R&D in the Network of International Trade: Multilateral versus Regional Trade Agreements

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Abstract

Recent empirical evidence has shown that trade liberalization promotes productivity growth at individual firms. This paper argues that different types of trade liberalization – multilateral versus regional – may lead to different productivity and productivity growth rates at the firm's level. Trade agreements between countries are modelled by a network: nodes stand for countries and every link indicates trade agreement between the linked countries. In this framework, the multilateral trade agreement is represented by the *complete* network while the overlap of regional trade agreements is represented by the *hub-and-spoke* trade system. Trade liberalization, which increases the network of trade agreements, reinforces incentives for firms to invest in costly productivity-enhancing activity, such as R&D, through the creation of new markets (scale effect) but it also dampens these incentives through the emergence of new competitors (competition effect). The joint action of these two effects within the multilateral and the hub-and-spoke trade systems gives rise to the result that for the same number of direct trade partners, the R&D effort of a country in the multilateral agreement is much lower than the R&D effort of a hub but higher than the R&D effort of a spoke in the hub-and-spoke trade system. This suggests that the conversion from multilateralism to regionalism increases R&D and productivity of "strong negotiators" – countries that sign sufficiently many regional trade agreements, but it decreases R&D of weaker negotiators that become spokes in the newly formed hub-and-spoke trade system.

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1 Introduction

In the era of unprecedented proliferation of regional trade agreements and simultaneous developments in the WTO, assessment of relative economic benefits of multilateralism versus regionalism takes on special significance. Numerous studies have concentrated on comparison of welfare benefits, trade volumes, GDP levels and GDP growth rates in multilateral versus regional trade arrangements. As a result, some systematic differences have been revealed.[1] However, the existing literature have completely neglected the issue of possible variations in the impact which different types of trade liberalization might have on countries' *productivity* and *productivity growth rates*.

The latter is surprising at least for two reasons. First, productivity and productivity improvements in the country are key determinants of GDP and GDP growth rate, and those are found to vary across different types of trade arrangements. Secondly, recent empirical evidence has shown that in general trade liberalization has *significant effect* on productivity level of the country. This effect proves to be positive both, at the industry and at the firm level. For example, Bustos (2007) finds that during the period of trade liberalization between Argentina and Brazil, companies in sectors benefiting from a comparatively higher reduction in Brazil's tariffs increased their technology spending. Likewise, Trefler (2004) observes that the U. S. tariff concessions caused a boost in labor productivity of the Canadian firms in the most impacted, export-oriented group of industries. Similar patterns are shown by Bernard et al. (2006) for the U. S., by Topolova (2004) for India, by Aw et al. (2000) for Korea and Taiwan, by Alvarez and Lopez (2005) for Chile, and by Van Biesebroeck (2005) for sub-Saharan Africa.[2] Additionally, the positive effect of trade liberalization on productivity is substantiated by the extensive theoretical work.[3]

The aim of this paper is to contribute to the literature on the impact of trade liberalization on firms' productivity by studying how this impact varies across two types of trade liberalization – multilateral versus regional. I consider one specific way in which a firm can improve its productivity – investing in costly research and development (R&D). Here R&D is viewed broadly as any activity aimed at reducing the marginal cost of production.[4]

[1]For an extensive research of theoretical models on this subject see Panagariya (2000). Other theoretical and empirical works include Krueger (1999), Bhagwati (1993), Kowalczyk and Wonnacott (1992), Deltas et al. (2005), Goyal and Sumit (2006), Diao et al. (2003).

[2]The evidence on industry-level productivity improvements is presented in Baggs et al. (2002) for Canada, in Pavcnik (2002) for Chile, in Muendler (2004) for Brazil, in Bernard et al. (2006) for the U. S., and in Del Gatto et al. (2006) for Europe.

[3]The theoretical models identify several channels through which international trade affects productivity at the industry and/or at the firm level: the improved allocation of resources through specialization (Grossman and Helpman (1991)), the knowledge spillovers effect (Rivera-Batiz and Romer (1991), Devereux and Lapham (1994)), the reallocation of economic activities from less to more productive firms (Melitz (2003), Bernard et al. (2007), Yeaple (2005)), the exploitation of economies of scale (Krugman (1980)), the pro-competitive effect of trade openness (Aghion et al. (2005), Peretto (2003), Licandro and Navas-Ruiz (2007)), and others .

[4]Examples include developing new production technology, training of employees, internal re-organization of resources

To study the impact of the particular type of trade liberalization on firm's incentives to innovate, I consider the mechanisms through which trade can affect the return to innovation within different types of trade systems. The two major mechanisms are the *scale* effect due to the increased size of the market (number of markets) and the *competition* effect due to the increased number of competitors in every market. The focus of this paper is on interaction of two effects within multilateral and regional types of trade agreements.

I model trade agreements between countries by a network. Nodes represent countries and any link indicates the existence of a trade agreement between the linked countries. In every country, there is a single firm producing one good. The good is sold domestically and in markets of the trade partner countries subject to oligopolistic competition. There is therefore an intra-industry trade between countries which are directly linked in the network.

The advantage of modelling trade agreements by a network is the possibility to capture inherent differences between various types of trade systems. These are the differences in the degree of countries' trade involvement (the number of trade agreements signed) and the nature of market interaction between countries (who trades and competes with whom, at which markets, how many traders are present in each market). Given the focus of the paper on interaction between the scale and the competition effects of trade liberalization within different types of trade systems, capturing exactly these differences is key.

I constrain the analysis to two specific classes of network structures associated with the multilateral and the regional scenarios of trade liberalization. The first class of networks is symmetric (or regular) networks. It incorporates the case of a *complete* network structure – a network where every country is directly linked to any other country. The complete network in this model represents the multilateral trade agreement. The second class of networks is asymmetric networks with two types of nodes: high- and low-degree nodes. This class of networks captures the basic characteristics of the so-called *hub-and-spoke* trade system, where some countries (hubs) have relatively large number of direct trade partners as compared to other countries (spokes), which are mainly involved in trade agreements with hubs. According to a number of contributions on regional trade agreements, the hub-and-spoke trade arrangement has become a typical outcome of the regional trade liberalization.[5]

The modelling approach in this paper is closely related to the common approach in the strand of literature on R&D *co-operation* between firms in oligopoly. This strand of literature is well

and factors of production.

[5]To my knowledge, the concept of hub-and-spoke trade arrangement was first introduced in Lipsey (1990) and Wonnacott (1990). It was further developed in Lipsey (1991), Wonnacott (1991, 1996), Kowalczyk and Wonnacott (1991, 1992), Baldwin (2003, 2005), De Benedictis et al. (2005), and others.

represented by the seminal papers D'Aspremont and Jacquemin (1988) and Goyal and Moraga (2002). They consider a framework of Cournot competition, where at a pre-competitive stage firms can exert a cost-reducing effort. The typical element of this approach is that the rationale of co-operation between firms is individuated in the existence of R&D spillovers, which creates an externality. Co-operation is intended to internalize such externality.

Similarly to models with R&D co-operation, in my model, firms compete in a Cournot fashion choosing individual R&D effort and production levels in a two-stage non-cooperative game. However, in contrast to the core assumption and emphasis in D'Aspremont and Jacquemin (1988), Goyal and Moraga (2002) and the related literature, the focus of this paper is not on R&D co-operation and R&D spillovers: both R&D collaboration and spillovers are absent from the model. Instead, I concentrate purely on the effects of market access and competition faced by firms within various types of trade agreements on innovation intensity of the firms. Besides, unlike the assumption of standard oligopolistic competition between firms in one common market imposed in D'Aspremont and Jacquemin (1988) and Goyal and Moraga (2002), the central assumption in the present framework is that firms compete not in one but in several separate markets and every market is accessible only to those firms which have a trade agreement with that market. Clearly, this assumption results in heterogeneity between firms in terms of their market size – the feature which is absent from the previous models.

The primary result of the paper is that the impact of trade liberalization on firms' R&D efforts does vary considerably across different types of trade agreements. While the signs of the scale and of the competition effect due to a new trade partner are the same in both the multilateral and the regional/hub-and-spoke trade system, the sizes of the effects differ. For example, with regard to the scale effect, gaining an access to a new market in either multilateral or bilateral context enhances incentives for firms to innovate. Yet, the "net worth", or the effective size, of the new market depends on the number of other firms present in the market and on the competitive power of these firms – their R&D and production levels. Those are both determined by the structure of the trade system.[6] Similarly, with respect to the competition effect, a new trade partner of a firm in both the multilateral and the regional agreement becomes an additional rival of the firm in its domestic market. Additionally, depending on the structure of the trade system, it may also become a rival in some or all or none of the firm's foreign markets. Besides, the competitive strength of the new rival is determined by his own position in the network of trade agreements and by the market interaction

[6]Consistently with the empirical evidence, I find that in both, multilateral and hub-and-spoke trade systems an increase in the number of direct trade partners enhances innovation and productivity of a firm. An increase in the number of direct trade partners of the firm's direct trade partners decreases innovation.

with his own trade partners.

The difference in the effective sizes of markets across the multilateral and the hub-and-spoke trade systems leads to the variation in *levels* of R&D efforts across systems when the number of trade partners is fixed. I obtain that for the *same number of direct trade partners*, the R&D effort of a hub in the hub-and-spoke trade system is higher than that of a country in the multilateral agreement. On the other hand, the R&D effort of a spoke is lower than that of a hub and lower than the R&D effort of a country in the multilateral agreement, even if a country in the multilateral agreement has the same number of direct trade partners as a spoke.[7] Additionally, for the aggregate levels of R&D activities I find that the aggregate R&D effort within the multilateral trade agreement exceeds that in the *star* – the simplest representative of the hub-and-spoke trade system.[8]

Some other findings of the paper concern the *growth rates* of innovation by firms as the network of trade agreements expands. I show that in the multilateral trade agreement, the growth rate of firm's individual R&D effort is declining in the size of the agrement.[9] This is explained by the fact that as the size of the agreement grows, the positive scale effect of a new market is increasingly compensated by the negative competition effect due to a rise in the number of rivals in *every* country of the agreement. In contrast, the expansion of the hub-and-spoke trade system does not necessarily lead to an increase in competition in every market. As a result, for any *equal* number of direct trade partners of a country in the multilateral trade agreement and of a hub (spoke) in the hub-and-spoke trade system, the growth of the R&D effort caused by a new direct trade partner is lower for a firm in the multilateral trade system than for a firm in a hub (spoke).

The paper is organized as follows. Section 2 presents the model and describes the two-stage game between firms. Sections 3 and 4 describe the solution of the second and of the first stage of the game, respectively. Section 5 discusses the scale and the competition effects of trade liberalization on firms' innovation decisions. The joint action of these two effects within multilateral and hub-and-spoke trade systems is studied in Scenario 1 and in Scenario 2 of trade liberalization. The scenarios are compared in Section 6 and their policy implications are discussed in Section 7. Results of Scenarios 1 and 2 established for the specific classes of networks induce a study of the effects of trade liberalization for a generic network. Section 8 presents implications of this study on the assumption of small external effects. Finally, Section 9 concludes.

[7]The same relative effects are found for the *welfare* and the *real income* values of countries in the stylized 3-country model by Deltas et al. (2005) and by Kowalczyk and Wonnacott (1992).

[8]Formally, the *star network* is a network in which there is a central country (hub) which is directly linked to every other country (spoke), while none of the other countries have a direct link with each other. The star in the present model is essentially a set of bilaterals of a hub with spokes, where each spoke has a trade agreement only with the hub.

[9]This finding is consistent with the hump-shaped relationship between competition and innovation derived by Aghion et al. (2005).

2 The model

Network of regional trade agreements

Consider a setting with N countries where some countries are participants of one or more trade agreements (TAs) within a certain industry. I model trade agreements between countries with a network: countries are the nodes of the network and each link indicates the existence of a trade agreement between the two linked countries. If two countries have negotiated a TA, then each offers the other a privileged access to its domestic market: the tariffs and restrictions on trade are reduced. Otherwise, for simplicity I assume that tariffs and restrictions on trade between countries which did not sign a TA are trade-prohibitive. So in fact, trade may only exist between countries which negotiated a TA, that is, only between countries which are directly linked in the network. For any $i \in 1 : N$, I will denote by N_i the set of countries with which country i has a trade link in the network of TAs. These are *direct trade partners* of i. Let $|N_i|$ be the cardinality of set N_i.[10] Also, let N_i^2 be the set of direct trade partners of direct trade partners of i, different from i. In other words, N_i^2 is the set of *two-links-away trade partners* of i in the network of TAs. Notice that some countries may simultaneously be direct and two-links-away trade partners of i. Let $|N_i^2|$ be the cardinality of set N_i^2

In this model, I take the network of trade agreements as exogenously given and fixed. Besides, since the trade agreement between any two countries are reciprocal, I assume that all links in the network are undirected and no multiple links exist.

