R&D in Trade Networks: The Role of Asymmetry*

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Abstract

This paper argues that asymmetry in countries' trade exposure is an important determinant of firms' R&D, productivity and countries' welfare. We model a choice of R&D in a given trade network focusing on asymmetric *hub-and-spoke* networks and symmetric networks. We find that R&D, productivity and total surplus are highest in a hub economy and lowest in a spoke, while intermediate levels are exhibited by countries in a symmetric network. Thus, regional/preferential trade agreements, resulting in asymmetric trade networks, benefit hubs but harm spokes. By contrast, multilateral trade agreements, resulting in a *complete* network, generate equal R&D and welfare benefits for all countries.

Keywords: Trade network, hub-and-spoke network, asymmetry, R&D, oligopolistic competition, trade agreements

JEL Classification: O31, D43, L13, F13, D85

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1. Introduction

The last three decades of globalization, expansion of the World Trade Organization (WTO) and unprecedented spread of preferential trade agreements between countries have resulted in international trade network turning progressively large and complex. One of its key features is large asymmetries in countries' exposure to international trade, where some countries trade with many foreign partners, while others trade with only a few. In the literature, such trade network is often described as *core-periphery* or *hub-and-spoke* in structure, both in overall terms and at the commodity-specific level.[1] Figure 1 provides an illustration.

The main message of this paper is that this asymmetry in countries' trade exposure is an important determinant of firms' innovation, productivity and countries' welfare. It benefits countries that trade with many but harms those that trade with a few.

This message has a number of relevant implications. First, it suggests that disregarding asymmetry of the trade system may lead to biased empirical estimates of the impact of trade on innovation, productivity, welfare and – in the long run – on countries' economic growth.[2] Second, it implies that firms' innovation incentives and productivity as well as countries' welfare depend on the type of their trade agreements with other countries – multilateral or preferential/regional – since each type of trade agreements is associated with a specific type of countries' involvement in the overall network of trade. Third, by bringing the main message of the paper to the context of inter-regional trade within one country, we obtain that asymmetry in inter-regional trade relations may be an important factor contributing to the commonly observed disparities in firms' productivity and wealth across regions.[3] Finally, interpreting asymmetry of the trade network more generally as asymmetry in firms' market coverage, the implications of our analysis are that "core" firms, that sell in a larger number of markets (for example, through online trade) or produce a good that meets higher demand due to being more central in the product space (mass product), should have more incentives to invest in R&D and exhibit higher productivity.

The effects of trade on firms' innovation and endogenous productivity growth has been a subject of extensive research in trade literature. Recent empirical studies find that trade openness increases firms' incentives to innovate and adopt new technologies.[4] Complementary to empirical work, theoretical studies identify various channels for this effect. Traditionally, most of these studies analyze a setting with just two countries, home and foreign, or offer numerical results for the setting with more than two countries.

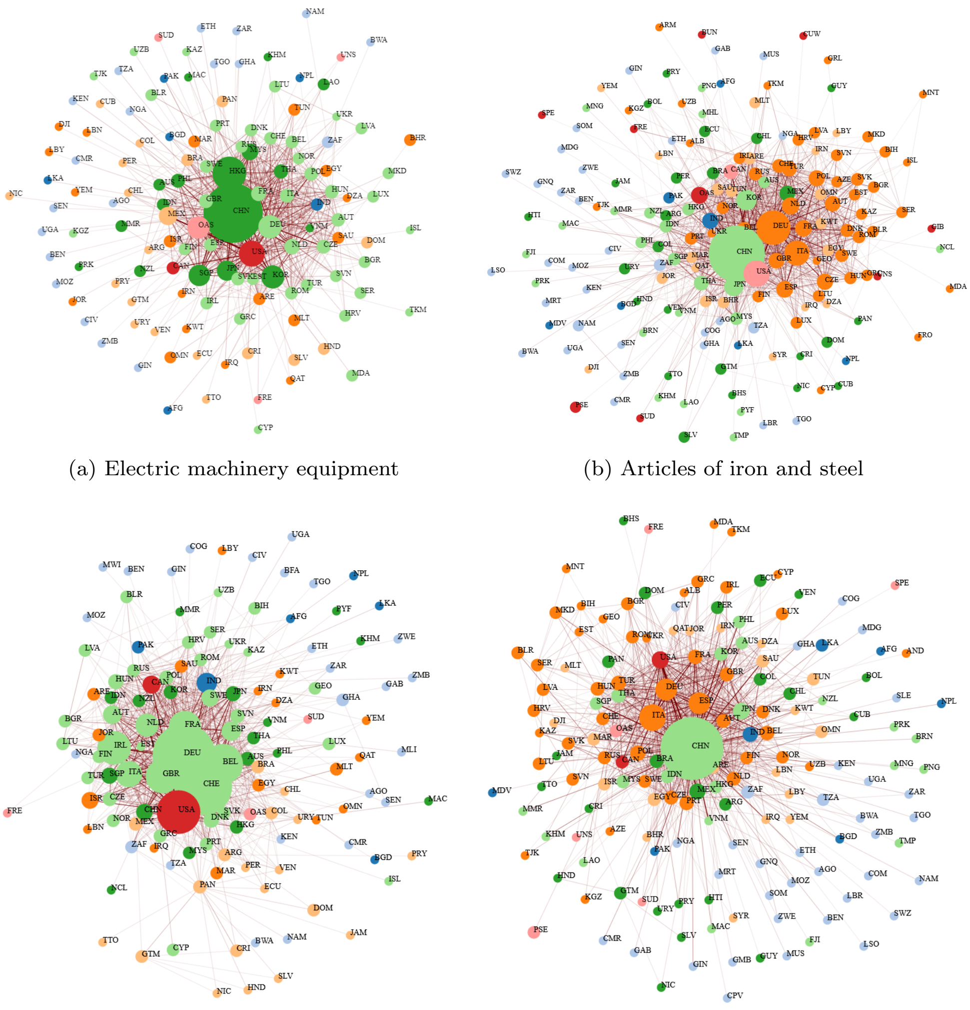
In this paper, we propose an analytical framework with multiple countries to examine how the impact of trade on firms' R&D and productivity depends on structural features of the trade network and in

