Together at Last: The Endogenous Formation of Free Trade Agreements and International R&D Networks

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Abstract

We study the endogenous formation of free trade agreements (FTAs) between countries and international R&D networks between firms. The government of each country can initiate bilateral FTAs to abolish the import tariffs of other countries, while firms decide whether (and with whom) to form R&D collaborations. We build a model of double-layer networks where the network of FTAs is formed in the first layer, and the R&D network in the second layer. Consistently with the stylized facts, we find that FTAs can promote international R&D collaboration between firms. In terms of efficiency, private incentives to form FTAs align with societal ones, but for R&D networks, private and social incentives conflict.

Keywords: Networks, R&D collaboration, free trade.

JEL Classification: D85, L13, L20, O31, F10.

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1 Introduction

Over the past decades, international R&D collaboration between firms has grown fast. For instance, by the late 1990s, international R&D partnerships accounted for about one half of the newly established R&D partnerships (Hagedoorn, 2002).[1] At the same time, the number of free trade agreements (FTAs) between countries rose substantially.[2] Despite its acknowledged importance, economists have done comparatively little work relating the increase in the number of FTAs to the spread of international R&D collaborations. It is quite possible though that international R&D collaboration is affected by the trade relationships among countries where the firms are located. Indeed, the removal of trade barriers allows firms to access new markets and might induce them to do more R&D, either independently or with others, responding to a greater demand for their products. This article develops a model to explore how FTAs between countries as well as international R&D networks between firms emerge endogenously.

The literature on network formation devotes considerable attention to understanding how an R&D network (e.g. Goyal and Moraga-González, 2001; Zikos, 2010; Zu et al., 2011; Kesavayuth et al., 2014) or an FTA network (e.g. Goyal and Joshi, 2006; Furusawa and Konishi, 2007) emerges in equilibrium. Rather than viewing the two network formation decisions as separate, this article treats both as endogenous and considers their possible interactions, potentially providing new insights into the impact of FTAs on international R&D networks and vice versa.

We envisage a model with three ex-ante identical firms located in three ex-ante symmetric countries. The firm in each country can sell both to the domestic and foreign markets.

[1] There are different types of R&D collaboration in the literature, the most common ones being Research Joint Ventures (RJVs) and R&D networks. As documented by Caloghirou et al. (2003), non-equity types of alliances such as R&D networks accounted for about 85% of the total number of R&D collaborations by the mid-1990s. It has been argued that such popularity for R&D networks is partly attributed to the fact that they are often easier to establish, administer and dissolve relative to RJVs, all of which are important factors in a rapidly changing business environment (Narula and Hagedoorn, 1999). In this article we specifically focus on R&D networks; for studies on RJVs, though in a different context, the reader is directed to the articles by d' Aspremont and Jacquemin (1988), Kamien et al. (1992), Poyago-Theotoky (1995, 1999), Gil-Molto et al. (2005), Falvey et al. (2013) and Manasakis et al. (2014), among others.

[2] For more information on FTAs see "Regional Trade Agreements" at http://www.wto.org.

The government of each country can initiate bilateral FTAs to abolish the import tariffs of partners, but will impose trade tariffs on countries with whom it has no FTA. The set of FTAs between countries makes up an FTA network. And firms decide whether (and with whom) to form R&D collaborations; these collaborations make up an R&D network. As a result, there are two layers of networks in our model: the first is an FTA network, and the second is an R&D network.

Our first result concerns the influence of FTAs on international R&D networks. We find that FTAs can promote international R&D collaboration between firms. Intuitively, an R&D collaboration between two firms is more beneficial to them if the corresponding countries sign a bilateral FTA. Note that when firms form an R&D link, they subsequently compete in the product market. As it turns out, the negative effect of product-market competition on the domestic firm's profits is outweighed by the gains from greater access to the foreign market. This finding is consistent with the stylized facts: FTAs have grown fast since the early 1990s, while international R&D collaboration has become a more prevalent phenomenon over the same period.

Our next result investigates the stability properties of FTA and international R&D networks. Here we find that the complete FTA network (where each country has FTAs with all others) along with the complete R&D network (where each firm collaborates in R&D with all others) is the unique double-layer pairwise stable network. In terms of social welfare, private incentives to form FTAs are adequate from a global welfare viewpoint. However, this result does not hold for firms' incentives to establish R&D networks; as it turns out, firms have stronger incentives to engage in R&D collaboration than is socially desirable.

These findings contribute to three strands of research. *First*, they contribute to the literature on R&D networks (e.g. Goyal and Moraga-González, 2001; Deroian and Gannon, 2006; Zikos, 2010; Zirulia, 2012; Kesavayuth et al., 2014). We develop this literature by casting the analysis within an open economy where firms compete in different markets. Each firm decides how much to produce in the domestic market and how much to export to the foreign markets. The ability of firms to have access both to the domestic and foreign markets allows us to consider their behavior in different market environments and also incorporate trade tariffs into the model. Our model therefore allows for an investigation of the impact of FTAs on international R&D collaborations and vice versa, a topic that has not been explored as yet in the literature.

Second, our article contributes to the literature on FTA networks (e.g. Goyal and Joshi, 2006; Furusawa and Konishi, 2007), which examines the formation of FTAs as a network formation game.[3] We broaden this focus by considering the effects of the formation of FTAs on international R&D networks. Accordingly we develop a new model of double-layer networks where any architecture of FTAs is determined endogenously in the first network layer, and the structure of an R&D network emerges in the second network layer.

Third, our article contributes to the literature on international trade (e.g. Kennan and Riezman, 1990; Bond and Syropoulos, 1996; Bond et al., 2004), which is concerned with the effects of FTAs on social welfare, as well as the incentives of FTA partners to impose tariffs on third countries. The trading architectures in previous studies are assumed to be "fixed". Thus the present article attempts to develop this literature by allowing trading architectures (i.e. FTA networks) to emerge endogenously through strategic interactions between countries.

Closest in spirit to our approach is the article by Zu et al. (2011) examining the interplay between market sharing agreements and R&D collaborations among three firms located in three different countries. There are, however, two important differences between Zu et al. (2011) and our article. First, Zu et al. (2011) consider market sharing agreements rather than FTAs. However, in reality, countries often discuss a range of FTAs, and the absence of an FTA is usually *not* the same as the prohibition of sales. The present article investigates the influence of FTAs on international R&D networks, where an FTA refers

[3] Goyal and Joshi (2006) study a model of n ex-ante identical firms located in n symmetric countries. The paper's main finding is that bilateralism leads to global free trade. Another finding is that if two countries sign a bilateral FTA, they lower their trade tariffs imposed on third countries. Furusawa and Konishi (2007) investigate a model with many countries trading a continuum of differentiated products. They show that the main finding of Goyal and Joshi (2006) is robust and holds for a setting with differentiated products and price competition.

to the reduction of trade tariffs between two countries to zero, an approach reflecting the real world more closely.

Moreover, in our article, trade tariffs are endogenous variables. Zu et al. (2011) do not consider trade tariffs. But as Goyal and Joshi (2006) found, the outcomes of a model where trade tariffs are endogenous is consistent with the spirit of The General Agreement on Tariffs and Trade (GATT) – that an increase in tariffs against third parties is *not* the result of regional trade agreements. It is an essential motivation for the present article to model trade tariffs as endogenous, aiming to formalize the aforementioned body of evidence. In doing so, we aim to encourage a broader investigation of FTAs and R&D networks, one that takes both decisions as endogenous and considers their possible interactions.

2 The model

2.1 Sequence of moves

We envisage a setting with three ex-ante identical firms located in three ex-ante symmetric countries. In each country there is one firm producing a homogenous good.[4] Given that firm i is located in country i, let $N = \{1, 2, 3\}$ be the set of firms (or countries). The interaction between firms and countries is governed by a five stage game. In *stage one*, the governments choose simultaneously their bilateral FTAs to abolish the import tariffs of partners. In *stage two*, the firms choose simultaneously their R&D collaborations in order to share knowledge emanating from cost-reducing R&D investments. In *stage three*, the governments decide simultaneously the level of trade tariffs they will impose on the countries with whom they have no FTA. In *stage four*, the firms choose simultaneously their individual R&D efforts. And in the *last stage*, each firm decides how much to produce in the domestic market as well as how much to export to the foreign markets.

The timing of moves reflects that some decisions are longer-term than others. For instance, the timing of moves makes the model an appropriate description of a situation

[4] All results hold if we assume that there is a set of three horizontally differentiated products.

in which FTAs are long-run decisions, while R&D collaborations can be adjusted on a shorter-term basis. In fact, using a survey with data from 255 Japanese small and medium manufacturers, Okamuro (2004) found that R&D collaborations have an average duration of 4.5 years. By contrast, FTAs are often more costly to establish and dissolve than R&D agreements. Thus, like in the case of the European Union, FTAs are likely to last relatively longer.