Demand and cost structure

In every country, there is a single firm producing one good. The firm in country i can sell its good in the domestic market and in the markets of those countries with which i has a trade agreement. Let the output of firm i (from country i) produced for consumption in country j be denoted by y_{ij}. The total output of firm i is given by $y_i = \sum_{j \in N_i \cup \{i\}} y_{ij}$.Each firm i exporting its good to country $j \in N_i \cup \{i\}$ faces an inverse linear demand in country j given by

$$p_j = a - b \left(y_{ij} + \sum_{k \in N_j \cup \{j\}, k \neq i} y_{kj} \right), \tag{2.1}$$

where $a, b > 0$ and $\sum_{k \in N_j \cup \{j\}} y_{kj} \leq a/b$.

Let τ_{ij} denote the trade costs faced by firm i per unit of its exports to country j. These costs include tariffs on unit of export from i to j, transportation costs, etc. The trade costs between i and j are not necessarily identical for i and j: in general, $\tau_{ij} \neq \tau_{ji}$ $\forall i, j \in 1 : N$. Besides, by definition,

[10] This is the degree of i in the network.

$\tau_{ij} \geq 0 \ \forall i, j \in 1:N, i \neq j$, and $\tau_{ii} = 0 \ \forall i \in 1:N$. The total trade costs faced by firm i are equal to

$$t_i(\{y_{ij}\}_{j \in N_i}) = \sum_{j \in N_i} \tau_{ij} y_{ij}. \tag{2.2}$$

In addition to production of the good and selling the good on the domestic and/or foreign market, each firm can invest in R&D. The R&D effort of the firm helps lower its marginal cost of production. The cost of production of firm i is therefore a function of its production, y_i, and the amount of research x_i that it undertakes. I assume that the cost function of each firm is linear and is given by

$$c_i(y_i, x_i) = (\alpha - x_i) y_i, \tag{2.3}$$

where $0 \leq x_i \leq \alpha \ \forall i \in 1:N$. In the following, I will also assume that a is sufficiently large as compared to α and the costs of trade between countries. Namely, let by

Assumption 1 $\quad a > \alpha + \max_{i,k \in 1:N} \{\alpha |N_i| + (|N_i| + 1)\tau_{ki} - \sum_{j \in N_i, j \neq k} \tau_{ji}\}$.

The R&D effort is costly: given the level $x_i \in [0, \alpha]$ of effort, the cost of effort of firm i is

$$z_i(x_i) = \delta_i x_i^2, \qquad \delta > 0. \tag{2.4}$$

Under this specification, the cost of *R&D* effort is an increasing function and exhibits diminishing returns.[11] The parameter δ measures the curvature of this function. In the following, I will assume that δ is sufficiently large so that the second order conditions hold and equilibria can be characterized in terms of the first-order conditions and are interior.[12]

Two-stage game

Firms' strategies consist of the level of R&D activities and a subsequent production strategy based on their R&D choice. Both strategies are chosen via interaction in a two-stage non-cooperative game. In the first stage, each firm chooses a level of its effort in R&D. The R&D effort of a firm defines its marginal cost of production. In the second stage, given these costs of production, firms operate in their domestic market and in markets of their trade partners by choosing production quantities $\{y_{ij}\}_{i \in 1:N, j \in N_i \cup \{i\}}$ for every market. Each firm chooses the profit-maximizing quantity for every market separately, on the Cournot assumption that the other firms' outputs are given.

Notice the specific nature of interaction between firms in this game. First, firms compete with each other not in one but in several separate markets. Secondly, since countries trade only with those

[11] An important justification of this assumption is that "the technological possibilities linking R&D inputs and innovative outputs do not display any economies of scale with respect to the size of the firm in which R&D is undertaken" (Dasgupta (1986), p. 523).

[12] The assumptions imposed on the parameters of the demand and cost functions are standard in the models with linear-quadratic specification of the objective function (the firm's profit function in this case). This is admittedly a special setting. Yet, even in this simple case, the analysis of the interaction between markets and R&D efforts of firms in the network is quite complicated.

countries with which they have a trade agreement (a direct link in the network), any firm competes only with its direct and two-links-away trade partners. Furthermore, any direct trade partner of firm i competes with i in its own market and in the market of firm i, while any two-links-away trade partner of i, who is not simultaneously its direct trade partner, competes with i only in the market(s) of their common direct trade partner(s). This two-links-away radius of immediate interaction between firms does not mean however that R&D and production choices of firms are not affected by other firms. As soon as the network of TAs is connected,[13] firms that are further than two links away from i affect R&D and production strategies of i indirectly, through the impact which they have on R&D and production choices of their own trade partners and trade partners of their partners, etc.

The game is solved using backward induction. Consider each stage in turn.

3 Solving the second stage

In the markets' competition stage, each firm $i \in 1 : N$ chooses a vector of its production plans $\{y_{ij}\}_{j \in N_i \cup \{i\}}$ so as to maximize its profit, conditional on R&D efforts $\{x_i\}_{i \in 1:N}$. The profit of firm i is

$$\begin{aligned} \pi_i &= \sum_{j \in N_i \cup \{i\}} \left(a - b y_{ij} - b \sum_{k \in N_j \cup \{j\}, k \neq i} y_{kj} \right) y_{ij} - (\alpha - x_i) y_i - \delta_i x_i^2 - \sum_{j \in N_i} \tau_{ij} y_{ij} = \\ &= \sum_{j \in N_i \cup \{i\}} \left(-b y_{ij}^2 - b \sum_{k \in N_j \cup \{j\}, k \neq i} y_{kj} y_{ij} \right) + (a - \alpha + x_i) y_i - \delta_i x_i^2 - \sum_{j \in N_i \cup \{i\}} \tau_{ij} y_{ij}. \end{aligned} \tag{3.1}$$

Notice that function π_i is additively separable and quadratic in the output levels $\{y_{ij}\}_{j \in N_i \cup \{i\}}$ of firm i. This leads to linear first-order conditions and guarantees existence and uniqueness of the solution of each firm's maximization problem.[14] The partial derivative of firm i's profit with respect to y_{ij} is

$$\frac{\partial \pi_i}{\partial y_{ij}} = -2b y_{ij} - b \sum_{k \in N_j \cup \{j\}, k \neq i} y_{kj} + a - \alpha + x_i - \tau_{ij} = -b y_{ij} - b \sum_{k \in N_j \cup \{j\}} y_{kj} + a - \alpha + x_i - \tau_{ij}.$$

Summing up the first-order conditions $\frac{\partial \pi_k}{\partial y_{kj}} = 0$ for all firms k competing in market j (including firm i), we obtain:

$$-b \sum_{k \in N_j \cup \{j\}} y_{kj} = \frac{1}{|N_j| + 2} \left((|N_j| + 1)(\alpha - a) - \sum_{k \in N_j \cup \{j\}} (x_k - \tau_{kj}) \right). \tag{3.2}$$

[13] The network is connected if there exists a path between any pair of nodes.
[14] Since $b > 0$, the second order conditions hold.

Plugging (3.2) into the first-order condition for firm i we find the Nash-Cournot equilibrium production level y_{ij} of firm i for consumption in country j:[15]

$$y_{ij} = \frac{1}{b(|N_j|+2)} \left(a - \alpha + (|N_j|+1)(x_i - \tau_{ij}) - \sum_{k \in N_j \cup \{j\}, k \neq i} (x_k - \tau_{kj}) \right), \quad i \in 1:N, j \in N_i \cup \{i\}. \tag{3.3}$$

So, the equilibrium output of firm i in country $j \in N_i \cup \{i\}$ is increasing in firm's own R&D effort and it is decreasing in R&D efforts of i's rivals in market j. Therefore, the higher the equilibrium R&D effort of i and the lower the equilibrium effort of every $k \in N_j \cup \{j\}$, $k \neq i$, the higher the share of market j gained by i.

Additionally, notice that everything else being equal, the presence of non-negative trade costs τ_{ij} and τ_{ji} gives firm i the competitive advantage over firm j on i's domestic market and implies at least as high production of i for the domestic market as for the market j. Indeed, as soon as $x_i = x_j$ for some $j \in N_i$, the equilibrium level of production for market i of firm i is at least as high as that of firm j. Similarly, if for some $j \in N_i$ $|N_i| = |N_j|$ and $\sum_{k \in N_i, k \neq j}(x_k - \tau_{ki}) = \sum_{k' \in N_j, k' \neq i}(x_{k'} - \tau_{k'j})$, the equilibrium level of production of firm i for the domestic market is at least as high as its production for market j.

4 Solving the first stage

At the preceding stage, firms choose R&D efforts. Plugging expression (3.3) for the output levels $\{y_{kj}\}_{k \in N_j \cup \{j\}}$ of Cournot competitors in country j into the profit function (3.1) of firm i, we obtain the function of the R&D effort levels $\{x_k\}_{k \in N_j \cup \{j\}}$. After some calculations, the profit of firm i can be written as

$$\begin{aligned} \pi_i \quad = \quad & \left[\frac{1}{b} \sum_{j \in N_i \cup \{i\}} \frac{(|N_j|+1)^2}{(|N_j|+2)^2} - \delta_i \right] x_i^2 + \frac{2}{b} \sum_{j \in N_i \cup \{i\}} \frac{|N_j|+1}{(|N_j|+2)^2} \left(a - \alpha + \sum_{k \in N_j, k \neq i} \tau_{kj} - (|N_j|+1)\tau_{ij} \right) x_i - \\ & - \frac{2}{b} \sum_{j \in N_i} \left[\frac{|N_i|+1}{(|N_i|+2)^2} + \frac{|N_j|+1}{(|N_j|+2)^2} \right] x_i x_j - \frac{2}{b} \sum_{j \in N_i} \sum_{k \in N_j, k \neq i} \frac{|N_j|+1}{(|N_j|+2)^2} x_i x_k + f(\{x_k\}_{k \in N_i \cup N_i^2}), \end{aligned} \tag{4.1}$$

[15] Notice that

$$\sum_{k \in N_j \cup \{j\}} y_{kj} = \frac{|N_j|+1}{b(|N_j|+2)}(a-\alpha) + \frac{1}{b(|N_j|+2)} \sum_{k \in N_j \cup \{j\}} (x_k - \tau_{kj}) \leq \frac{|N_j|+1}{b(|N_j|+2)} a - \frac{1}{b(|N_j|+2)} \sum_{k \in N_j \cup \{j\}} \tau_{kj} < \frac{a}{b}$$

and $\forall k \in 1:N$ $\forall j \in N_k \cup \{k\}$

$$y_{kj} \geq \frac{1}{b(|N_j|+2)}(a - \alpha - (|N_j|+1)\tau_{kj} - |N_j|\alpha + \sum_{k' \in N_j, k' \neq k} \tau_{k'j}) = \frac{1}{b(|N_j|+2)}(a - (\alpha + \alpha|N_j| + (|N_j|+1)\tau_{kj} - \sum_{k' \in N_j, k' \neq k} \tau_{k'j})) > 0.$$

where $f(\{x_k\}_{k\in N_i\cup N_i^2})$ is a function of R&D efforts of i's competitors in different markets which does not distort i's equilibrium effort:

$$f(\{x_k\}_{k\in N_i\cup N_i^2}) = \frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{1}{(|N_j|+2)^2}\left(a-\alpha-(|N_j|+1)\tau_{ij}-\sum_{k\in N_j\cup\{j\},k\neq i}(x_k-\tau_{kj})\right)^2.$$

The profit function (4.1) of firm i is quadratic in i's own R&D effort x_i. Besides, if δ_i is sufficiently high, so that the R&D cost function z_i is sufficiently steep, the profit function of i is concave in x_i. To be more precise, for a given network of trade agreements, as soon as

$$\delta_i > \frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}, \qquad \forall i\in 1:N, \tag{4.2}$$

the second order conditions hold and the profit maximizing R&D efforts of all firms can be found as a solution to the system of linear first-order conditions:

$$\left[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}+\delta_i\right]x_i + \frac{1}{b}\sum_{j\in N_i}\left[\frac{|N_i|+1}{(|N_i|+2)^2}+\frac{|N_j|+1}{(|N_j|+2)^2}\right]x_j + \tag{4.3}$$

$$+\frac{1}{b}\sum_{j\in N_i}\sum_{k\in N_j,k\neq i}\frac{|N_j|+1}{(|N_j|+2)^2}x_k = \frac{1}{b}\sum_{j\in N_i}\frac{|N_j|+1}{(|N_j|+2)^2}\left(a-\alpha+\sum_{k\in N_j,k\neq i}\tau_{kj}-(|N_j|+1)\tau_{ij}\right),$$

for all $i\in 1:N$. In the matrix form, this system can be written as

$$\Sigma\cdot\mathbf{x}=\mathbf{u}, \tag{4.4}$$

where $\mathbf{x}\in\mathbb{R}^N$ is a vector of unknowns, $\mathbf{u}\in\mathbb{R}^N$, and Σ is $(N\times N)$ square matrix. As soon as the network of trade agreements is connected, the matrix Σ is generically nonsingular and the right-hand side vector $\mathbf{u}$ is non-zero. Then (4.4) has a unique *generic* solution in $\mathbb{R}^N$, denoted by $\mathbf{x}^*$. Below I show that if δ_i satisfies an additional restriction, stronger than condition (4.2), this solution is ensured to be such that for all $i\in 1:N$, $0<x_i^*\leq\alpha$.

