{xx}\frac{dx}{ds} - g_{x\hat{x}}\frac{d\hat{x}}{ds} > 0$ it suggests that LMF's R&D reaction curve always moves to the right regardless of whether $g_{x\hat{x}}$ is positive or negative.

When $g_{x\hat{x}} < 0$ ($g_{x\hat{x}} > 0$), this implies LMF's R&D reaction curve is downward-sloping (upward-sloping). Given that $g_{xs} > 0$, it means $\frac{dx}{ds} > 0$ and $\frac{d\hat{x}}{ds} > 0$ ($\frac{d\hat{x}}{ds} < 0$). Graphically, these results imply that an increase in LMF's government R&D subsidy shifts LMF's R&D reaction curve to the right.

Appendix D

Differentiating π with respect to $\hat{x}$ shows

$$\pi_{\hat{x}} = (R_y - C_y)y_L L_{\hat{x}} + R_{\hat{y}}\hat{y}_{\hat{L}}\hat{L}_{\hat{x}}$$

$$= \left(\frac{\pi_L}{y_L}\right) y_L L_{\hat{x}} + R_{\hat{y}}\hat{y}_{\hat{L}}\hat{L}_{\hat{x}}$$

Eq. (4-1) suggests $\pi_L = \frac{\pi}{L}$, hence

$$\pi_{\hat{x}} = \left(\frac{\pi}{L}\right) L_{\hat{x}} + R_{\hat{y}}\hat{y}_{\hat{L}}\hat{L}_{\hat{x}} < 0.$$

Appendix E

The first-order condition of the profit function of PMF is $\hat{g}(x, \hat{x}; \hat{s}) = \hat{\pi}_{\hat{x}} = 0$. Taking the total differential of it and rearrange the terms shows

$$\hat{g}_{\hat{x}\hat{s}} = -\hat{g}_{\hat{x}x}x_{\hat{s}} - \hat{g}_{\hat{x}\hat{x}}\hat{x}_{\hat{s}} > 0$$

When $\hat{g}_{\hat{x}x} < 0$, this implies PMF's R&D reaction curve is downward-sloping. The above condition holds (i.e., $\hat{g}_{\hat{x}\hat{s}} > 0$) only if both $x_{\hat{s}}$ and $\hat{x}_{\hat{s}}$ are positive, which suggests that PMF's reaction curve moves to the right as its government increases R&D subsidy.

If $\hat{g}_{\hat{x}x} > 0$, an upward-sloping R&D reaction curve for PMF shifts to the left when its government increases R&D subsidy, which is consistent with the requirement that $x_{\hat{s}} < 0$ and $\hat{x}_{\hat{s}} > 0$.

Appendix F

Eq. (20) shows the profit function of PMF as

$$\hat{g}(x,\hat{x};\hat{s}) = \hat{\pi} = \hat{R}\left(y(L),\hat{y}(\hat{L})\right) - \hat{C}\left(\hat{y}(\hat{L});\hat{x}\right) - (\hat{v}-\hat{s})\hat{x}$$

$$\hat{\pi}_x = \hat{R}_y y_L L_x + (\hat{R}_{\hat{y}} - \hat{C}_{\hat{y}})\hat{y}_{\hat{L}}\hat{L}_x$$

According to Eq. (4-2), it can be derived that $\hat{\pi}_{\hat{L}} = \left(\hat{R}_{\hat{y}} - \hat{C}_{\hat{y}}\right)\hat{y}_{\hat{L}} = 0$.

Hence, $\hat{\pi}_x = \hat{R}_y y_L L_x < 0$.

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