The previous multi-stage game is solved backwards from stage five to stage three. Then we turn to the second stage, the R&D network formation stage, which is solved by applying the well-established equilibrium notion of pairwise stability (Jackson and Wolinsky, 1996) explained in the sequel. The final step is to solve stage one, the FTA network formation stage, by using again the notion of pairwise stability, similarly to stage two.

2.2 Networks of R&D collaboration and FTAs

Let g^l denote the networks of R&D collaborations given that $l = RD$, and the networks of FTAs given that $l = T$; $l \in \{T, RD\}$. An R&D (or FTA) link between the firm (or country) i and the firm (or country) j under the network g^l is represented by $ij \in g^l$. Formally, an R&D (or FTA) network is a collection of bilateral links between firms (or countries). Denote as $g^l + ij$ the network obtained when firms (countries) i and j add a new link between them to the existing network g^l. Denote as $g^l - ij$ the network obtained when firms (countries) i or j sever the link between them in the existing network g^l. Further, define $N_i(g)$ as the set of firms directly connected to firm i under a network g^l. Let G^{RD} (G^T) be the set of all possible R&D (FTA) networks. For any given pair of network structures (g^T, g^{RD}), the first part (g^T) specifies the type of the FTA network, and the second part (g^{RD}) the R&D collaboration network.

2.3 R&D effort levels and spillovers

Firms invest in R&D to reduce their marginal costs. Denote firm i's R&D effort as e_i. The cost of exerting R&D effort is given by $Z(e_i) = \gamma e_i^2$, where $\gamma > 0$ captures the efficiency of the R&D technology (d'Aspremont and Jacquemin, 1988). Following Goyal and Moraga-González (2001), we model public spillovers. That is, if two firms have no direct R&D collaboration, they can enjoy 'public' spillovers from each other denoted by $\beta \in [0,1)$. But if two firms have a collaborative link, they can enjoy full 'private' spillovers, i.e. $\beta = 1$. Thus the effective R&D effort of firm i representing the overall reduction in firm i's marginal cost due to R&D is given by:

$$E_i = e_i + \sum_{k \in N_i(g)} e_k + \beta \sum_{l \notin N_i(g)} e_l. \tag{1}$$

2.4 Marginal costs

Denote as q_i^j the quantity sold by firm i in country j. The total quantity sold by firm i in all markets is therefore $q_i = \ q_i^i + \sum_{j \neq i} q_i^j$. The marginal cost of firm i under the pair of network structures (g^T, g^{RD}), when producing the quantity q_i^i in the domestic market and exporting the quantity $\sum_{j \neq i} q_i^j$, is given by $c_i = c - E_i$, with $c > 0$.

2.5 Payoffs

The inverse demand function in country i is given by $P_i(Q_i) = a - Q_i$, where Q_i is the total demand in country i, $Q_i = \sum_{j=1}^{3} q_j^i$, and $0 \leq Q_i < a$. To ensure that all equilibrium variables are non-negative, we assume that $a > c$. By calculation, note that when $\gamma \geqslant 5$ all equilibrium variables are non-negative for all $\beta \in (0,1]$, and profit functions are concave. For simplicity we set $\gamma = 5$.

The profit of firm i is defined as the difference between revenues and costs (i.e. costs from production, trade tariffs and R&D activities):

$$\pi_i = (a - Q_i)q_i^i + \sum_{j \neq i}(a - Q_j)q_i^j - c_i q_i - \sum_{j \neq i} t_i^j q_i^j - \gamma e_i^2, \tag{2}$$

where t_i^j denotes the trade tariff that country j imposes on each unit of good imported from country i, with $t_i^j = t_j^i = 0$ if there is an FTA between countries i and j.

Each country chooses trade tariffs to maximize its social welfare defined as the sum of consumer surplus (CS), producer surplus (PS) and tariff revenues (TR). Thus social welfare in country i under the pair of network structures (g^T, g^{RD}) is given by:

$$W_i = \underbrace{\frac{Q_i^2}{2}}_{CS} + \underbrace{\pi_i}_{PS} + \underbrace{\sum_{j \neq i} t_j^i \, q_j^i}_{TR}. \tag{3}$$

Without loss of generality, we label FTA network "the first layer of network" and R&D network "the second layer of network", given that an R&D network is formed after an FTA network.

2.6 Stability and efficiency

We adapt the definition of pairwise stability introduced by Jackson and Wolinsky (1996) to examine the stability properties of FTA networks and international R&D networks. Following Jackson and Wolinsky (1996), we say that a network is *pairwise stable* if no agent (firm or country) has an incentive to delete unilaterally one of its links, and no pair of agents want to form a new link (with one benefiting strictly and the other at least weakly).

Building on the concept of pairwise stability, we further consider a double layer network structure, where FTA networks are formed in the first layer and international R&D networks in the second layer. To examine the stability of this structure, we adapt the concept of "double-layer pairwise stability" proposed by Zu et al. (2011):

Definition 1 *Let $g^{RD}(g^T)$ be one of the pairwise stable R&D collaboration networks under a given FTA network g^T. The double layer network (g^T, g^{RD}) is double-layer pairwise stable if:*

(i) for all $ij \in g^T$, $W_i(g^T, g^{RD}(g^T)) \geqslant W_i(g^T - ij, g^{RD}(g^T - ij))$
and $W_j(g^T, g^{RD}(g^T)) \geqslant W_j(g^T - ij, g^{RD}(g^T - ij))$, and

(ii) for all $ij \notin g^T$, if $W_i(g^T, g^{RD}(g^T)) < W_i(g^T + ij, g^{RD}(g^T + ij))$, then

$$W_i(g^T, g^{RD}(g^T)) > W_i(g^T + ij, g^{RD}(g^T + ij)).$$

This definition says that the pair of network structures (g^T, g^{RD}) is double-layer pairwise stable if both layers of networks are pairwise stable. We also assess the efficiency properties of the double-layer networks using global welfare. We say that a network $(g^T, g^{RD}) \in (G^T, G^{RD})$ is *efficient* if it is not dominated in terms of global welfare by any other network; that is, if $W(g^T, g^{RD}) \geqslant W(g^{T\prime}, g^{RD\prime})$ for all $(g^{T\prime}, g^{RD\prime}) \in (G^T, G^{RD})$, where $W(g^T, g^{RD}) = \sum_{i=1}^{3} W_i(g^T, g^{RD})$.

2.7 Notation for equilibrium outcomes

For a hypothetical choice variable z_x^y and a pair of network structures (g^T, g^{RD}), let $z_x^y(g^T, g^{RD})$ denote a variable at the subgame-perfect Nash equilibrium. The lower subscript x denotes the position of a country in the FTA network, while the superscript y denotes the position of a firm in the R&D network, with $\{x, y\} \in \{E, L, I, H, S, C\}$. Accordingly, the following cases are possible regarding the various positions that a country (or firm) can occupy in a given network:

$x(\text{or } y) = E$ stands for the country (or firm) in the empty FTA (or R&D) network

$x(\text{or } y) = L$ stands for the linked country (or firm) in the partial FTA (or R&D) network

$x(\text{or } y) = I$ stands for the isolated country (or firm) in the partial FTA (or R&D) network

$x(\text{or } y) = S$ stands for the spoke country (or firm) in the star FTA (or R&D) network

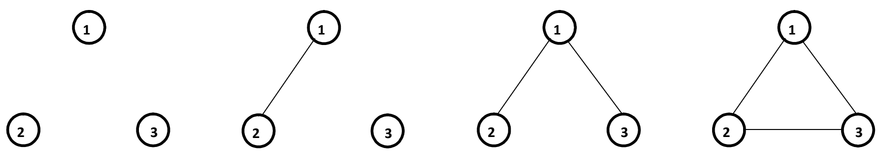
$x(\text{or } y) = H$ stands for the hub country (or firm) in the star FTA (or R&D) network

$x(\text{or } y) = C$ stands for the country (or firm) in the complete FTA (or R&D) network.

3 Endogenous double-layer networks

3.1 Equilibrium in the second network layer

In this section we use the definition of pairwise stability to investigate the stability properties of R&D networks in the second network layer, given different trading regimes in the first network layer. Consider first the empty FTA network, g_e^T, where no country has an FTA. Figure 1 illustrates all possible R&D network structures under the empty FTA network.



(g_e^T, g_e^{RD}) (g_e^T, g_p^{RD}) (g_e^T, g_s^{RD}) (g_e^T, g_c^{RD})

Figure 1: R&D networks structures under the empty FTA network

The following Lemma summarizes our findings.[5]

Lemma 1 *Under the empty FTA network, the pairwise stable R&D networks are:*

(i) (g_e^T, g_e^{RD}) *for all* $\beta \in [\beta_4, 1)$

(ii) (g_e^T, g_p^{RD}) *for all* $\beta \in [0, \beta_1)$ *and* $\beta \in (\beta_3, \beta_4]$

(iii) (g_e^T, g_s^{RD}) *for all* $\beta \in [\beta_2, \beta_3]$

(iv) (g_e^T, g_c^{RD}) *for all* $\beta \in [0, \beta_2]$ *and* $\beta \in [\beta_3, 1)$

where $0 < \beta_1 < \beta_2 < \beta_3 < \beta_4 < 1$.