First, note that in the i^{th} first-order condition in (4.3), the value of the expression on the right-hand side and the coefficients multiplying all x_k, $k\in N_i\cup N_i^2\cup\{i\}$, are positive. Therefore, the value of x_i is the larger the smaller the values of x_j and x_k for all $j\in N_i$ and $k\in N_i^2$. Hence, the condition sufficient for $x_i^*>0$ is that (4.3) evaluated at $x_j=x_k=\alpha$ $\forall j\in N_i$, $k\in N_i^2$ defines the value of x_i, which is greater than zero. It is easy to show that this condition is provided by Assumption 1. Similarly, the sufficient condition for $x_i^*\leq\alpha$ is that (4.3) evaluated at $x_j=x_k=0$ $\forall j\in N_i$, $k\in N_i^2$ defines x_i, which is smaller or equal than α. This condition is equivalent to

Assumption 2 $\delta_i\geq\frac{1}{\alpha b}\sum_{j\in N_i\cup\{i\}}\frac{|N_j|+1}{(|N_j|+2)^2}\left(\alpha|N_j|+a+\sum_{k\in N_j,k\neq i}\tau_{kj}-(|N_j|+1)\tau_{ij}\right)$, $\forall i\in 1:N$.

Under Assumption 1, the right-hand side of inequality in Assumption 2 is strictly larger than $\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}$ from the earlier restriction on δ_i in (4.2). Therefore, Assumption 2 is stronger.

Together, Assumptions 1 and 2 guarantee that solution $\mathbf{x}^*$ of a system of the first-order conditions (4.3)(or (4.4)) is such that $0 < x_i^* \leq \alpha$ for all $i \in 1 : N$, and the second order conditions hold. Moreover, if the inequality in Assumption 2 is strict, solution $\mathbf{x}^*$ is interior.

The specification of the first-order conditions (4.3) suggests that an increase in R&D efforts of i's direct and/or two-links-away trade partners trigger a downward shift in i's response. Intuitively, by extracting higher R&D efforts, i's rivals capture larger share of the markets and dampen incentives of i to invest in R&D. We say that the efforts of firm i and its direct and two-links-away trade partners are *strategic substitutes* from i's perspective.

The first-order conditions (4.3) imply that in equilibrium the profit function of firm i is given by

$$\begin{aligned}\pi_i &= \left[-\frac{1}{b} \sum_{j \in N_i \cup \{i\}} \frac{(|N_j|+1)^2}{(|N_j|+2)^2} + \delta_i \right] x_i^{*2} + \\ &+ \frac{1}{b} \sum_{j \in N_i \cup \{i\}} \frac{1}{(|N_j|+2)^2} \left(a - \alpha - (|N_j|+1)\tau_{ij} - \sum_{k \in N_j \cup \{j\}, k \neq i} (x_k^* - \tau_{kj}) \right)^2 .\end{aligned} \tag{4.5}$$

The short proof of this statement is provided in the Appendix.

5 The impact of trade liberalization on equilibrium R&D efforts

In the framework of the present model, trade liberalization can be defined as an expansion of the network of trade agreements through an increase in the number of links – concluded trade agreements, and/or links together with nodes – countries participating in one or several trade agreements.

First, consider an impact of trade liberalization on equilibrium R&D efforts of firms in two countries which negotiate a trade agreement with each other. There are two major mechanisms at work. On the one hand, a new trade agreement creates an additional market for firms in both countries (scale effect). This amplifies the return to productivity-enhancing investment, increasing the equilibrium R&D effort of each firm. On the other hand, the new agreement opens the markets of both countries to a new competitor (competition effect). This has two opposite effects on R&D. Enhanced competition dampens the return to R&D through a reduction in the domestic market share of each firm; yet, it also increases the return to R&D through a depreciation of markups, which rises the size of the domestic market. Thus, overall trade opening between two countries has an ambiguous effect on their equilibrium R&D efforts.

In addition, trade liberalization between any two countries affects R&D decisions of firms in other countries, too. For example, when i and j negotiate a trade agreement, R&D efforts of other direct trade partners of i and j are affected because firms in these countries face higher competition in i

and j. Then the impact on R&D efforts of the direct trade partners of i and j "spreads" to a larger network: direct trade partners of the direct trade partners of i and j face different R&D efforts and hence, competitive power of their trade partners, which has an impact on their own optimal R&D, etc.

Thus, scale and competition effects of trade liberalization (in any part of the network) can reinforce or dampen incentives for firms to invest in R&D, the sign and strength of the impact being determined by the precise network structure. In the following section, I address this issue in case of multilateral and regional trade liberalization, where each type of liberalization is represented by the specific type of network.

6 Two scenarios of trade liberalization: Multilateralism versus regionalism

Scenario 1: Symmetric network of trade agreements. Multilateral trade system

Consider a class of symmetric (regular) networks of degree $n \geq 1$.[16] Given the aim of the paper, we are mainly interested in one representative of this class – a *complete* network. A complete network of degree more than one represents a multilateral trade system, where all participant countries have a trade agreement with each other and neither country has a trade agreement with a third party. In this framework, an expansion of the multilateral trade system represents a scenario of multilateral trade liberalization. When multilateral trade liberalization involves all world economies, the resulting trade system is a "global free trade" – one of the primary objectives of the WTO.

In addition, the class of symmetric networks comprises a case of one or several *simple bilaterals*, where every country signs a trade agreement with one and only one other country.[17] This case corresponds to the symmetric network of degree one.

Assume that δ_i is the same for all firms, so that R&D activities are equally costly in every country. Besides, let $\tau_{ij} = \tau_{ji} = \tau$ for all trade partners i, j, that is, the trade costs per unit of exports are the same across all pairs of trade partners. In such a setup, all countries/firms in the network are identical and hence, exert identical R&D efforts. Denote the level of this effort by x. Then the (single) first-order condition (4.3) can be written as follows:

$$\left[-\frac{(n+1)^3}{(n+2)^2} + \delta b\right] x + 2n\frac{n+1}{(n+2)^2}x + n\frac{(n+1)(n-1)}{(n+2)^2}x = \frac{(n+1)^2}{(n+2)^2}(a-\alpha) + \frac{n+1}{(n+2)^2}(-2\tau n + \tau n).$$

[16] A network is *symmetric*, or *regular*, if every node in the network has the same degree (number of direct contacts). A degree of each node in the symmetric network is called a *degree* of the symmetric network.

[17] Up to the early 1990s, trade agreements were, with only a few exceptions, a set of non-intersecting bilateral or "small" multilateral trade agreements (the latter are also called plurilateral RTAs). The source of this evidence is for example, Lloyd and Maclaren (2004).

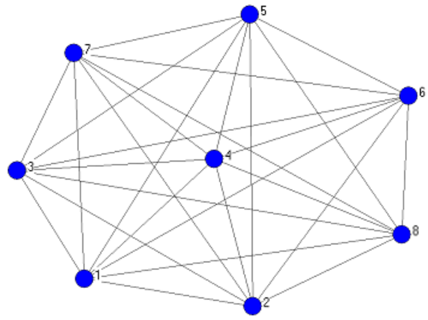


Figure 1: Complete network of degree 7 – multilateral trade agreement between 8 countries

Multiplying both sides by $(n+2)^2$, we obtain

$$x \cdot \left[-(n+1)^3 + \delta b(n+2)^2 + 2n(n+1) + n(n+1)(n-1)\right] = (n+1)^2(a-\alpha) - n(n+1)\tau.$$

From this equation, an equilibrium effort x^* can be computed to be

$$x^* = \frac{a - \alpha - \frac{n}{n+1}\tau}{-1 + \delta b\left(1 + \frac{1}{n+1}\right)^2}. \tag{6.1}$$

Now, using this expression for x^* and formula (4.5) for the equilibrium profit function, we derive the profit of any firm in the symmetric network:

$$\begin{aligned} \pi \;&=\; \left(-\frac{1}{b}\frac{(n+1)^3}{(n+2)^2} + \delta\right)\left(\frac{a-\alpha-\frac{n}{n+1}\tau}{-1+\delta b(1+\frac{1}{n+1})^2}\right)^2 + \frac{n}{b(n+2)^2}\left(a-\alpha-2\tau-n\frac{a-\alpha-\frac{n}{n+1}\tau}{-1+\delta b(1+\frac{1}{n+1})^2}\right)^2 \\ &+\; \frac{1}{b(n+2)^2}\left(a-\alpha-n\left(\frac{a-\alpha-\frac{n}{n+1}\tau}{-1+\delta b\left(1+\frac{1}{n+1}\right)^2}-\tau\right)\right)^2. \end{aligned} \tag{6.2}$$

The usual comparative statics analysis leads to the following result:

Proposition 1 *Suppose that for some $\bar{n} \geq 1$,*[18]

$$a \;>\; \alpha(1+\bar{n}) + 2\tau, \quad \textit{and} \tag{6.3}$$

$$\delta \;\geq\; \frac{1}{\alpha b}\frac{(\bar{n}+1)}{(\bar{n}+2)^2}((\alpha\bar{n}+a)(\bar{n}+1) - \tau\bar{n}). \tag{6.4}$$

Then for any $n < \bar{n}$, firm's equilibrium R&D effort x^* is monotonically increasing in n, while firm's profit π is monotonically decreasing in n.

Proposition 1 is illustrated with Figure 2, where the equilibrium R&D effort and profit of a firm in the symmetric network are drawn against the network degree n.[19]

From Proposition 1 it follows that multilateral trade liberalization reinforces R&D efforts of firms but depreciates profits. At the same time, Figure 2 shows that the pace of an increase in R&D and

[18] These parameter restrictions guarantee that Assumptions 1 and 2 hold for all $n \leq \bar{n}$. This is implied by two facts: (i) Assumptions 1 and 2 hold for $n = \bar{n}$, and (ii) the right-hand side of inequalities in Assumptions 1 and 2 are increasing functions of n (the right-hand side of inequality in Assumption 2 is increasing in n, *provided* that Assumption 1 holds).

[19] The simulation is done for the specific parameter values: $\alpha = 7$, $b = 1$, $\bar{n} = 10$, and $\tau = 2$; a and δ fulfill the requirements of Proposition 1.

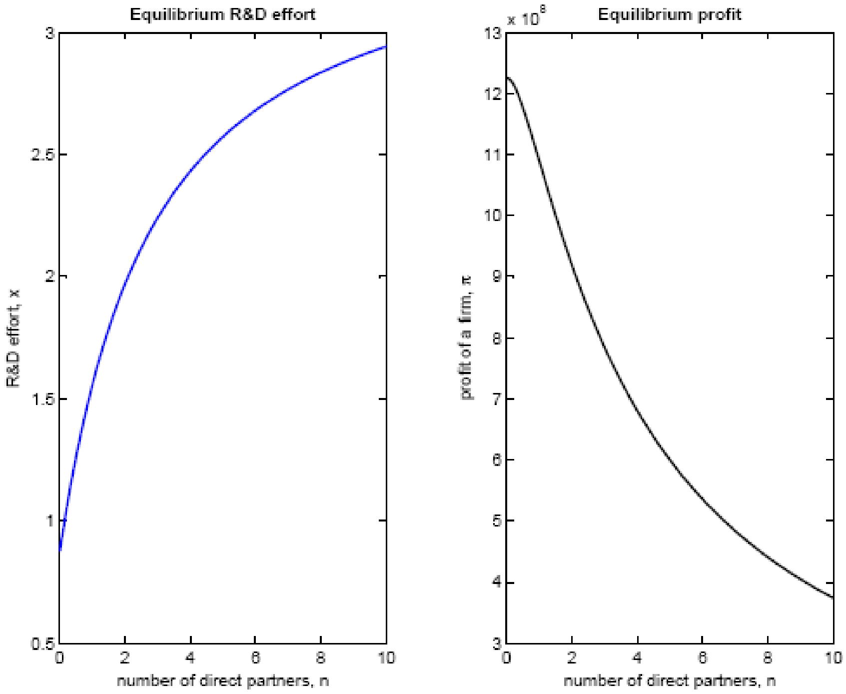


Figure 2: Equilibrium R&D effort and profit of a country in a symmetric network of degree n

the pace of a decrease in profits are both declining as the number of participant countries (size of the agreement) grows.

With respect to R&D, these observation suggest that in the multilateral agreement (and in any other agreement which can be represented by the symmetric network) the competition effect of trade liberalization on firms' R&D is *increasingly negative* but the positive scale effect of trade liberalization dominates. The intuition underlying the increasingly negative competition effect is easy to grasp. Indeed, for a given firm in the multilateral agreement, a new entrant represents an additional market but it also brings an additional competitor to *every* other market of the agreement. When the size of the agreement grows, the competition-enhancing role of an entrant becomes more important. In addition, the "net worth" of the entrant itself, that is, the size of its market is declining in the size of the agreement since an increasingly large number of firms have an access to that market.

Furthermore, notice that Proposition 1 allows to compare equilibrium R&D effort and profit of an individual firm in the multilateral agreement with those in the bilateral agreement and in autarky. Denote by x_a^* and π_a the equilibrium R&D effort and profit of a firm in autarky, by x_b^* and π_b – the R&D effort and profit of a firm in the bilateral agreement, and by $x^*(n)$ and $\pi(n)$ – the R&D effort and profit of a firm in the multilateral agreement of degree n (of size $n+1$). Then we obtain

Corollary 1 *For any* $2 \leq n < \bar{n}$, $x_a^* < x_b^* < x^*(n)$ *and* $\pi_a > \pi_b > \pi(n)$.

The individual R&D investment of a firm is higher in the multilateral agreement than in the bilateral agreement and in autarky, while the profit of a firm in multilateral agreement is the lowest.

Finally, for aggregate levels of R&D, Proposition 1 and Corollary 1 imply that an aggregate level of R&D activities within the multilateral trade system is increasing in the size of the system and exceeds an aggregate R&D effort of the same number of countries where each country negotiated one bilateral trade agreement.

Scenario 2: Asymmetric network of trade agreements. Hub-and-spoke trade system

I now proceed to the scenario of regional trade liberalization. In the process of regional trade liberalization, some countries (or groups of countries) negotiate one or several *bilateral* or/and *plurilateral* agreements with each other. Thus, in contrast to the multilateral type of liberalization considered in Scenario 1, each country may actually be a party to *several different* trade agreements where other countries do not necessarily have an agreement with each other. As a result, a complex trade system emerges where various regional (preferential) agreements overlap. Still, according to a range of studies, "the arrangement of preferential trade agreements in the world is not completely random" (Baldwin (2005)). The emerging system is described as a *hub-and-spoke* trade system, where some countries (hubs) have relatively large number of direct trade partners as compared to other countries (spokes), which are mainly involved in trade agreements with hubs.

In this model, I take the finding of a hub-and-spoke structure of regional trade system as an assumption and study the implications of this structure for R&D choices of firms. I approximate the hub-and-spoke structure by the asymmetric network with two types of nodes – nodes of high degree n (hubs) and of low degree m (spokes), $1 \leq m < n$. I assume that a *fixed positive* share of direct trade partners of hubs and spokes is represented by countries of the opposite type. For any hub, other hubs form a share $0 \leq \psi < 1$ of its direct trade partners while a share $0 < 1 - \psi \leq 1$ is represented by spokes. Similarly, for any spoke, other spokes form a share $0 \leq \varphi < 1$ of its direct trade partners and the remaining positive share $0 < 1 - \varphi \leq 1$ is represented by hubs.[20] The assumption of fixed (and identical across countries of the same type) shares ψ and φ significantly simplifies calculations and enriches the comparative statics analysis. For example, it allows to study the effects of variation in the proportion of hubs to spokes among countries' direct trade partners while the number of these direct trade partners remains unchanged.[21]

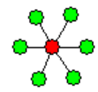
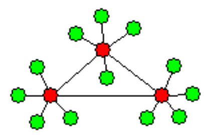
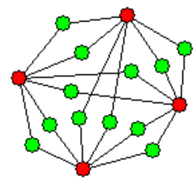
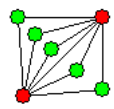
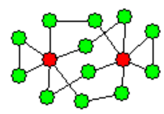
In this framework, the basic characteristics of "real" hub-and-spoke trade systems, such as a substantial difference in the number of direct trade partners of hubs and spokes and predominance of hubs among trade partners of spokes, can be captured by cases where $n \gg m$ and $\varphi = 0$ or small.

[20] Notice that in case when $\psi = 1$ ($\varphi = 1$), we obtain the complete network of degree n (m).

[21] See Proposition 2.

Some examples of these cases are demonstrated in Table 1.[22]

Table 1: Examples of hub-and-spoke trade system

Network characteristics	Network
Type 1: Single star (n bilaterals of a hub with spokes) $n > 1$, $m = 1$, $\psi = 0$, $\varphi = 0$	
Type 2: Stars with linked hubs $n > 1$, $m = 1$, $\psi > 0$, $\varphi = 0$	
Type 3: Stars sharing spokes $n > 1$, $m > 1$, $\psi = 0$, $\varphi = 0$	
Type 4: Stars with linked hubs, sharing spokes $n > 1$, $m > 1$, $\psi > 0$, $\varphi = 0$	
Type 5: Stars where some spokes are linked with ech other $n > 1$, $m > 1$, $\psi = 0$, $\varphi > 0$	

Remark: Red nodes stand for hubs, green nodes stand for spokes.

As in Scenario 1, assume that R&D activities of firms are equally costly in all countries and the costs of trade between any two countries are the same: $\delta_i = \delta$ for all $i \in 1 : N$ and $\tau_{ij} = \tau_{ji} = \tau$ for any pair $i, j \in 1 : N$. Together with the structural assumptions described above this implies that in any given hub-and-spoke trade system, all hubs exert identical R&D effort (x_h) and likewise, all spokes exert identical R&D effort (x_s). Then the system (4.3) of the first-order conditions reduces to two equations:

$$\begin{aligned} \Bigg(& - (1-\psi)n\frac{(m+1)^2}{(m+2)^2} - (n\psi+1)\frac{(n+1)^2}{(n+2)^2} + \delta b + \psi n\frac{2(n+1)}{(n+2)^2} + (1-\psi)n\frac{m+1}{(m+2)^2}((1-\varphi)m-1) \\ & + \psi n\frac{n+1}{(n+2)^2}(\psi n - 1)\Bigg)\cdot x_h + (1-\psi)n\left(\frac{n+1}{(n+2)^2} + \frac{m+1}{(m+2)^2} + \frac{n+1}{(n+2)^2}n\psi + \frac{m+1}{(m+2)^2}\varphi m\right)\cdot x_s \\ & = (a-\alpha-2\tau)\left((1-\psi)n\frac{m+1}{(m+2)^2} + \psi n\frac{n+1}{(n+2)^2}\right) + \frac{n+1}{(n+2)^2}(a-\alpha+n\tau) \end{aligned} \quad (6.5)$$

[22] In the next section I will use the specific structures of Table 1 in order to investigate how different types of hub-and-spoke system compare in terms of firms' R&D investments.

$$
\begin{aligned}
\Bigg(\quad & - \quad (1-\varphi)m\frac{(n+1)^2}{(n+2)^2} - (\varphi m+1)\frac{(m+1)^2}{(m+2)^2} + \delta b + \varphi m\frac{2(m+1)}{(m+2)^2} + (1-\varphi)m\frac{n+1}{(n+2)^2}((1-\psi)n-1) \\
& + \quad \varphi m\frac{m+1}{(m+2)^2}(\varphi m-1)\Bigg)\cdot x_s + (1-\varphi)m\left(\frac{n+1}{(n+2)^2} + \frac{m+1}{(m+2)^2} + \frac{n+1}{(n+2)^2}n\psi + \frac{m+1}{(m+2)^2}\varphi m\right)\cdot x_h \\
& = \quad (a-\alpha-2\tau)\left((1-\varphi)m\frac{n+1}{(n+2)^2} + \varphi m\frac{m+1}{(m+2)^2}\right) + \frac{m+1}{(m+2)^2}(a-\alpha+m\tau) \qquad (6.6)
\end{aligned}
$$

These equations uniquely identify equilibrium R&D efforts of a hub and a spoke. Tedious calculations lead to the closed-form solution (x_h^*, x_s^*), which has a cumbersome representation and therefore, is left for the Appendix.[23] Nevertheless, equilibrium R&D efforts of a hub and a spoke reveal simple functional dependence on parameters n, m, ψ, and φ, provided that certain parameter restrictions hold. This gives rise to clear-cut comparative statics.

Proposition 2 *Suppose that for some $\bar{n} > 1$,*[24]

$$
\begin{aligned}
a &> \alpha(1+\bar{n}) + 2\tau, \quad \textit{and} && (6.7)\\
\delta &\geq \underline{\delta} = \frac{1}{\alpha b}\left[\frac{\bar{n}+1}{(\bar{n}+2)^2}\bar{n}(\alpha\bar{n}+a-2\tau) + \frac{2}{9}((\alpha\bar{n}+a)(\bar{n}+1)-\tau\bar{n})\right]. && (6.8)
\end{aligned}
$$

Then there exists $\Delta > 0$ such that for any $\delta \geq \max\{\Delta, \underline{\delta}\}$ and for any $m < n < \bar{n}$, the following statements hold:

1. *the equilibrium R&D effort x_h^* of a hub is monotonically increasing in n and monotonically decreasing in m and in ψ;*

2. *the equilibrium R&D effort x_s^* of a spoke is monotonically decreasing in n and increasing in φ. Besides, x_s^* is monotonically increasing in m if at least one of the conditions is satisfied:*

   (a) the trade costs are sufficiently high: $\tau \geq \frac{1-\varphi}{3-2\varphi}(a-\alpha)$;

   (b) the share of other spokes among direct trade partners is at least 1/3: $\varphi \geq \frac{1}{3}$;

   (c) the gap between n and m is relatively small: $n \leq m^2$, that is, $1 < \frac{n}{m} \leq m$.

Proposition 2 states that as soon as the specified parameter restrictions (and conditions (a) – (c)) hold, the equilibrium R&D effort of a hub (spoke) is increasing in the number of its direct trade partners but is decreasing in the number of direct trade partners of spokes (hubs). Besides, for both a hub and a spoke, the higher the share of hubs among their direct trade partners, the lower the optimal R&D effort. Thus, for either of firms in the hub-and-spoke system, the larger the number of directly accessible markets and the lower the number of competitors in these markets, the higher the incentives to innovate. This observation suggests that just as in the multilateral agreement, in

[23]See the proof of Proposition 2.

[24]As in Proposition 1, these parameter restrictions guarantee that Assumptions 1 and 2 hold for all $m < n \leq \bar{n}$.

the hub-and-spoke trade system, the competition effect of trade liberalization on R&D is negative but the positive scale effect dominates.

The negative impact of competition on equilibrium R&D decisions of spokes help understanding conditions (a) – (c), which guarantee that an increase in m enhances spokes' R&D investments. Recall that the specification of a hub-and-spoke trade system in this model is such that an increase in the number m of spoke's direct trade partners is associated with an increase in the number of *both* types of partners – hubs and spokes.[25] Since the market of a hub is "small" – smaller than the market of a spoke, an increase in the spoke's foreign market share may actually be smaller than a decrease in the share of the domestic market. As a result, the positive scale effect of an increase in m on R&D investment of a spoke may be dominated by the negative competition effect. Conditions (a) – (c) ensure that this would not be the case if the trade costs of firms are sufficiently high to confine the amount of exports from new trade partners, or if hubs represent only a minor share of direct trade partners of a spoke, or alternatively, if the differences in the market size of a hub and a spoke are comparable.

The results of Proposition 2 are illustrated with Figures 4 and 5 in the Appendix.[26]

Comparison of Scenario 1 and Scenario 2

In this section I use the results of Scenario 1 and 2 in order to address the main question of the paper. I concentrate on how different types of trade liberalization – multilateral versus regional – and the resulting structures of trade agreements – complete versus hub-and-spoke – compare in terms of R&D investments of firms within these structures.

The comparison is made in two steps. First, I investigate the basic relationship between the R&D level of a firm in the multilateral trade agreement and of a firm (hub and spoke) in the regional hub-and-spoke trade system. After that I proceed to the more detailed analysis in which I distinguish between different types of the hub-and-spoke trade structure. The aim of this analysis is to gain better understanding of how the structure of a trade system matters for the firm's R&D decision. In particular, I will study how the R&D effort of a firm in the multilateral agreement places in the ranking of R&D efforts of firms across various types of the hub-and-spoke structure. Consider each step in turn.

Step 1 To gain some insights about the sources of variation in R&D efforts of a firm across the multilateral and the hub-and-spoke trade systems, let us first abstract from the issue of differences

[25] The proportion of spokes to hubs among the new trade partners is determined by φ: the lower φ, the higher the relative number of hubs.