Lemma 1 shows that different R&D networks can be stable as spillovers vary. More specifically, the empty R&D network is pairwise stable if spillovers are sufficiently high. The rationale follows from the fact that (public) spillovers can be seen as a substitute for collaborative links, because they can occur between firms without an R&D link between

[5] By calculation we obtain $\beta_1 \approx 0.04$ and $\beta_3 \approx 0.94$ as the solutions to the equation $\pi_E^L(g_e^T, g_p^{RD}) = \pi_E^H(g_e^T, g_s^{RD})$; $\beta_2 \approx 0.92$ as the solution to the equation $\pi_E^C(g_e^T, g_c^{RD}) = \pi_E^S(g_e^T, g_s^{RD})$; and $\beta_4 \approx 0.96$ as the solution to the equation $\pi_E^E(g_e^T, g_e^{RD}) = \pi_E^L(g_e^T, g_p^{RD})$. Additional information is available from the authors on request.

them (Goyal and Moraga-González, 2001). Thus, as long as spillovers are high, firms have no incentive to form R&D links, and the empty network emerges in equilibrium.

As (public) spillovers become lower, the increase in knowledge-sharing emanating from R&D collaboration becomes more pronounced relative to non-collaboration. This in turn endows firms with incentives to form some links with each other, meaning that denser networks emerge in equilibrium, as spillovers become lower. As Lemma 1 states, the partial R&D network is pairwise stable for $\beta \in (\beta_3, \beta_4]$, the star R&D network for $\beta \in [\beta_2, \beta_3]$, and the complete R&D network for $\beta \in [0, \beta_2]$. Besides, the complete R&D network is stable when spillovers are very high, i.e. $\beta \in [0.94, 1]$, the reason being that collaborating in R&D implies a profit gain for the spoke firms in the star network.

Consider next the partial FTA network, g_p^T, where two countries have a bilateral FTA and one is isolated. Figure 2 shows that given the partial FTA network in the first network layer (denoted by a dashed line), there are six possible R&D networks in the second network layer (denoted by solid lines).

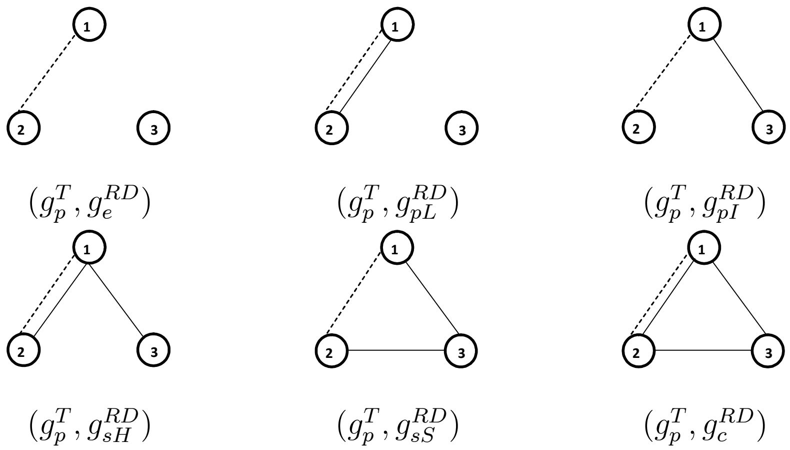


Figure 2: R&D networks structures under the partial FTA network

The following Lemma summarizes.[6]

Lemma 2 *Under the partial FTA network, the pairwise stable R&D networks are:*

[6]By calculation we obtain $\beta_5 \approx 0.94$ as the solution to the equation $\pi_I^S(g_p^T, g_{sH}^{RD}) = \pi_I^C(g_p^T, g_c^{RD})$; and $\beta_6 \approx 0.96$ as the solution to the equation $\pi_I^I(g_p^T, g_{pL}^{RD}) = \pi_I^S(g_p^T, g_{sH}^{RD})$. Additional information is available on request.

(i) (g_p^T, g_{pL}^{RD}) *for all* $\beta \in (\beta_6, 1)$

(ii) (g_p^T, g_{sH}^{RD}) *for all* $\beta \in (\beta_5, \beta_6]$

(iii) (g_p^T, g_c^{RD}) *for all* $\beta \in [0, \beta_5]$ *and* $\beta \in (\beta_6, 1)$

where $0 < \beta_5 < \beta_6 < 1$.

As Lemma 2 suggests, under the partial FTA network, the empty R&D network is no longer stable. This is because both firms located in the two linked countries of the FTA network have an incentive to collaborate with each other. Intuitively, when an FTA is formed between two countries, the firm in each country enjoys greater access to the market of the other firm, but also incurs higher competition in its domestic market. It turns out that the former positive effect dominates the latter negative; thus an FTA softens competition between firms. In turn, the softer competition encourages R&D collaboration as firms become less exposed to the competition effect implied by R&D collaboration. Consequently, only networks containing links between firms emerge in equilibrium under the partial FTA network, as Lemma 2 states.

We proceed to consider the star FTA network, g_s^T, where a country (the hub) has two FTAs, and the other two countries (the spokes) have one FTA each. Figure 3 shows that given the star FTA network in the first network layer (denoted by two dashed lines), there are six possible R&D networks in the second network layer (denoted by solid lines).

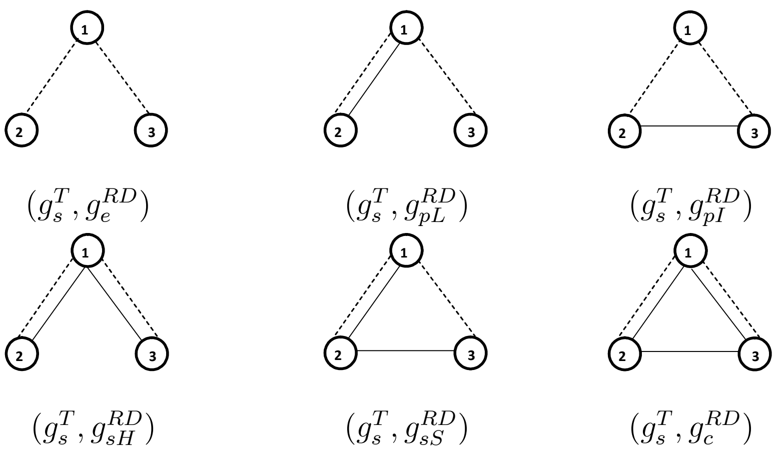


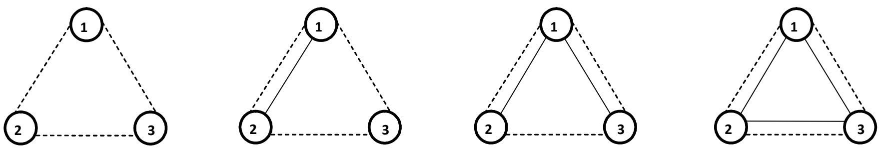
Figure 3: R&D networks structures under the star FTA network

The following lemma presents our findings.

Lemma 3 *Under the star FTA network, the R&D network* (g_s^T, g_c^{RD}) *is uniquely pairwise stable for all* $\beta \in [0, 1)$.

Lemma 3 suggests that, under the star FTA network, the complete R&D network is uniquely pairwise stable. All other R&D networks are no longer stable because firms in the partial network have an incentive to deviate to the star and then the complete network. The partial R&D network is not stable because there is an FTA between the country where the isolated firm is located and the country where a linked firm is located. Intuitively, an FTA softens competition between firms, as explained earlier. The softer competition encourages the linked firms to form R&D links with their isolated counterpart, which in turn destabilizes the partial R&D network. Likewise, the competition between the hub and spoke firms under the star R&D network is softer as a result of FTAs, thereby providing the spoke firms with incentives to form R&D links with each other. By collaborating in R&D, the spoke firms can also limit the extent of their cost disadvantage relative to the hub.

Last, consider the complete FTA network, g_c^T, where each country has an FTA with all others. Figure 4 shows that given the complete FTA network in the first network layer (denoted by dashed lines), there are four possible R&D networks in the second network layer (denoted by solid lines).



(g_c^T, g_e^{RD}) (g_c^T, g_p^{RD}) (g_c^T, g_s^{RD}) (g_c^T, g_c^{RD})

Figure 4: R&D networks structures under the complete FTA network

The following lemma summarizes our findings.

Lemma 4 *Under the complete FTA network, the R&D network* (g_c^T, g_c^{RD}) *is uniquely pairwise stable for all* $\beta \in [0, 1)$.