[26] Both figures are produced using the same parameter values as for Figure 2 in Scenario 1. In addition, for Figure 4, I set $\psi = \varphi = 0$ and for Figure 5, $n = 6$, $m = 2$.

between firms in terms of their competitive market power. That is, assume for a while that all firms within one trade system and across systems are equally competitive. In that case, all firms operating in the market of any country obtain the same share of the market. Then, given the fixed number of direct trade partners, what determines the aggregate market size of a firm is purely the *number* of other firms (competitors) present in each trade partner country. The fewer competitors, the larger the aggregate market size of a firm and the higher the return to R&D investment.

In this simplified framework, for any number n of direct trade partners, the aggregate market size of a hub in *any* hub-and-spoke trade system is larger than that of a firm in the multilateral agreement. The reverse is true for spokes. For any number m of direct trade partners, the total market size of a spoke is smaller than that of a country in the multilateral agreement. To make sure of the first statement, observe that while in the multilateral agreement (of degree n), the number of competitors of a firm is n in *each* of its n foreign markets, in the hub-and-spoke trade system, the number of competitors of a hub is n only in $\psi \cdot n$ of its foreign markets and it is less than n in the rest of the markets. The similar argument leads to the statement for spokes.

These conclusions derived on the assumption of equal competitiveness of firms prove to hold without this assumption, too. Formally, the result is an immediate implication of Proposition 2 and the short proof is provided in the Appendix. Here, I state the result as

Corollary 2 *For any $0 \leq \psi, \varphi < 1$ and for any $n, m > 1$ such that $n > m$,*

$$x_h^* > x^*(n) > x^*(m) > x_s^*.$$

Besides, the same inequalities hold when a hub and a spoke belong not to one but to (any) different types of hub-and-spoke structure.[27]

Step 2 Now, I proceed to the comparison of equilibrium R&D efforts of firms across various types of the hub-and-spoke trade structure. To that end, I will restrict attention to the specific types of the hub-and-spoke structure presented in Table 1. Notice that by Corollary 2, it only remains to compare separately, R&D efforts of hubs and R&D efforts of spokes since R&D of a hub is always higher than R&D of a spoke both in one and in different types of the hub-and-spoke structure.

As before, assume that competitive power of all firms (hubs and spokes) across all structures is the same and consider the differences in market sizes of hubs and spokes across these structures. With regard to hubs, observe that for any number n of hub's direct trade partners, a hub in the star (Type 1 system) enjoys the lowest competition in any of its foreign markets as compared to hubs

[27]Recall from Scenario 1 that $x^*(n)$ denotes the equilibrium R&D effort of a firm in the multilateral agreement of degree n.

in the other systems. Therefore, the total market size of a hub in the star is the largest. Further, as a number of firms (competitors) in markets of hub's direct trade partners grows, the aggregate market size of the hub decreases. This is the case when either the number m of spoke's direct trade partners grows (Type 3 system), or the share ψ of hubs among direct trade partners increases (Type 2 system), or when both changes in m and ψ happen simultaneously (Type 4 system). Besides, the larger the increase in m and/or ψ, the smaller the size of the aggregate hub's market.

For spokes the situation is symmetric. Given any number n of hub's direct trade partners, a spoke in the star (Type 1 system) has access to a single foreign market. Therefore, spoke's market in the star is smaller than spoke's market in any other hub-and-spoke trade system.[28] As a number of direct trade partners of a spoke increases (Type 3 system), the market of a spoke extends. It extends even further if the share φ of spokes among direct trade partners grows (Type 5 system). Besides, the larger the increase in the number of direct trade partners and/or φ, the larger the aggregate market size of a spoke.

As in Step 1, the insights gained on the assumption of equal market power of firms prove to be correct when the assumption is relaxed. This leads to Corollary 3, which is formally derived in the Appendix. To state the corollary, I denote by x^*_{hi} the equilibrium R&D effort of a hub and by x^*_{si} – the equilibrium R&D effort of a spoke in the hub-and-spoke trade system of Type i, $i \in 1:5$.

Corollary 3 *Consider Types 1–5 of the hub-and-spoke trade structure. Suppose that (i) n is the same across all types, (ii) m is the same across all types where $m > 1$ (Types 3, 4 and 5), and (iii) ψ is the same across all types where $\psi > 0$ (Types 2 and 4). Let $x^*(n)$ and $x^*(m)$ be defined for n and $m > 1$, identical to those in Types 1 – 5 of the hub-and-spoke structure. Then firms' equilibrium R&D efforts in Types 1–5 of the hub-and-spoke structure and in the multilateral agreement rank as follows:*

$$x^*_{h1} > x^*_{h3} > x^*_{h4} > x^*(n) > x^*(m) > x^*_{s5} > x^*_{s3} > x^*_{s1}.$$

Besides, with respect to the equilibrium R&D effort x^*_{h2} of a hub and x^*_{s2} of a spoke in Type 2 system, the following inequalities hold:

$$x^*_{h1} > x^*_{h2} > x^*_{h4} \qquad \text{and} \qquad x^*_{s4} > x^*_{s2}.$$

Corollary 3 is illustrated with Figure 3 and Figure 6 (in the Appendix).

Thus, the R&D efforts of firms in the multilateral and various types of hub-and-spoke trade systems vary substantially. The highest R&D incentives exist for a hub, especially for a hub in the star (Type 1 system), whereas for a spoke the incentives are the lowest. As the number of direct trade

[28] In fact, on the assumption of equal firms' competitiveness, the market size of a spoke in Type 2 system is the same as in the star.

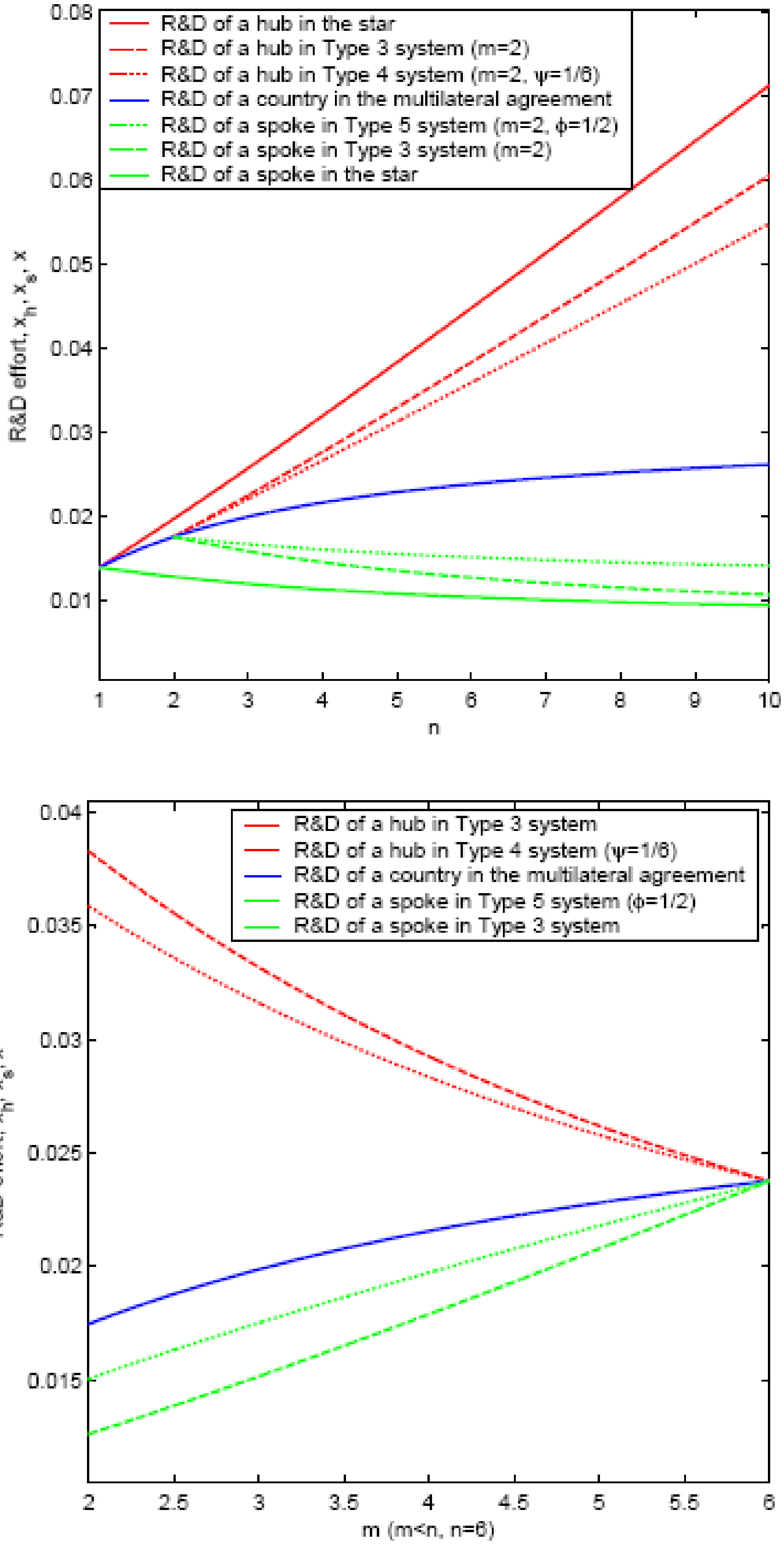


Figure 3: Equilibrium R&D efforts in the multilateral and in the hub-and-spoke trade system as a function of n (the upper sub-figure) and as a function of m (the lower sub-figure).

partners of a spoke and/or the share of spokes among direct trade partners of each firm increase, the levels of R&D investment of hubs and spokes draw closer together. They "meet" at the level of R&D investment of a firm in the multilateral agreement, which therefore, takes an average position: it is lower than R&D of a hub but higher than R&D of a spoke.

In addition to comparison of individual R&D investments by firms, I consider the aggregate levels of R&D activities within the multilateral trade agreement versus that in the star. I find that although individual R&D of a hub in the star is much higher than R&D of a single country in the multilateral agreement, a "bunch" of several bilaterals of one country (a hub) with the others (spokes) generates *lower* aggregate R&D than the multilateral agreement between the same total number of countries. This observation is demonstrated by Figure 7 in the Appendix.

Finally, Figures 3 and 6 provide some insights concerning the *growth rates* of firms' individual R&D efforts as the network of trade agreements expands. They show that under the conditions of Proposition 2 (parameter restrictions (6.7)–(6.8) and conditions (a)–(c)), for any equal number of direct trade partners of a country in the multilateral trade agreement and of a hub (spoke) in the hub-and-spoke trade system, the growth of the R&D effort caused by a new direct trade partner is lower for a firm in the multilateral trade system than for a hub (spoke). The intuition for this result is simple. Observe that in the multilateral agreement an increase in the number of direct trade partners (foreign markets) of a firm augments the number of competitors in *all* firm's markets: domestic and foreign. As opposed to that, in the hub-and-spoke trade system, the same increase in the number of direct trade partners of a hub or a spoke enhances competition in their domestic market but *does not increase* the number of competitors in *all* of their foreign markets. In fact, given the specification of the hub-and-spoke structure in this model, an increase in the number n (m) of direct trade partners of a hub (spoke) augments the number of competitors only in $\psi \cdot n < n$ ($\varphi \cdot m < m$) of its foreign markets. As a result, the negative competition effect of new trade partners in the multilateral agreement is stronger than in the hub-and-spoke trade system, so that the incentives for R&D enhancement due to new trade agreements are higher within the hub-and-spoke structure than within the multilateral system.

7 Policy implications

The previous analysis suggests that the structure of the network of trade agreements and the position of a country in this network are key for understanding the differences in R&D and productivity levels of firms across multilateral and regional types of trade systems. This adduces new arguments for the ongoing debate on gains and losses of multilateralism versus regionalism, especially with respect to intensive proliferation of regional trade agreements among WTO member countries. The paper suggests that the conversion from multilateralism to regionalism improves R&D (and productivity level) of "strong negotiators" – the countries which sign and sustain sufficiently many regional trade agreements. However, it reduces R&D incentives for the other countries, which become "spokes" in the newly formed regional hub-and-spoke trade system. In addition, the conversion to regionalism may actually decrease R&D of *all* countries if even relatively successful negotiators sign only a few regional trade agreements.

The finding of a substantially lower R&D and productivity levels in a spoke economy as compared to those in a hub and in a country within the multilateral system, supports the argument of earlier studies about the disadvantageous position of spokes. For instance, Baldwin (2003), Kowalczyk and Wonnacott (1992), Deltas et al. (2005), Lloyd and Maclaren (2004), and De Benedictis et al. (2005) find that welfare and income levels are lower for spokes than for hubs and than for countries in the complete network. In agreement with the literature, this paper suggests that spoke economies would benefit from choosing the multilateralist alternative as it would allow improving their innovation and productivity.

In addition, the paper indicates the positive impact of the expansion of the WTO on R&D and productivity of *every* member country. In the same manner, the consolidation of several smaller plurilateral blocks or their accession to the WTO enhances R&D in every country.[29]

Recall that for the specific classes of networks considered in Scenario 1 and Scenario 2, we found that, everything else being equal, the equilibrium R&D effort of a firm is increasing in the number of its direct trade partners (scale and competition effects of trade liberalization) but decreasing in the number of its two-links-away trade partners (competition effect only).[30] In the following section I further investigate the issue of the impact which direct and two-links-away trade partners have on R&D of a firm in a *generic* network under the assumption of *small external effects*.

8 Equilibrium R&D efforts in arbitrary network: The case of small external effects

Consider the system of first-order optimality conditions (4.3). In this section I study properties of the solution to this system when the magnitude of local effects – effects of interaction between firms in the

[29] According to Fiorentino et al. (2007), the number of merging regional trade agreements is currently increasing. Examples include EC-GCC, SACU-MERCOSUR, among others.

[30] Notice that in the multilateral trade agreement of degree n, every direct trade partner of a firm is also $(n-1)$-times its two-links-away trade partner since it is a direct trade partner of any of $(n-1)$ remaining direct trade partners of the firm. The increasingly negative competition effect of trade liberalization in the multilateral agreement is caused by the increasing importance of a role of a new trade partner as a two-links-away trade partner of a firm.

network – is arbitrarily small. I seek for the ranking of optimal R&D decisions of firms in accordance with simple characteristics of firms' positions in the network, such as the nodal degrees and the sum of neighbors' degrees. To derive this ranking, I employ the asymptotic approach suggested by Bloch and Quérou (2008).[31]

As before, for simplicity I assume that δ_i is the same for all firms. Notice that the system of linear first-order conditions (4.3) can be written as

$$\delta x_i - \frac{1}{b}\left[\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}x_i - \sum_{j\in N_i}\left(\frac{|N_i|+1}{(|N_i|+2)^2}+\frac{|N_j|+1}{(|N_j|+2)^2}\right)x_j - \sum_{j\in N_i}\sum_{k\in N_j,k\neq i}\frac{|N_j|+1}{(|N_j|+2)^2}x_k\right] =$$
$$= \frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{|N_j|+1}{(|N_j|+2)^2}\left(a-\alpha+\sum_{k\in N_j,k\neq i}\tau_{kj}-(|N_j|+1)\tau_{ij}\right), \qquad i\in 1:N.$$

In the matrix form this has a simple representation

$$\left(\delta\mathbf{I}-\frac{1}{b}\mathbf{B}\right)\cdot\mathbf{x}=\frac{1}{b}\tilde{\mathbf{u}}.$$

Alternatively,

$$(\mathbf{I}-\lambda\mathbf{B})\cdot\mathbf{x}=\lambda\tilde{\mathbf{u}}, \tag{8.1}$$

where $\lambda=\frac{1}{b\delta}$. In this system, matrix $\lambda\mathbf{B}$ is the matrix of local effects. Below, I investigate the solution to (8.1) when the norm of matrix $\lambda\mathbf{B}$ capturing the magnitude of local effects is small.

First, following Bloch and Quérou (2008), I define a vector sequence $\mathbf{f}=(\mathbf{c}^1,\mathbf{c}^2,\ldots,\mathbf{c}^m,\ldots)$, where each vector $\mathbf{c}^m$ is given by

$$\mathbf{c}^m=\lambda^m\tilde{\mathbf{u}}\mathbf{B}^{m-1}.$$

The first terms of this sequence are

$$\begin{aligned}\mathbf{c}^1 &= \lambda\tilde{\mathbf{u}},\\ \mathbf{c}^2 &= \lambda^2\tilde{\mathbf{u}}\mathbf{B},\\ \mathbf{c}^3 &= \lambda^3\tilde{\mathbf{u}}\mathbf{B}^2.\end{aligned}$$

Using the sequence $\mathbf{f}$, I can now state the approximation result, which provides an equivalence between the ranking of the components of the solution $\mathbf{x}^*$ to (8.1) and the lexicographic ordering of the components of $\mathbf{f}$ when the magnitude of $\|\lambda\mathbf{B}\|$ is close to zero.

Proposition 3 *Consider a system of linear equations* (8.1)*. Suppose that* $\|\lambda B\|$ *is sufficiently small:*[32] *for a given* $0<\bar{\varepsilon}<1$, $\|\lambda B\|\leq\frac{\bar{\varepsilon}}{N}$*. Then there exists a unique solution* $\mathbf{x}^*$ *and* $K>1$ *such that for*

[31] As emphasized in Bloch and Quérou (2008), at least two arguments can defend the usefulness of studying network effects whose magnitude is small. First, when the matrix of interactions is complex, this may be the only way to evaluate the equilibrium R&D decisions for an *arbitrary* network structure. Secondly, by continuity, the insights obtained for small external effects continue to hold as the magnitude of externalities increases.

[32] As in Bloch and Quérou (2008), I use the l_∞ vector norm defined by $\|\mathbf{A}\|=\max_{i,j}|a_{ij}|$

any $i, j \in 1 : N$, $i \neq j$,

$$|x_i^* - x_j^* - (c_i^M - c_j^M)| \leq \lambda \cdot \frac{\bar{\varepsilon}^{K+1}}{1-\bar{\varepsilon}} \cdot 2\|\tilde{\mathbf{u}}\|,$$

where $(c_M)_i$ *and* $(c_M)_j$ *are the first unequal elements of the sequences* $\mathbf{f}_i = (\mathbf{c}_i^1, \mathbf{c}_i^2, \ldots, \mathbf{c}_i^m, \ldots)$ *and* $\mathbf{f}_j = (\mathbf{c}_j^1, \mathbf{c}_j^2, \ldots, \mathbf{c}_j^m, \ldots)$*:* $\mathbf{c}_i^M \neq \mathbf{c}_j^M$ *and* $\mathbf{c}_i^m = \mathbf{c}_j^m$ *for all* $m < M$*.*

Thus, if the upper bound for the magnitude of local effects is close to zero,

$$x_i^* > x_j^* \Leftrightarrow \mathbf{f}_i \succ \mathbf{f}_j,$$

where $\mathbf{f}_i \succ \mathbf{f}_j$ stands for lexicographic dominance of $\mathbf{f}_i$ over $\mathbf{f}_j$. This means that in order to compare equilibrium R&D efforts of different firms, one can restrict attention to the first order term $\mathbf{c}^1$, or if the first order terms are equal, to the second order term $\mathbf{c}^2$, etc. As a result, the ranking of optimal R&D choices of firms reduces to the ranking of characteristics of firms' positions in the network.

Consider a pair of firms (i, i'), $i, i' \in 1 : N$, such that $\tilde{\mathbf{u}}_i \neq \tilde{\mathbf{u}}_{i'}$. Then by Proposition 3, if

$$\|\lambda B\| \leq \frac{\bar{\varepsilon}}{N}$$

for some $0 < \bar{\varepsilon} < 1$, then the difference between x_i^* and $x_{i'}^*$ can be approximated by the difference between $\tilde{\mathbf{u}}_i$ and $\tilde{\mathbf{u}}_{i'}$ such that the measurement error does not exceed $\lambda \cdot \frac{\bar{\varepsilon}^{K+1}}{1-\bar{\varepsilon}} \cdot 2\|\tilde{\mathbf{u}}\|$, where

$$\|\tilde{\mathbf{u}}\| = \max_i \sum_{j \in N_i \cup \{i\}} \frac{|N_j|+1}{(|N_j|+2)^2} \Bigg(a - \alpha + \sum_{k \in N_j, k \neq i} \tau_{kj} - (|N_j|+1)\tau_{ij} \Bigg).$$

So, when the local effects are small, the R&D effort chosen by firm i is at least as high as the R&D effort of firm i' if and only if

$$\sum_{j \in N_i \cup \{i\}} \frac{|N_j|+1}{(|N_j|+2)^2} \Bigg(a - \alpha + \sum_{k \in N_j, k \neq i} \tau_{kj} - (|N_j|+1)\tau_{ij} \Bigg) \geq \\ \geq \sum_{j \in N_{i'} \cup \{i'\}} \frac{|N_j|+1}{(|N_j|+2)^2} \Bigg(a - \alpha + \sum_{k \in N_j, k \neq i'} \tau_{kj} - (|N_j|+1)\tau_{i'j} \Bigg). \quad (8.2)$$

The inequality (8.2) suggests that at the first order the R&D effort of firm i is increasing in the number $|N_i|$ of i's direct trade partners as soon as the new trade partner j' is such that

$$\frac{|N_i|+2}{(|N_i|+3)^2} \Bigg(a - \alpha + \sum_{k \in N_i} \tau_{ki} + \tau_{j'i} \Bigg) - \frac{|N_i|+1}{(|N_i|+2)^2} \Bigg(a - \alpha + \sum_{k \in N_i} \tau_{ki} \Bigg) + \\ + \frac{|N_{j'}|+1}{(|N_{j'}|+2)^2} \Bigg(a - \alpha + \sum_{m \in N_{j'}, m \neq i} \tau_{mj'} - (|N_{j'}|+1)\tau_{ij'} \Bigg) > 0.$$

Alternatively, this can be written as

$$\frac{|N_i|+2}{(|N_i|+3)^2}\tau_{j'i} + \frac{|N_{j'}|+1}{(|N_{j'}|+2)^2} \Bigg(a - \alpha + \sum_{m \in N_{j'}, m \neq i} \tau_{mj'} - (|N_{j'}|+1)\tau_{ij'} \Bigg) > \\ > \frac{|N_i|^2 + 3|N_i| + 1}{(|N_i|+2)^2(|N_i|+3)^2} \Bigg(a - \alpha + \sum_{k \in N_i} \tau_{ki} \Bigg). \quad (8.3)$$

It is easy to see that the left-hand side of inequality (8.3) is increasing in $\tau_{j'i}$ and $\{\tau_{mj'}\}_{m\in N_{j'},m\neq i}$. On the other hand, it is decreasing in $|N_{j'}|$ and $\tau_{ij'}$. This means that the additional direct trade partner j' of i increases i's incentives to innovate as soon as the trade cost $\tau_{j'i}$ of j' in market i and the trade costs $\{\tau_{mj'}\}_{m\in N_{j'},m\neq i}$ of i's competitors in market j' are sufficiently high, while the number of competitors $|N_{j'}|$ of i in market j' and the cost $\tau_{ij'}$ of exporting from i to j' are low. This suggests that in accordance with the earlier discussion in the paper, opening trade with an additional trade partner increases the R&D investment of firm i if the market size of i actually increases.

In addition, the inequality (8.2) suggests that at the first order the R&D effort of firm i is decreasing in the number $|N_j|$, $j \in N_i$, of i's two-links-away trade partners, at least as soon as the trade cost $\tau_{k'j}$ of the additional two-links-away trade partner k' with $j \in N_i$ is lower or equal than the trade cost τ_{ij} of i with j.

The finding of a positive effect of direct trade partners and a negative effect of two-links-away trade partners of i on i's equilibrium R&D effort, together with the conditions which guarantee these effects, are consistent with the findings of Scenarios 1 and 2 discussed earlier in the paper.

9 Conclusion

This paper develops a model of international trade with firm-level productivity improvements via R&D. Firms in different countries sell their product and compete in a Cournot fashion with other firms in the domestic market and in the markets of their trade partner countries. The trade partner countries of any country/firm are defined by the network of trade agreements: countries which are linked in the network are (direct) trade partners of each other.

I focus on two specific types of networks: the complete and the hub-and-spoke network. In the model, these networks represent trade arrangements which arise as a result of multilateral or regional trade liberalization, respectively. I study how the structure of the trade arrangement and the position of a country in this structure affect R&D investments by firms. In this manner I address the issue of variation in the impact that multilateral and regional types of trade liberalization may have on firms' R&D and productivity.

I show that the R&D response of firms to trade liberalization is the net outcome of two different effects: one, stimulating R&D through the creation of new markets (scale effect), and the other, deterring R&D through the emergence of new competitors (competition effect). I find that although the signs of both effects are the same across the multilateral and the regional/hub-and-spoke trade systems, the sizes of the effects differ. Basically, a new country entering the multilateral or the hub-and-spoke trade system represents different "value added" for firms in every system since the effective size of the new market and the competitive impact of the new firm depend on the structure of the trade system.

The variation in the market sizes of countries across the multilateral and the hub-and-spoke trade systems explains the variation in levels of R&D efforts when the number of firms' trade partners is fixed. For the *same number of direct trade partners*, the R&D effort of a hub in the hub-and-spoke trade system is higher than the R&D effort of a country in the multilateral agreement. On the other hand, R&D of a spoke is lower than R&D of a hub and lower than R&D of a country in the multilateral agreement, even if a country in the multilateral agreement has the same number of direct trade partners as a spoke.