As mentioned earlier, if two countries sign an FTA, the two firms located in these countries have a stronger incentive to collaborate in R&D, since the competition effect of the R&D collaboration is weaker than in the absence of an FTA. By the same logic, each firm will have an incentive to form R&D links with all others, given the complete FTA network. Thus, as Lemma 4 reports, the complete R&D network emerges as the unique pairwise stable network.

Combining the previous lemmas, we can readily state the following result:

Proposition 1 *Free trade agreements are beneficial to international R&D collaborations.*

FTAs expand the interval of spillovers in which the complete R&D network is stable, but contract the interval of spillovers in which other R&D networks are stable. This indicates an important link between FTAs and R&D networks – that FTAs can promote the formation of R&D networks, as Proposition 1 states. The present result is consistent with the stylized facts. Over the past decades, international R&D collaboration between firms has grown fast while FTAs between countries have become a more prevalent phenomenon.

3.2 Equilibrium in the first network layer

To investigate the stability properties of FTA networks we turn to the first layer of network, given different international R&D networks in the second network layer. To do this, we employ again the definition of pairwise stability. As the analysis is very similar to that presented in the previous section, we proceed to summarize our main findings as follows:[7]

Lemma 5 *(i) Under the empty R&D network, the pairwise stable FTA networks are:*

(g_p^T, g_e^{RD}) *for all* $\beta \in [0, \beta_7]$, *and* (g_c^T, g_e^{RD}) *for all* $\beta \in [0, 1)$

(ii) Under the partial R&D network, the pairwise stable FTA networks are:

[7]Similarly to the previous section, we identify critical values of β for which FTA networks are pairwise stable under a given R&D network. Specifically, $\beta_7 \approx 0.19$ is defined as the solution to the equation $W_S^E(g_s^T, g_e^{RD}) = W_I^E(g_p^T, g_e^{RD})$; $\beta_8 \approx 0.67$ is the solution to the equation $W_I^I(g_p^T, g_{pL}^{RD}) = W_S^I(g_s^T, g_{pL}^{RD})$; and $\beta_9 \approx 0.13$ is the solution to the equation $W_I^S(g_p^T, g_{sH}^{RD}) = W_S^S(g_s^T, g_{sS}^{RD})$.

(g_p^T, g_{pL}^{RD}) for all $\beta \in [0, \beta_8)$, and (g_c^T, g_p^{RD}) for all $\beta \in [0, 1)$

(iii) Under the star R&D network, the pairwise stable FTA networks are:

(g_p^T, g_{sH}^{RD}) for all $\beta \in [0, \beta_9)$, and (g_c^T, g_s^{RD}) for all $\beta \in [0, 1)$

(iv) Under the complete R&D network, the FTA networks (g_c^T, g_c^{RD}) is uniquely pairwise stable for all $\beta \in [0, 1)$

where $0 < \beta_9 < \beta_7 < \beta_8 < 1$.

We elaborate on some aspects of Lemma 5. First, the lemma suggests that the partial FTA network is pairwise stable if spillovers are sufficiently low, given the empty, partial, or star R&D network. When spillovers are sufficiently low, forming an FTA is not particularly valuable for the isolated country within the partial FTA network. Signing an FTA increases competition in the domestic market and thus consumer surplus goes up. At the same time, an FTA leads to a decrease in both tax revenues and producer surplus. It turns out that the former positive effect of an FTA (on consumer surplus) is not strong enough to outweigh the latter negative effect (on tax revenues and producer surplus) – because the extent of knowledge-sharing through spillovers which are low cannot boost consumer surplus sufficiently. Thus the partial FTA network emerges in equilibrium, as Lemma 5 reports. By contrast, if spillovers are sufficiently high, the domestic market becomes more competitive. Therefore, the increase in consumer surplus outweighs the concomitant decrease in tax revenues and producer surplus, in turn providing support for welfare-enhancing deviations from the partial FTA network.

Second, Lemma 5 suggests that the complete FTA network is uniquely pairwise stable, given the complete R&D network. In this case, each firm has R&D links with all others, meaning that all firms are competitive. Consider the partial FTA network: if the isolated country initiates an FTA, then competition in its (domestic) market will become higher. As it turns out, the resulting increase in consumer surplus outweighs the decrease in producer surplus and tax revenues. Consequently, due to the FTA, the isolated country's welfare will go up, thereby providing the isolated country with an incentive to form this FTA. By the same logic, there are welfare-enhancing deviations in the star FTA network leading to the complete FTA network in equilibrium, as Lemma 5 reports.

3.3 Equilibrium double-layer networks

We now combine the previous lemmas to see which network structures, both for FTAs and international R&D networks, emerge endogenously as double-layer pairwise stable. The following proposition presents our findings:

Proposition 2 *The complete FTA network along with the complete R&D network is the unique double-layer pairwise stable network for all* $\beta \in [0, 1)$.

From the previous analysis we know that the complete FTA network is always pairwise stable in the first network layer, regardless of the R&D network in the second layer (Lemmas 1-4). The complete R&D network is uniquely pairwise stable in the second network layer, given the complete FTA network (Lemma 5). Each layer of the other double layer structures might be pairwise stable, but both layers are not pairwise stable for the same values of spillovers. Therefore, the complete-complete network is uniquely double-layer pairwise stable, as Proposition 2 states.

Proposition 2 might appear initially surprising when compared with the outcome in a closed economy. In particular, Goyal and Moraga-González (2001) have shown that the partial R&D network is pairwise stable when the market environment is very competitive (i.e. firms compete in a homogeneous-good market), whereas the complete R&D network is uniquely pairwise stable when firms operate in independent markets. By contrast, we find that when markets are very competitive, the complete R&D network is the unique pairwise stable network.

The intuition behind the difference in the equilibrium R&D networks stems from the fact that we allow for FTAs among countries. When FTAs are formed, the domestic market becomes more competitive while the foreign markets become less competitive for the domestic firm, because the domestic firm can gain access to these markets at zero trade tariffs. It turns out that the latter effect outweighs the former, implying that overall competition is lower. This in turn gives rise to the complete R&D network even if markets are very competitive, like in our setting, a result that contrasts sharply with the equilibrium outcome in a closed economy.

4 Efficient double-layer networks

The next step is to see which FTA networks along with which international R&D networks are efficient. Using global social welfare as our measure of efficiency leads to the following proposition.[8]

Proposition 3 *The following double-layer networks are globally efficient:*

(i) The complete FTA network along with the star R&D network for all $\beta \in [0, \beta_{10}]$

(ii) The complete FTA network along with the partial R&D network for all $\beta \in [\beta_{10}, \beta_{11}]$

(iii) The complete FTA network along with the empty R&D network for all $\beta \in [\beta_{11}, 1)$

where $0 < \beta_{10} < \beta_{11} < 1$.

Figure 5 provides a graphical representation of Proposition 3 by illustrating global social welfare in the different double-layer network structures, where the first layer is the complete FTA network.

[8] Define $\beta_{10} \approx 0.27$ as the solution to the equation $W(g_c^T, g_s^{RD}) = W(g_c^T, g_p^{RD})$; and $\beta_{11} \approx 0.45$ as the solution to the equation $W(g_c^T, g_p^{RD}) = W(g_c^T, g_e^{RD})$.

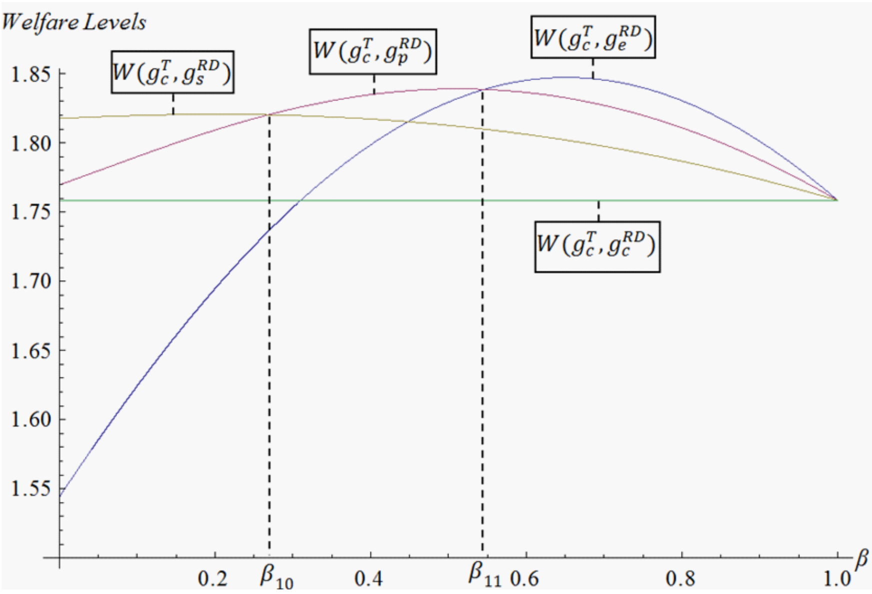


Figure 5: Global welfare levels of efficient networks

Proposition 3 suggests that the complete FTA network is globally efficient. As explained earlier, for a given R&D network, an FTA implies a positive effect on the welfare of the country who initiated the FTA. Specifically, consumer surplus increases due to greater competition in domestic market; also the domestic firm's profits from its foreign operations increase following greater access to the foreign market. However, an FTA implies negative effects as well: it lowers tax revenues and also tends to reduce the domestic firm's profits due to higher competition in the domestic market. It turns out that the former positive effects outweigh the latter negative. Thus the complete FTA network emerges as globally efficient, a result consistent with Goyal and Joshi (2006) and Furusawa and Konishi (2007) for a setting without R&D networks.