In addition, consistently with the findings of empirical literature, I obtain that in both the multilateral and the regional trade systems, R&D of a firm increases in response to a new market opening. However, the size of this increase varies across different types of trade systems. I show that for any equal number of direct trade partners of a country in the multilateral trade agreement and of a hub (spoke) in the hub-and-spoke trade system, the growth of the R&D effort caused by a new direct trade partner is lower for a firm in the multilateral trade system than for a firm in a hub (spoke).

Results of the study of trade liberalization effects on firms' R&D within the specific network structures induced the investigation of a more general case. For an *arbitrary* network of trade agreements and small external effects of interaction between firms, I obtain the results which are consistent with the previous analysis. I find that new direct trade partners of a firm (mostly) increase its R&D investment. Besides, the smaller the number of competitors in the new markets, the larger the increase in R&D.

The paper suggests some policy implications. For example, with regard to the benefits and losses from the conversion of many WTO members to regionalism, the paper implies that this conversion is likely to improve R&D and productivity level of "strong negotiators" (hubs) – the countries which sign sufficiently many regional trade agreements. At the same time, the regionalist alternative reduces R&D of weaker negotiators, which are mainly involved in one or a few trade agreements with hubs.

10 Appendix

Appendix A: Proofs

Derivation of the profit function in (4.5)

The profit function in (4.1) can be written as

$$\begin{aligned}\pi_i &= 2x_i^*\Bigg[\frac{1}{b}\sum_{j\in N_i}\frac{|N_j|+1}{(|N_j|+2)^2}\Big(a-\alpha+\sum_{k\in N_j,k\neq i}\tau_{kj}-(|N_j|+1)\tau_{ij}\Big)-\\ &- \frac{1}{b}\sum_{j\in N_i}\Big[\frac{|N_i|+1}{(|N_i|+2)^2}+\frac{|N_j|+1}{(|N_j|+2)^2}\Big]x_j^*-\frac{1}{b}\sum_{j\in N_i}\sum_{k\in N_j,k\neq i}\frac{|N_j|+1}{(|N_j|+2)^2}x_k^*\Bigg]-\\ &- \Big[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}+\delta_i\Big]x_i^{*2}+f(\{x_k\}_{k\in N_i\cup N_i^2}).\end{aligned}$$

By the first-order conditions (4.3), this reduces to

$$\begin{aligned}\pi_i &= 2\Big[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}+\delta_i\Big]x_i^{*2}-\Big[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}+\delta_i\Big]x_i^{*2}+\\ &+ f(\{x_k\}_{k\in N_i\cup N_i^2})=\Big[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(|N_j|+1)^2}{(|N_j|+2)^2}+\delta_i\Big]x_i^{*2}+\\ &+ \frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{1}{(|N_j|+2)^2}\Bigg(a-\alpha-(|N_j|+1)\tau_{ij}-\sum_{k\in N_j\cup\{j\},k\neq i}(x_k^*-\tau_{kj})\Bigg)^2.\end{aligned}$$

Proof of Proposition 1

The proof is established in two steps.

1. R&D effort x^* is monotonically increasing in n

   Taking a derivative of x^* in (6.1) with respect to n, we obtain:

$$\begin{aligned}\frac{\partial x^*}{\partial n} &= \frac{-\frac{\tau}{(n+1)^2}\big(-1+\delta b(1+\frac{1}{n+1})^2\big)+2\delta b(1+\frac{1}{n+1})\frac{1}{(n+1)^2}\big(a-\alpha-\frac{n}{n+1}\tau\big)}{\big(-1+\delta b(1+\frac{1}{n+1})^2\big)^2}=\\ &= \frac{\frac{1}{(n+1)^2}\Big(\tau+\delta b(1+\frac{1}{n+1})\big(-\tau(1+\frac{1}{n+1})+2(a-\alpha-\frac{n}{n+1}\tau)\big)\Big)}{\big(-1+\delta b(1+\frac{1}{n+1})^2\big)^2}.\end{aligned}$$

   The sign of this derivative is positive as soon as

$$2\big(a-\alpha-\frac{n}{n+1}\tau\big)>\tau\big(1+\frac{1}{n+1}\big).$$

   One can readily see that this inequality holds due to the restriction on a in (6.3).

2. profit π is monotonically decreasing in n

   Due to the computational complexity, I present only a schematic proof of this statement.

Taking the derivative of π in (6.1) with respect to n, we obtain the expression represented by the product of the ratio $\frac{1}{b(2n-4b\delta+n^2-4bn\delta-bn^2\delta+1)^3}$ and the quadratic polynomial of τ. The ratio is negative for any $n \geq 1$ due to the restriction on δ in (6.4). On the other hand, the value of the polynomial is positive for any $n \geq 1$ as soon as parameters satisfy the restrictions (6.3) and (6.4). The latter is established via two steps.

- First, I find that due to the restriction (6.4) the coefficient of the polynomial at the quadratic term τ^2 is negative for any given $n \geq 1$. Besides, the constant term is positive. Hence, the graph of the quadratic function is a parabola with downward-directed branches and two real roots – one positive and one negative.
- Since the unit trade cost τ is positive and by the restriction (6.1) it does not exceed $\frac{1}{2}(a-\alpha)$, to establish that the value of the polynomial is positive for all $\tau \in (0, \frac{1}{2}(a-\alpha))$, it suffices to show that the value of the polynomial is positive at $\tau := \frac{1}{2}(a-\alpha)$. One can find that this is indeed the case, provided that (6.3) and (6.4) hold.

Thus, for all $n \geq 1$ and any parameter values satisfying the conditions (6.3) and (6.4), the derivative of π with respect to n is negative, so that the profit function is decreasing in n.

■

Sketch of the proof of Proposition 2

The equilibrium R&D effort of a hub and a spoke are given by the solution to the system of equations (6.5)– (6.6):

$$x_s^* = \frac{\begin{aligned}&\Big((a-\alpha-2\tau)(1-\varphi)m(n+1)(m+2)^2+(m+1)(n+2)^2\big[(a-\alpha-2\tau)\varphi m+a-\alpha+m\tau\big]\Big)\cdot\\ &\cdot\Big((n+2)^2\big[b\delta(m+2)^2-n(1-\psi)(m+1)(2+\varphi m)\big]-(n\psi+1)(n+1)(n(1-\psi)+1)(m+2)^2\Big)-\\ &-(1-\varphi)m\Big((n\psi+1)(n+1)(m+2)^2+(\varphi m+1)(m+1)(n+2)^2\Big)\cdot\\ &\cdot\Big((a-\alpha-2\tau)\big[n\psi(n+1)(m+2)^2+(n-n\psi)(m+1)(n+2)^2\big]+(n+1)(m+2)^2(a-\alpha+n\tau)\Big)\end{aligned}}{\begin{aligned}&\Big((n+2)^2\big[b\delta(m+2)^2-n(1-\psi)(m+1)(2+\varphi m)\big]-(n\psi+1)(n+1)(n(1-\psi)+1)(m+2)^2\Big)\cdot\\ &\cdot\Big(-(1-\varphi)m(m+2)^2(n\psi+2)(n+1)+(n+2)^2\delta b(m+2)^2-\\ &-(n+2)^2\big[(\varphi m+1)(m+1)^2-m\varphi(m+1)(1+\varphi m)\big]\Big)-\\ &-(1-\varphi)(1-\psi)mn\Big((n+1)(m+2)^2(1+n\psi)+(m+1)(n+2)^2(1+\varphi m)\Big)^2\end{aligned}}$$

$$x_h^* = \frac{\begin{array}{c}(a-\alpha-2\tau)\big(n\psi(n+1)(m+2)^2+(n-n\psi)(m+1)(n+2)^2\big)+(n+1)(m+2)^2(a-\alpha+n\tau)- \\ -x_s^*(n-n\psi)\big((m+1)(n+2)^2+(n+1)(m+2)^2+\varphi m(m+1)(n+2)^2+n\psi(n+1)(m+2)^2\big)\end{array}}{\begin{array}{c}b\delta(n+2)^2(m+2)^2-(n\psi+1)(n+1)^2(m+2)^2-(n-n\psi)(m+1)^2(n+2)^2+ \\ +n\psi(2n+2)(m+2)^2+((1-\varphi)m-1)(n-n\psi)(m+1)(n+2)^2+n\psi(n\psi-1)(n+1)(m+2)^2\end{array}}$$

Taking a derivative of x_h^* and x_s^* with respect to each of the parameters m, n, φ and ψ, we obtain a ratio, where the denominator is unambiguously positive while the sign of the numerator is determined by the sign of a cubic polynomial in δ. As soon as δ is sufficiently large – greater than the largest real root of the polynomial, the sign of the polynomial is defined by the sign of the coefficient at the highest degree.

Thus, to simplify calculations, I assume that δ is large enough ($\delta > \Delta$) and focus on the sign of the polynomial's coefficient at δ^3. Then I obtain that under the parameter restriction (6.7), partial derivatives $\frac{\partial x_s^*}{\partial n}$, $\frac{\partial x_h^*}{\partial m}$, and $\frac{\partial x_h^*}{\partial \psi}$ are negative and the derivative $\frac{\partial x_s^*}{\partial \varphi}$ is positive. As regarding the derivative $\frac{\partial x_s^*}{\partial m}$, this derivative is positive if and only if the following inequality holds:

$$(a-\alpha-2\tau)(1-\varphi)\cdot A+(a-\alpha-2\tau)\cdot B+\tau\cdot C > (a-\alpha-2\tau)(1-\varphi)\cdot D-(a-\alpha-2\tau)\varphi\cdot E, \qquad (10.1)$$

where

$$\begin{aligned}
A &= m^6n^4+7m^6n^3+18m^6n^2+20m^6n+8m^6+12m^5n^4+84m^5n^3+216m^5n^2+240m^5n+96m^5,\\
B &= -30m^4n^4\varphi+50m^4n^4-300m^4n^3\varphi+380m^4n^3-840m^4n^2\varphi+1000m^4n^2-960m^4n\varphi\\
&\quad +1120m^4n-384m^4\varphi+448m^4+40m^3n^4\varphi+100m^3n^4-320m^3n^3\varphi+880m^3n^3\\
&\quad -1280m^3n^2\varphi+2400m^3n^2-1600m^3n\varphi+2720m^3n-640m^3\varphi+1088m^3+240m^2n^4\varphi\\
&\quad +120m^2n^4+240m^2n^3\varphi+1200m^2n^3-480m^2n^2\varphi+3360m^2n^2-960m^2n\varphi+3840m^2n\\
&\quad -384m^2\varphi+1536m^2+288mn^4\varphi+112mn^4+576mn^3\varphi+1024mn^3+384mn^2\varphi+2816mn^2\\
&\quad +3200mn+1280m+16n^5\varphi+96n^4\varphi+64n^4+192n^3\varphi+448n^3+128n^2\varphi+1152n^2+1280n+512,\\
C &= 160n^4+1024m+1280n+768m^2+256m^3+32m^4+1280n^2+640n^3+512+16n^5\\
&\quad +1929m^2n^2+960m^2n^3+640m^3n^2+320m^3n^3+80m^4n^2+24m^2n^5+80m^3n^4+40m^4n^3\\
&\quad +1286mn^3+8m^3n^5+10m^4n^4+m^4n^5+2560mn+2560mn^2+1920m^2n+640m^3n\\
&\quad +80m^4n+32mn^5+320mn^4+240m^2n^4,\\
D &= m^4n^5+6m^3n^5+12m^2n^5+8mn^5,\\
E &= 2m^4n^5+14m^3n^5+36m^2n^5+40mn^5.
\end{aligned}$$

Notice that A, B, C, D, and E are all positive, so that the left-hand side of (10.1) is positive, while the sign of the right-hand side is determined by relative values of $(1-\varphi)\cdot D$ and $\varphi\cdot E$. It is easy to see that $2D < E$. Hence, for $\varphi \geq 1/3$, $(1-\varphi) \cdot D < \varphi \cdot E$ and the right-hand side of (10.1) is negative. This establishes condition (b) of the proposition.

Observe also that $C > D$. Then as soon as $\tau \geq (a - \alpha - 2\tau)(1-\varphi)$, inequality (10.1) holds. This justifies condition (a).

Finally, condition (c) follows from the series of inequalities. First, when $n \leq m^2$,

$$A > m^4n^5 + 12m^3n^5 + 7m^2n^5 + 84mn^5. \tag{10.2}$$

Secondly, since $m > n$,

$$m^4n^5 + 12m^3n^5 + 7m^2n^5 + 84mn^5 > m^4n^5 + 6m^3n^5 + 13m^2n^5 + 84mn^5 > D. \tag{10.3}$$

Combining (10.2) and (10.3), we obtain that $A > D$, so that inequality (10.1) is satisfied.

■

Proof of Corollary 2

First, notice that a complete network of degree n (m) can be regarded as a hub-and-spoke network "composed of only hubs", that is, where $\psi = 1$ (composed of only spokes where $\varphi = 1$). Then inequality $x_h^* > x^*(n)$ follows from part 1 of Proposition 2 stating that x_h^* is decreasing in ψ. Similarly, $x^*(m) > x_s^*$ is implied by the result that ∂x_s^* is increasing in φ. At last, inequality $x^*(n) > x^*(m)$ follows from Proposition 1.

■

Proof of Corollary 3

Consider the first series of inequalities in Corollary 3:

$$x_{h1}^* > x_{h3}^* > x_{h4}^* > x^*(n) > x^*(m) > x_{s5}^* > x_{s3}^* > x_{s1}^*.$$

There, the first three inequalities follow from part 1 of Proposition 2: $x_{h1}^* > x_{h3}^*$ since x_h^* is decreasing in m, while $x_{h3}^* > x_{h4}^* > x^*(n)$ since x_h^* is decreasing in ψ. Similarly, the last three inequalities are implied by part 2 of Proposition 2: $x^*(m) > x_{s5}^* > x_{s3}^*$ since x_s^* is increasing in φ, while $x_{s3}^* > x_{s1}^*$ since x_s^* is increasing in m. The intermediate inequality $x^*(n) > x^*(m)$ is a result of Proposition 1.

Likewise, with regard to the equilibrium R&D efforts x_{h2}^* and x_{s2}^* in Type 2 system, the inequality $x_{h1}^* > x_{h2}^*$ follows from the fact that x_h^* is decreasing in ψ, while $x_{h2}^* > x_{h4}^*$ and $x_{s4}^* > x_{s2}^*$ are the result of x_h^* and x_s^* being decreasing and increasing in m, respectively.

■

Proof of Proposition 3

The proof is suggested by the proof of Lemma 2.3 and Lemma 7.1 in Bloch and Quérou (2008).

Consider the system of linear equations (8.1). Since $\|\lambda \mathbf{B}\| \leq \frac{\bar{\varepsilon}}{N} < \frac{1}{N}$, Lemma 7.1 in Bloch and Quérou (2008) states that (8.1) possesses a unique solution and

$$\|\mathbf{x}^* - \lambda \tilde{\mathbf{u}} \cdot \sum_{k=0}^{K} \lambda^k \mathbf{B}^k\| \leq \frac{N^{K+1}\|\lambda \mathbf{B}\|^{K+1}\lambda\|\tilde{\mathbf{u}}\|}{1 - N\|\lambda \mathbf{B}\|} \leq \frac{\lambda \bar{\varepsilon}^{K+1}\|\tilde{\mathbf{u}}\|}{1-\bar{\varepsilon}}.$$

Observe that $\mathbf{c}^m$ is defined so that

$$\lambda \tilde{\mathbf{u}} \sum_{k=0}^{K} \lambda^k \mathbf{B}^k = \sum_{m=1}^{K+1} \mathbf{c}^m.$$

So,

$$\|\mathbf{x}^* - \sum_{m=1}^{K+1} \mathbf{c}^m\| \leq \frac{\lambda \bar{\varepsilon}^{K+1}\|\tilde{\mathbf{u}}\|}{1-\bar{\varepsilon}}.$$

By definition of the l_∞ vector norm, this means that $\forall i \in 1:N$

$$|\mathbf{x}_i^* - \sum_{m=1}^{K+1} \mathbf{c}_i^m| \leq \frac{\lambda \bar{\varepsilon}^{K+1}\|\tilde{\mathbf{u}}\|}{1-\bar{\varepsilon}}. \tag{10.4}$$

Consider a pair (i, j) of players and let M be the first element of the sequences $\mathbf{f}_i$, $\mathbf{f}_j$ such that $\mathbf{c}_i^M \neq \mathbf{c}_j^M$. Applying (10.4) to i and j, we obtain

$$|\mathbf{x}_i^* - \mathbf{x}_j^* - (\mathbf{c}_i^M - \mathbf{c}_j^M)| \leq 2 \cdot \frac{\lambda \bar{\varepsilon}^{K+1}\|\tilde{\mathbf{u}}\|}{1-\bar{\varepsilon}}.$$

This concludes the proof.

■

Appendix B: Figures

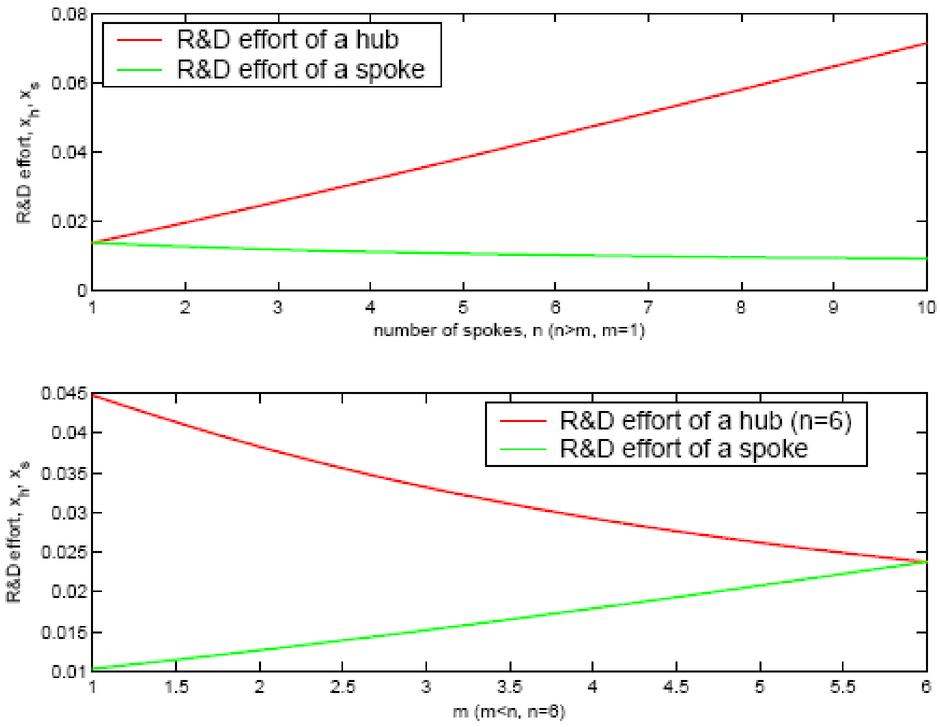


Figure 4: Equilibrium R&D efforts in the hub-and-spoke trade system as a function of n (the upper sub-figure) and as a function of m (the lower sub-figure).

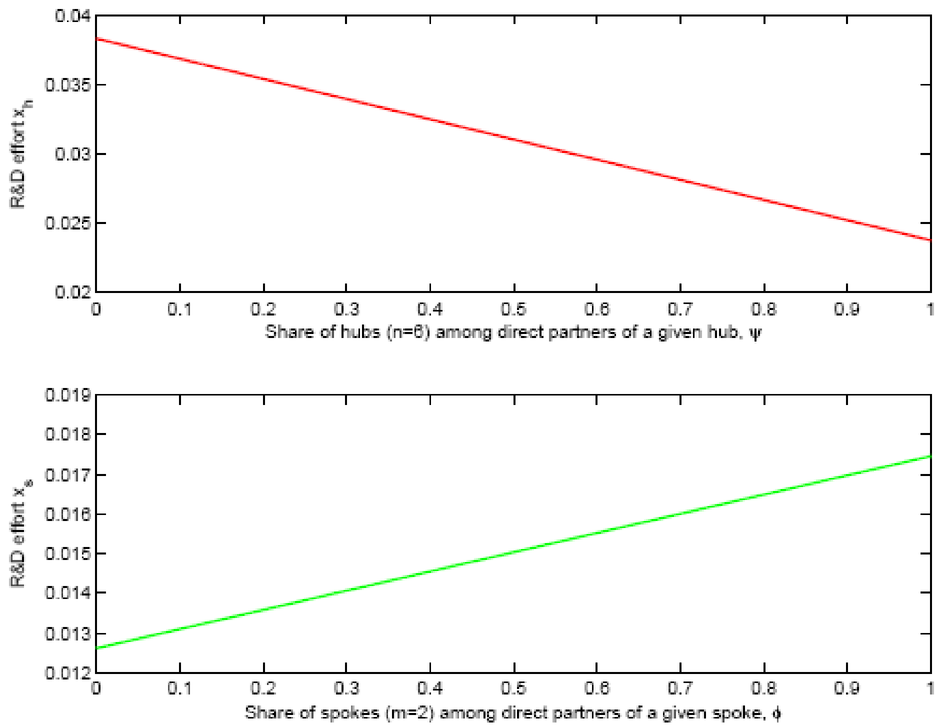


Figure 5: Equilibrium R&D efforts in the hub-and-spoke trade system as a function of ψ (the upper sub-figure) and as a function of φ (the lower sub-figure).

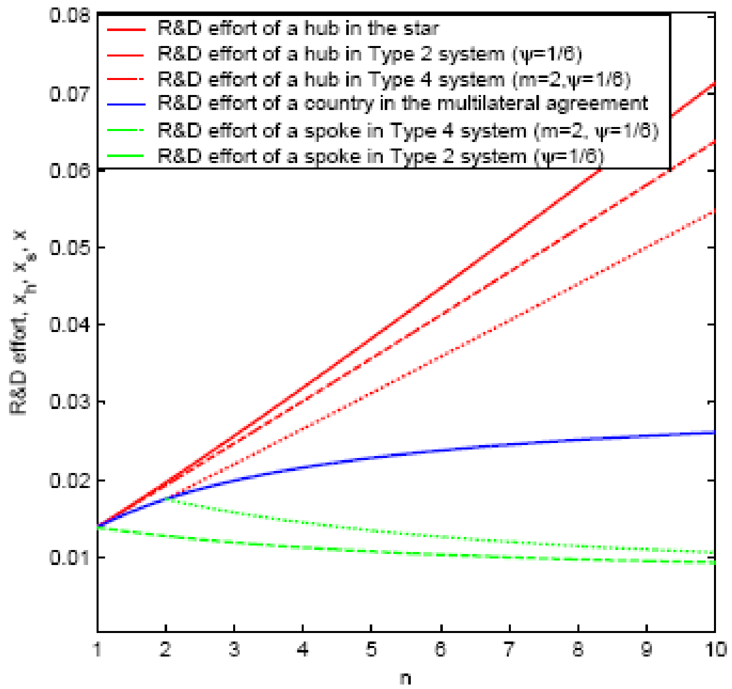


Figure 6: Equilibrium R&D efforts in Type 2 system as compared to R&D efforts in other hub-and-spoke systems and to R&D of a country in the multilateral agreement.

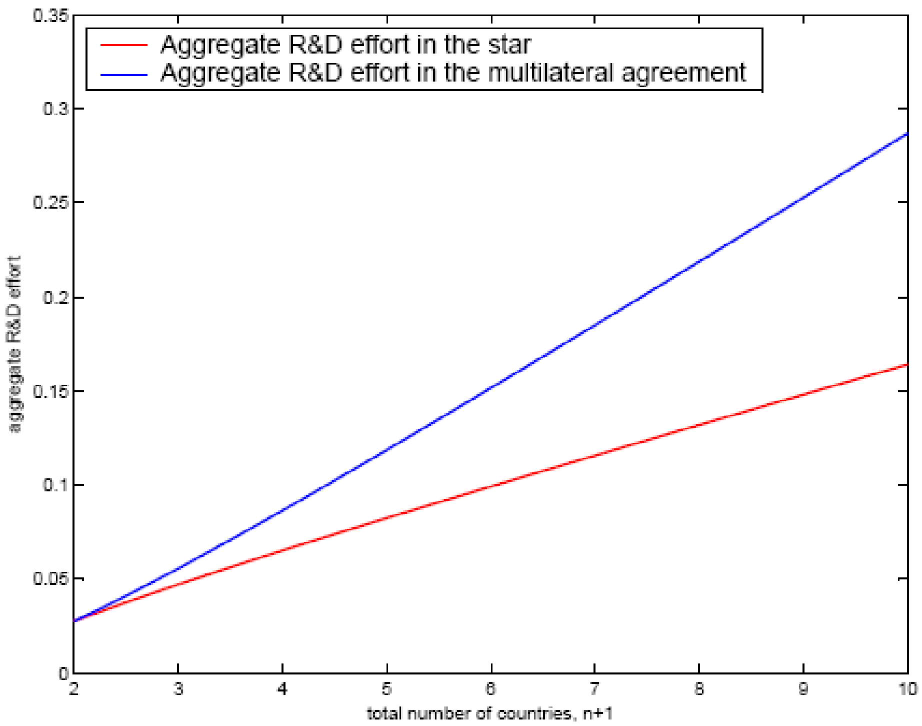


Figure 7: Aggregate equilibrium R&D efforts of n countries in the star and in the multilateral agreement.

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