Proposition 3 further suggests that the complete R&D network is not efficient. For a given FTA network, R&D collaborations tend to increase global welfare, because they reduce firms' costs and thereby increase firms' quantities and profits. On the other hand, R&D collaborations are detrimental to global welfare because well-connected firms undertake very little R&D efforts due to increased competition implied by R&D collaboration. When an R&D network is sparse, the competition effect is relatively weak, and thus, it is dominated by the positive impact of R&D collaboration on welfare. By contrast, in a dense R&D network, the competition effect is more pronounced and thus outweighs the welfare-enhancing effect of R&D collaboration. This is the reason why the complete R&D network is not efficient in the present setting.

Taken together, Propositions 2 and 3 show that the complete R&D network is stable but not efficient. At the same time, the complete FTA network is both stable and efficient. This in turn suggests that, in pursuit of their private interests, countries may achieve an outcome that is also socially desirable, while the number of R&D collaborations is likely to be excessive from a social viewpoint.

5 Conclusion

This article provides some of the first insights into the endogenous formation of FTAs between countries and R&D networks between firms. Building a double-layer network model, we found that FTAs extend the interval of spillovers in which the complete R&D network is stable, but contract the interval of spillovers in which other R&D networks are stable. In line with the stylized facts, this result indicates an important link between FTAs and R&D networks – that FTAs can promote the formation of R&D networks.

Another finding of the paper concerns the double-layer network structures that will emerge endogenously. Here we found that the complete FTA network along with the complete R&D network is the unique stable network. In terms of social welfare, private incentives to form bilateral FTAs are adequate from a global welfare viewpoint, but for R&D networks, there is a conflict between private and social incentives.

More generally this research suggests that the joint consideration of FTAs and R&D networks, rather than viewing them as separate decisions, may be important for understanding how these two phenomena occur in equilibrium. This approach allows for an examination of their possible interaction effects, which had not been studied in the literature. Although there are no simple policy implications, our finding that the number of R&D collaborations, but not the number of FTAs, is excessive from a social viewpoint calls for more caution regarding the provision of subsidies to R&D collaborations, a central policy tool over the last decades in the European Union, the United States and Japan. A similar suggestion was made by Klette et al. (2000) – that the provision of R&D subsidies should be accompanied by a more thorough evaluation of their social returns. Our framework can certainly accommodate further research on this topic. In future work it would be interesting to explore, for instance, the impact of asymmetries across markets and firms on the formation of FTAs and R&D networks.

Appendix

A1. Equilibrium Outcomes

In this section we present the equilibrium outcomes for the different configurations of FTA and R&D networks. Note that the second order conditions are always fulfilled, and the equilibrium outcomes are non-negative for all values of the spillover parameter.[9]Let $a_1 = a - c > 0$. Equilibrium outcomes are as follows:

A1.1 The empty FTA networks

A1.1.1 The empty-empty network (g_e^T, g_e^{RD})

$t_i^j = 30a_1(467 + 192\beta - 160\beta^2 + 192\beta^3 - 48\beta^4)/\Delta_2$

$e_E^E = 3a_1(3 - 2\beta)(467 + 351\beta - 158\beta^2 + 84\beta^3 - 24\beta^4)/\Delta_2$

$q_i^i = 20a_1(934 + 543\beta - 318\beta^2 + 276\beta^3 - 72\beta^4)/\Delta_2$

$q_i^j = 20a_1(934 + 543\beta - 318\beta^2 + 276\beta^3 - 72\beta^4)/\Delta_2$

$CS_E^E = 1800(a_1)^2(467 + 351\beta - 158\beta^2 + 84\beta^3 - 24\beta^4)^2/(\Delta_2)^2$

$W_E^E = 15(a_1)^2K_2/(\Delta_2)^2;$ $\qquad \pi_E^E = 15(a_1)^2K_1/(\Delta_2)^2$

where Δ_1=781+933β-474β^2+252β^3-72β^4.

Δ_2=42497+23157β-13026β^2+15912β^3-5568β^4+1296β^5-288β^6.

K_1 = 20282277 + 32399526β + 3390253β^2 - 1816224β^3 + 4564080β^4 - 2890560β^5 + 564576β^6 + 96768β^7 - 198144β^8 + 69120β^9 - 6912β^{10}.

K_2 = 55176517 + 84852966β - 1520347β^2 - 7035264β^3 + 15780240β^4 - 10121280β^5 + 2436576β^6 - 340992β^7 - 129024β^8 + 69120β^9 - 6912β^{10}.

[9] It turns out that some expressions for the equilibrium outcomes are very lengthy. Although they are not reported here, they are available from the authors upon request along with relevant plots.

A1.1.2. The empty-complete network (g_e^T, g_c^{RD})

$t_i^j =$ $1929a_1/6398$; $e_E^C = 108a_1/3199$

$\pi_E^C = 4234107(a_1)^2/20467202$

$q_i^i = 1363a_1/3199$; $q_i^j = 797a_1/6398$

$CS_E^C = 2332800(a_1)^2/10233601$; $W_E^C = 5218560(a_1)^2/10233601$

A1.2 The partial FTA networks

A1.2.1. The partial-complete network (g_p^T, g_c^{RD})

$t_1^3 = t_2^3 = 1168331a_1/8066794$

$t_3^1 = t_3^2 = 1222986a_1/4033397$

$\pi_L^C = 107805289687385(a_1)^2/520585323507488$

$\pi_I^C = 122520384582963(a_1)^2/520585323507488$

$e_L^C = 610183a_1/16133588$

$e_I^C = 310557a_1/8066794$

$q_1^1 = q_1^2 = q_2^1 = q_2^2 = 10155865a_1/32267176$

$q_1^3 = q_2^3 = 2047795a_1/16133588$

$q_3^1 = q_3^2 = 5482541a_1/32267176$

$q_3^3(g_p^T, g_c^{RD}) = 6939739a_1/16133588$

$CS_L^C = 665344416421441(a_1)^2/2082341294029952$

$CS_I^C = 121778486138241(a_1)^2/520585323507488$

$W_L^C = 1147808956043549(a_1)^2/2082341294029952$

$W_I^C = 71092416143781(a_1)^2/130146330876872$

A1.3 The star FTA networks

A1.3.1. The star-complete network (g_s^T, g_c^{RD})

$t_2^3 = t_3^2 = 38580a_1/264481$

$\pi_H^C = 18848195145(a_1)^2/69950199361$

$\pi_S^C = 14079601050(a_1)^2/69950199361$

$e_H^C = 12099a_1/264481;\ e_S^C = 10170a_1/264481$

$q_1^1 = q_2^1 = q_3^1 = 74230a_1/264481$

$q_1^2 = q_1^3 = q_2^2 = q_3^3 = 83875a_1/264481$

$q_2^3 = q_3^2 = 45295a_1/264481$

$CS_H^C = 24795418050(a_1)^2/69950199361$

$CS_S^C = 926289225(a_1)^2/2855110178$

$W_H^C = 6234801885(a_1)^2/9992885623$

$W_S^C = 77042336325(a_1)^2/139900398722$

A1.4 The complete FTA networks

A1.4.1. The complete empty network (g_c^T, g_e^{RD})

$e_i = 3a_1(3-2\beta)/\Delta_3$

$\pi_E^C = 15(a_1)^2(53+36\beta-12\beta^2)/(\Delta_3)^2$

$e_E^C = 3a_1(3-2\beta)/\Delta_3$; $q_i^i = q_i^j = 20a_1/\Delta_3$

CS_E^C= $1800(a_1)^2/(\Delta_3)^2$

W_E^C= $15(a_1)^2(173+36\beta-12\beta^2)/(\Delta_3)^2$

where Δ_3=71-12β+12β^2.

A1.4.2. The complete partial network (g_c^T, g_p^{RD})

$\pi_C^L = 15(a_1)^2(11+15\beta-6\beta^2)^2(68+12\beta-3\beta^2)/4(\Delta_4)^2$

$\pi_C^I = 15(a_1)^2(4+9\beta-3\beta^2)^2(53+36\beta-12\beta^2)/(\Delta_4)^2$

$e_C^L = 3a_1(22+19\beta-27\beta^2+6\beta^3)/2\Delta_4$

$e_C^I = 3a_1(3-2\beta)(4+9\beta-3\beta^2)/\Delta_4$

$q_1^i = q_2^i = 10a_1(11+15\beta-6\beta^2)/\Delta_4$

$q_3^i = 20a_1(4+9\beta-3\beta^2)/\Delta_4$

$CS_C^L = CS_C^I = 1800(a_1)^2(5+8\beta-3\beta^2)^2/(\Delta_4)^2$

$W_C^L = 15(a_1)^2K_3/4(\Delta_4)^2$; $\quad W_C^I = 15(a_1)^2K_4/(\Delta_4)^2$

where Δ_4=344+537β-216β^2+63β^3-18β^4.

K_3=20228+62292β+26241β^2-35154β^3+4329β^4+972β^5-108β^6.

K_4=3848+13992β+9501β^2-7434β^3-1071β^4+972β^5-108β^6.

A1.4.3. The complete star network(g_c^T, g_s^{RD})

$\pi_C^H = 1155(a_1)^2(26-9\beta+3\beta^2)^2/(\Delta_5)^2$

$\pi_C^S = 6000(a_1)^2(68+12\beta-3\beta^2)/(\Delta_5)^2$

$e_C^H = 3a_1(26 - 9\beta + 3\beta^2)/\Delta_5$

$e_C^S = 60a_1(2 - \beta)/\Delta_5; \quad q_2^i = q_3^i = 400a_1/\Delta_5$

$q_1^i = 20a_1(26 - 9\beta + 3\beta^2)/\Delta_5$

$CS_C^H = CS_C^S = 1800(a_1)^2(22 - 3\beta + \beta^2)^2/(\Delta_5)^2$

$W_C^H = 15(a_1)^2 K_5/3\beta^4(\Delta_5)^2; \quad W_C^S = 600(a_1)^2 K_6(\Delta_5)^2$

where Δ_5=1522-213β+111β^2.

K_5=110132-51876β+24609β^2-4878β^3+813β^4.

K_6=2132-276β+129β^2-18β^3+3β^4.

A1.4.4. The complete complete network (g_c^T, g_c^{RD})

$e_i = 3a_1/71; \quad e_C^C = 3a_1/71$

$\pi_C^C = 1155(a_1)^2/5041$; $q_i^i = q_i^j = 20a_1/71$

$CS_C^C = 1800(a_1)^2/5041$; $W_C^C = 2955(a_1)^2/5041$

A2. Proofs[10]

A2.1 Proof of Lemma 1

Firstly, (g_e^T, g_e^{RD}) is pairwise stable for all $\beta \in [\beta_4, 1)$. From (g_e^T, g_e^{RD}) firms can deviate to (g_e^T, g_p^{RD}). However, $\pi_E^E(g_e^T, g_e^{RD}) > \pi_E^L(g_e^T, g_p^{RD})$ for all $\beta \in (\beta_4, 1)$ and $\pi_E^E(g_e^T, g_e^{RD}) = \pi_E^L(g_e^T, g_p^{RD})$ if $\beta = \beta_4$. Hence, no firms have strict incentive to form the R&D collaborative link between them. This establishes that (g_e^T, g_e^{RD}) is pairwise stable for all $\beta \in [\beta_4, 1)$. It also shows, of course, that (g_e^T, g_p^{RD}) is not pairwise stable for all $\beta \in (\beta_4, 1)$.

[10] Relevant plots are available on request.

Secondly, (g_e^T, g_p^{RD}) is pairwise stable for all $\beta \in (\beta_3, \beta_4]$ and $\beta \in [0, \beta_1)$. From (g_e^T, g_p^{RD}), the possible deviation of firms is either (g_e^T, g_e^{RD}) or (g_e^T, g_s^{RD}). In the former case, $\pi_E^L(g_e^T, g_p^{RD}) > \pi_E^E(g_e^T, g_e^{RD})$ for all $\beta \in (\beta_3, \beta_4)$ and $\beta \in [0, \beta_1)$. In the latter, $\pi_E^L(g_e^T, g_p^{RD}) > \pi_E^H(g_e^T, g_s^{RD})$ for all $\beta \in (\beta_3, \beta_4]$ and $\beta \in [0, \beta_1)$. Note that if $\beta = \beta_4$ then the R&D collaborative link between two linked firms in the partial R&D network will not be severed since no firms are better off if they delete the R&D link because $\pi_E^L(g_e^T, g_p^{RD}) = \pi_E^E(g_e^T, g_e^{RD})$. However, if $\beta = \beta_3$ then the R&D link between a linked firm in the partial R&D network and the isolated firm will be formed since the isolated firm in the partial R&D network has the strict incentive to become the spoke firm in the star R&D network if $\beta = \beta_3$. This confirms that (g_e^T, g_p^{RD}) is pairwise stable for all $\beta \in (\beta_3, \beta_4)$ and $\beta \in [0, \beta_1)$. This also establishes that (g_e^T, g_e^{RD}) and (g_e^T, g_s^{RD}) are not pairwise stable for these values of spillovers.

Thirdly, (g_e^T, g_s^{RD}) is the pairwise stable R&D network for all $\beta \in [\beta_2, \beta_3]$. From (g_e^T, g_s^{RD}), the possible deviation of firms is either (g_e^T, g_p^{RD}) or (g_e^T, g_c^{RD}). In the former case, $\pi_E^H(g_e^T, g_s^{RD}) > \pi_E^L(g_e^T, g_p^{RD})$ and $\pi_E^S(g_e^T, g_s^{RD}) > \pi_E^I(g_e^T, g_p^{RD})$ for all $\beta \in (\beta_2, \beta_3)$. In the latter, $\pi_E^S(g_e^T, g_s^{RD}) > \pi_E^C(g_e^T, g_c^{RD})$ for all $\beta \in (\beta_2, \beta_3)$. Note that if $\beta = \beta_2$ then the R&D collaborative link between two spoke-firms in the star R&D network will not be formed since no firms are better off if they establish the R&D link between them because $\pi_E^C(g_e^T, g_c^{RD}) = \pi_E^S(g_e^T, g_s^{RD})$. In addition, if $\beta = \beta_3$ then the R&D link between the hub-firm and the spoke-firm in the star R&D network will not be severed because the no firms have strict incentive to do so. This confirms that (g_e^T, g_s^{RD}) is pairwise stable for all $\beta \in [\beta_2, \beta_3]$. This also establishes that (g_e^T, g_p^{RD}) and (g_e^T, g_c^{RD}) is not pairwise stable for these values of spillovers.

Fourthly, (g_e^T, g_c^{RD}) is pairwise stable for all $\beta \in [0, \beta_2]$. From (g_e^T, g_c^{RD}), the possible deviation of firms is (g_e^T, g_s^{RD}). However, $\pi_E^C(g_e^T, g_c^{RD}) > \pi_E^S(g_e^T, g_s^{RD})$ for all $\beta \in [0, \beta_2)$. Note that if $\beta = \beta_2$ then the R&D collaborative link between any two firms in the complete R&D network will not be deleted since no firms are better off if they cut the R&D link between them because $\pi_E^C(g_e^T, g_c^{RD}) = \pi_E^S(g_e^T, g_s^{RD})$. This confirms that (g_e^T, g_c^{RD}) is pairwise stable for all $\beta \in [0, \beta_2]$. This also establishes that (g_e^T, g_s^{RD}) is not pairwise stable for these values of spillovers. Q.E.D.

A2.2 Proof of Lemma 2

Firstly, (g_p^T, g_{pL}^{RD}) is the pairwise stable R&D network for all $\beta \in (\beta_6, 1)$. From (g_p^T, g_{pL}^{RD}) firms can deviate either to (g_p^T, g_{sH}^{RD}) or (g_p^T, g_e^{RD}). However, $\pi_I^I(g_p^T, g_{pL}^{RD}) > \pi_I^S(g_p^T, g_{sH}^{RD})$ and $\pi_L^L(g_p^T, g_{pL}^{RD}) > \pi_L^E(g_p^T, g_e^{RD})$ for all $\beta \in (\beta_6, 1)$. This establishes that (g_p^T, g_{pL}^{RD}) is pairwise stable for all $\beta \in (\beta_6, 1)$. It also shows, of course, that the neither (g_p^T, g_{sH}^{RD}) nor (g_p^T, g_e^{RD}) is pairwise stable for all $\beta \in (\beta_6, 1)$.

Secondly, (g_p^T, g_{sH}^{RD}) is the pairwise stable R&D network for all $\beta \in (\beta_5, \beta_6]$. From (g_p^T, g_{sH}^{RD}), the possible deviation of firms is (g_p^T, g_{pL}^{RD}) or (g_p^T, g_{pI}^{RD}) or (g_p^T, g_c^{RD}). In the first case, $\pi_L^H(g_p^T, g_{sH}^{RD}) > \pi_L^L(g_p^T, g_{pL}^{RD})$ and $\pi_I^S(g_p^T, g_{sH}^{RD}) \geqslant \pi_I^I(g_p^T, g_{pL}^{RD})$ for all $\beta \in (\beta_5, \beta_6]$. In the second, $\pi_L^H(g_p^T, g_{sH}^{RD}) > \pi_L^L(g_p^T, g_{pI}^{RD})$ and $\pi_L^S(g_p^T, g_{sH}^{RD}) > \pi_L^I(g_p^T, g_{pI}^{RD})$ for all $\beta \in (\beta_5, \beta_6]$. Finally, $\pi_L^S(g_p^T, g_{sH}^{RD}) > \pi_L^C(g_p^T, g_c^{RD})$ and $\pi_I^S(g_p^T, g_{sH}^{RD}) > \pi_I^C(g_p^T, g_c^{RD})$ for all $\beta \in (\beta_5, \beta_6]$. This confirms that (g_p^T, g_{sH}^{RD}) is pairwise stable for all $\beta \in (\beta_5, \beta_6]$.

Thirdly, (g_p^T, g_c^{RD}) is the pairwise stable R&D network for all $\beta \in [0, \beta_5]$. From (g_p^T, g_{pI}^{RD}), the possible deviation of firms is either (g_p^T, g_{sH}^{RD}) or (g_p^T, g_{sS}^{RD}). In the first case, $\pi_L^C(g_p^T, g_c^{RD}) > \pi_L^S(g_p^T, g_{sH}^{RD})$ and $\pi_I^C(g_p^T, g_c^{RD}) \geqslant \pi_I^S(g_p^T, g_{sH}^{RD})$ for all $\beta \in [0, \beta_5]$. In the second case, $\pi_L^C(g_p^T, g_c^{RD}) > \pi_L^S(g_p^T, g_{sS}^{RD})$ for all $\beta \in [0, \beta_5]$.It establishes that the Partial-Complete network (g_p^T, g_c^{RD}) is the pairwise stable R&D network for all $\beta \in [0, \beta_5]$.

Next, all other networks are not pairwise stable for all $\beta \in [0, 1)$. From (g_p^T, g_e^{RD}), firms have the incentive to deviate to (g_p^T, g_{pL}^{RD}) because $\pi_L^L(g_p^T, g_{pL}^{RD}) > \pi_L^E(g_p^T, g_e^{RD})$ for all $\beta \in [0, 1)$. (g_p^T, g_{pI}^{RD}) is not pairwise stable because $\pi_L^H(g_p^T, g_{sH}^{RD}) > \pi_L^L(g_p^T, g_{pI}^{RD})$ and $\pi_L^S(g_p^T, g_{sH}^{RD}) > \pi_L^I(g_p^T, g_{pI}^{RD})$ for all $\beta \in [0, 1)$. It shows that firms in (g_p^T, g_{pI}^{RD}) have the incentive to alter the network structure to (g_p^T, g_{sH}^{RD}). (g_p^T, g_{sS}^{RD}) is not a pairwise stable R&D network because firms in the network have the incentive to deviate to (g_p^T, g_c^{RD}). It is easily confirmed by inequalities: $\pi_L^C(g_p^T, g_c^{RD}) > \pi_L^S(g_p^T, g_{sS}^{RD})$ for all $\beta \in [0, 1)$. Q.E.D.

A2.3 Proof of Lemma 3

Firstly, (g_s^T, g_c^{RD}) is pairwise stable for all $\beta \in [0,1)$. From (g_s^T, g_c^{RD}) firms can deviate either to (g_s^T, g_{sH}^{RD}) or (g_p^T, g_{sS}^{RD}). However, $\pi_S^C(g_s^T, g_c^{RD}) > \pi_S^S(g_s^T, g_{sH}^{RD})$; $\pi_H^C(g_s^T, g_c^{RD}) > \pi_H^S(g_s^T, g_{sS}^{RD})$ and $\pi_S^C(g_s^T, g_c^{RD}) > \pi_S^S(g_s^T, g_{sS}^{RD})$ for all $\beta \in [0,1)$. This establishes that (g_s^T, g_c^{RD}) is pairwise stable for all $\beta \in [0,1)$. It also shows, of course, that the neither (g_s^T, g_{sS}^{RD}) nor (g_s^T, g_{sH}^{RD}) is pairwise stable for all $\beta \in [0,1)$.

Second, all other networks are not pairwise stable for all $\beta \in [0,1)$. From (g_s^T, g_e^{RD}), firms can deviate either to (g_s^T, g_{pI}^{RD}) or (g_s^T, g_{pL}^{RD}). In the former, $\pi_S^L(g_s^T, g_{pI}^{RD}) > \pi_S^E(g_s^T, g_e^{RD})$ whereas in the latter $\pi_S^L(g_s^T, g_{pL}^{RD}) > \pi_S^E(g_s^T, g_e^{RD})$ and $\pi_S^H(g_s^T, g_{pL}^{RD}) > \pi_H^E(g_s^T, g_e^{RD})$ for all $\beta \in [0,1)$. It shows that firms in (g_s^T, g_e^{RD}) have the incentive to make both deviations. (g_s^T, g_{pI}^{RD}) is not pairwise stable because firms have the incentive to alter the network structure to (g_s^T, g_{sS}^{RD}). It is shown by the inequalities: $\pi_H^S(g_s^T, g_{sS}^{RD}) > \pi_H^I(g_s^T, g_{pI}^{RD})$ and $\pi_S^H(g_s^T, g_{sS}^{RD}) > \pi_S^L(g_s^T, g_{pI}^{RD})$ for all $\beta \in [0,1)$. Moreover, $\pi_H^H(g_s^T, g_{sH}^{RD}) > \pi_H^L(g_s^T, g_{pL}^{RD})$ and $\pi_S^S(g_s^T, g_{sH}^{RD}) > \pi_S^I(g_s^T, g_{pL}^{RD})$ for all $\beta \in [0,1)$. It exhibits that firms in (g_s^T, g_{pL}^{RD}) always have the incentive to alter the network structure to (g_s^T, g_{sH}^{RD}) for all $\beta \in [0,1)$. Q.E.D.

A2.4 Proof of Lemma 4

First, (g_c^T, g_c^{RD}) is pairwise stable for all $\beta \in [0,1)$. From (g_c^T, g_c^{RD}) firms can deviate to (g_c^T, g_s^{RD}). However, $\pi_C^C(g_c^T, g_c^{RD}) > \pi_C^S(g_c^T, g_s^{RD})$ for all $\beta \in [0,1)$. This establishes that (g_c^T, g_c^{RD}) is pairwise stable for all $\beta \in [0,1)$. It also shows, of course, that (g_c^T, g_s^{RD}) is never pairwise stable.

Second, all other network structures are not pairwise stable. (g_c^T, g_e^{RD}) is never pairwise stable since $\pi_C^L(g_c^T, g_p^{RD}) > \pi_C^E(g_c^T, g_e^{RD})$ for all $\beta \in [0,1)$. It confirms that (g_c^T, g_e^{RD}) should be altered to (g_c^T, g_p^{RD}). (g_c^T, g_p^{RD}) is never pairwise stable because $\pi_C^H(g_c^T, g_s^{RD}) > \pi_C^L(g_c^T, g_p^{RD})$ for all $\beta \in [0,1)$. It shows that firms in (g_c^T, g_p^{RD}) have the incentive to alter the network structure to (g_c^T, g_s^{RD}). Q.E.D.

A2.5 Proof of Lemma 5

Empty R&D network

First, (g_p^T, g_e^{RD}) is pairwise stable for all $\beta \in [0, \beta_7)$. From (g_p^T, g_e^{RD}), governments can deviate to (g_e^T, g_e^{RD}) or (g_s^T, g_e^{RD}). Because $W_H^E(g_s^T, g_e^{RD}) > W_L^E(g_p^T, g_e^{RD})$ for all $\beta \in [0, 1)$ but $W_S^E(g_s^T, g_e^{RD}) < W_I^E(g_p^T, g_e^{RD})$ for all $\beta \in [0, \beta_7)$, it shows that the country having no FTA in (g_p^T, g_e^{RD}) have no incentive to alter the network structure to (g_s^T, g_e^{RD}) for all $\beta \in [0, \beta_7)$. Moreover, $W_L^E(g_p^T, g_e^{RD}) > W_E^E(g_e^T, g_e^{RD})$ so governments in (g_e^T, g_e^{RD}) always have the incentive to deviate to (g_p^T, g_e^{RD}). It shows that (g_p^T, g_e^{RD}) is the pairwise stable FTA network for all $\beta \in [0, \beta_7]$ and (g_e^T, g_e^{RD}) is never pairwise stable FTA network for all $\beta \in [0, 1)$.

Second, (g_c^T, g_e^{RD}) is pairwise stable FTA network for all $\beta \in [0, 1)$. From (g_c^T, g_e^{RD}), governments can deviate to (g_s^T, g_e^{RD}). However, $W_C^E(g_c^T, g_e^{RD}) > W_S^E(g_s^T, g_e^{RD})$ for all $\beta \in [0, 1)$. This establishes that (g_c^T, g_e^{RD}) is the pairwise stable FTA network for all $\beta \in [0, 1)$. It also shows, of course, that (g_s^T, g_e^{RD}) is never pairwise stable for all $\beta \in [0, 1)$. Q.E.D.

Partial R&D network

First, (g_p^T, g_{pL}^{RD}) is a pairwise stable FTA network for all $\beta \in [0, \beta_8]$. From (g_p^T, g_{pL}^{RD}), the possible deviation of governments is either (g_e^T, g_p^{RD}) or (g_s^T, g_{pL}^{RD}). *In the former*, $W_L^L(g_p^T, g_{pL}^{RD}) > W_E^L(g_e^T, g_p^{RD})$ for all $\beta \in [0, 1)$. *In the latter*, $W_L^L(g_p^T, g_{pL}^{RD}) < W_H^L(g_s^T, g_{pL}^{RD})$ for all $\beta \in [0, 1)$ but $W_I^I(g_p^T, g_{pL}^{RD}) > W_S^I(g_s^T, g_{pL}^{RD})$ for all $\beta \in [0, \beta_8)$. It confirms that (g_p^T, g_{pL}^{RD}) is pairwise stable FTA network for all $\beta \in [0, \beta_8)$. It also shows that (g_e^T, g_p^{RD}) is never a pairwise stable FTA network for all $\beta \in [0, 1)$.

Second, (g_c^T, g_p^{RD}) is a pairwise stable FTA network for all $\beta \in [0, 1)$. From (g_s^T, g_p^{RD}), governments can deviate either to (g_s^T, g_{pL}^{RD}) or (g_s^T, g_{pI}^{RD}). However, $W_C^L(g_c^T, g_p^{RD}) > W_S^L(g_s^T, g_{pL}^{RD})$ and $W_C^I(g_c^T, g_p^{RD}) > W_S^I(g_s^T, g_{pL}^{RD})$ for all $\beta \in [0, 1)$. This establishes that governments in (g_c^T, g_p^{RD}) have no incentives to deviate to (g_s^T, g_{pL}^{RD}) for all $\beta \in [0, 1)$. Moreover $W_C^L(g_c^T, g_p^{RD}) > W_S^L(g_s^T, g_{pI}^{RD})$ for all $\beta \in [0, 1)$ so governments in (g_c^T, g_p^{RD}) have no incentives to alter the FTA network structure to (g_s^T, g_{pI}^{RD}) for all $\beta \in [0, 1)$. It shows that (g_c^T, g_p^{RD}) is the pairwise stable FTA network for all $\beta \in [0, 1)$, and neither (g_s^T, g_{pI}^{RD}) nor (g_s^T, g_{pL}^{RD}) is a pairwise stable FTA network for all $\beta \in [0, 1)$.

Third, (g_p^T, g_{pI}^{RD}) is not a pairwise stable FTA network for all $\beta \in [0, 1)$. Since $W_H^I(g_s^T, g_{pI}^{RD}) >$

$W_L^I(g_p^T, g_{pI}^{RD})$ and $W_S^L(g_s^T, g_{pI}^{RD}) > W_I^L(g_p^T, g_{pI}^{RD})$ for all $\beta \in [0,1)$ so governments in (g_p^T, g_{pI}^{RD}) have the incentive to alter the FTA network structure to form (g_s^T, g_{pI}^{RD}) for all $\beta \in [0,1)$.

Q.E.D.

Star R&D network

First, (g_p^T, g_{sH}^{RD}) is a pairwise stable FTA network for all $\beta \in [0, \beta_9)$. From (g_p^T, g_{sH}^{RD}), the possible pairwise deviation of governments is (g_e^T, g_s^{RD}) or (g_s^T, g_{sH}^{RD}) or (g_s^T, g_{sS}^{RD}). *In the first*, $W_L^H(g_p^T, g_{sH}^{RD}) > W_E^H(g_e^T, g_s^{RD})$ and $W_L^S(g_p^T, g_{sH}^{RD}) > W_E^S(g_e^T, g_s^{RD})$ for all $\beta \in [0,1)$. *In the second*, $W_L^H(g_p^T, g_{sH}^{RD}) < W_H^H(g_s^T, g_{sH}^{RD})$ for all $\beta \in [0,1)$ but $W_I^S(g_p^T, g_{sH}^{RD}) > W_S^S(g_s^T, g_{sH}^{RD})$ for all $\beta \in [0, \beta_9)$. *In the third*, $W_L^S(g_p^T, g_{sH}^{RD}) < W_S^H(g_s^T, g_{sS}^{RD})$ but $W_I^S(g_p^T, g_{sH}^{RD}) > W_S^S(g_s^T, g_{sS}^{RD})$ for all $\beta \in [0, \beta_9)$. It confirms that (g_p^T, g_{sH}^{RD}) is a pairwise stable FTA network for all $\beta \in [0, \beta_9)$. It also shows that (g_e^T, g_s^{RD}) is never a pairwise stable FTA network for all $\beta \in [0,1)$.

Second, (g_c^T, g_s^{RD}) is a pairwise stable FTA network for all $\beta \in [0,1)$. From (g_s^T, g_s^{RD}), governments can deviate either to (g_s^T, g_{sH}^{RD}) or (g_s^T, g_{sS}^{RD}). However, in the former $W_C^S(g_c^T, g_s^{RD}) > W_S^S(g_s^T, g_{sH}^{RD})$ while in the latter $W_C^H(g_c^T, g_s^{RD}) > W_S^H(g_s^T, g_{sS}^{RD})$ and $W_C^S(g_c^T, g_s^{RD}) > W_S^S(g_s^T, g_{sS}^{RD})$ for all $\beta \in [0,1)$. This establishes that governments in (g_c^T, g_s^{RD}) have no incentives to deviate to any of the star FTA the network for all $\beta \in [0,1)$. It also shows that both (g_c^T, g_{sH}^{RD}) and (g_c^T, g_{sS}^{RD}) are not pairwise stable FTA networks for all $\beta \in [0,1)$.

Third, (g_p^T, g_{sS}^{RD}) network is not the pairwise stable FTA network for all $\beta \in [0,1)$. Governments in (g_p^T, g_{sS}^{RD}) always have the incentive to alter the FTA network to (g_s^T, g_{sS}^{RD}) because $W_S^H(g_s^T, g_{sS}^{RD}) > W_I^H(g_p^T, g_{sS}^{RD})$ and $W_H^S(g_s^T, g_{sS}^{RD}) > W_L^S(g_p^T, g_{sS}^{RD})$ for all $\beta \in [0,1)$. It shows that (g_p^T, g_{sS}^{RD}) is never a pairwise stable FTA network for all $\beta \in [0,1)$. Q.E.D.

Complete R&D network

First, (g_c^T, g_c^{RD}) is pairwise stable FTA network for all $\beta \in [0,1)$. From (g_c^T, g_c^{RD}) governments can deviate to (g_s^T, g_c^{RD}). However, $W_C^C(g_c^T, g_c^{RD}) > W_S^C(g_s^T, g_c^{RD})$ for all $\beta \in [0,1)$. This establishes that (g_c^T, g_c^{RD}) is the pairwise stable FTA network for all $\beta \in [0,1)$. It also shows, of course, that (g_s^T, g_c^{RD}) is never pairwise stable for all $\beta \in [0,1)$.

Second, all other network are not the pairwise stable FTA networks for all $\beta \in [0,1)$. (g_p^T, g_c^{RD}) is never a pairwise stable FTA network for all $\beta \in [0,1)$ since $W_H^C(g_s^T, g_c^{RD}) > W_L^C(g_p^T, g_c^{RD})$ and $W_S^C(g_s^T, g_c^{RD}) > W_I^C(g_p^T, g_c^{RD})$ for all $\beta \in [0,1)$. It exhibits that governments in (g_p^T, g_c^{RD}) always have the strict incentive to alter the FTA network structure to (g_s^T, g_c^{RD}). Moreover, $W_L^C(g_p^T, g_c^{RD}) > W_E^C(g_e^T, g_c^{RD})$ for all $\beta \in [0,1)$. It confirms that (g_e^T, g_c^{RD}) is never a pairwise stable FTA network for all $\beta \in [0,1)$. Q.E.D.

A2.6 Proof of Proposition 3

In our model, if every country chooses its tariffs to maximize global welfare instead of its own national welfare, all the optimal internal tariffs are equal to zero[11]. To prove this result, we consider the empty FTA networks. It can be verified that $\frac{\partial W(g_e^T, g^{RD})}{\partial t_i^j} \mid_{t_i^j=0} < 0$ and $\frac{\partial^2 W(g_e^T, g^{RD})}{\partial (t_i^j)^2} \mid_{t_i^j=0} < 0$. Therefore, the efficient network must consist of the complete FTA network as the first layer of network. Figure 5 illustrates global social welfare in different double-layer network structures, where the first network layer is the complete FTA network. Q.E.D.

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