[1] See, for example, Wonnacott (1990, 1991, 1996), Kowalczyk and Wonnacott (1992), Puga and Venables (1997), Baldwin (2004), Yang and Gupta (2005), De Benedictis et al. (2005), Deltas et al. (2006), Horaguchi (2007), Chong and Hur (2008), Kali and Reyes (2007), Alba et al. (2008), Fagiolo et al. (2009), De Benedictis and Tajoli, 2011, and König et al., 2014.

[2] This bias is already anticipated by empirical research that emphasizes the importance of trade network topology for countries' economic growth and trade benefits (Kali and Reyes, 2007; Yang and Gupta, 2005).

[3] Strong wealth polarization exists in many countries. For example, according to the statistics reported by The Economist (March 10th, 2011), Britain and the U.S.A. have the widest regional disparities in a group of developed countries covered by the survey. Average GDP per head in central London is more than nine times larger than in parts of Wales; and the District of Columbia in the U.S. is five times as rich as Mississippi. Italy and Germany have the smallest regional spread, yet incomes in their most affluent areas are still almost three times those of the poorest.

[4] For example, Verhoogen (2008) reports that Mexican exporting firms are more likely than non-exporters to use more advanced production techniques, and Bustos (2011) finds that Mercosur trade agreement generated an increase in new technology spending by Argentinian exporters. Similar findings are reported by Lileeva and Trefler (2010) for Canada, Bernard et al. (2006, 2007) for the U. S., Topalova (2004) for India and Alvarez and Lopez (2005) for Chile.



(a) Electric machinery equipment

(b) Articles of iron and steel

(c) Pharmaceutical products

(d) Ceramic products

Figure 1: The world trade network at the commodity level in year 2016. The colours represent geographic regions. The node size is proportional to the export market share of the country. The link thickness is proportional to its world trade share. Source: UN Comtrade Database (WITS Trade Data Visualization).

particular, its asymmetry. Building on the models of intra-industry trade in oligopoly setting (Goyal and Joshi, 2006; Saggi, 2006; Chen and Joshi, 2010), we assume that there is a single firm in every country producing some homogeneous good that can be sold in the domestic market and in each of the foreign markets.[5] A firm's ability to sell in foreign markets, however, depends on the level of import tariffs and other trade costs, making trade possible only between those countries where these costs are sufficiently low.[6] Such possibility of trade is denoted by a link. Given a configuration of trade links, firms then compete in different markets by choosing their cost-reducing R&D and afterwards, output levels for the separate product markets. In this setting we are interested in the effects of trade network asymmetry on firms' incentives to innovate. The key idea is that asymmetry in trade relations creates heterogeneity in aggregate demand and competition faced by firms in different countries, which in turn, affects R&D.

[5] We opt for oligopolistic competition, rather than monopolistic competition, which is more commonly assumed in international trade theory, since process R&D merges better with Brander (1981) oligopoly model than with Krugman (1980) monopolistic competition model.

[6] These could be countries that are geographically close or have a history of established relations with each other (e.g. due to colonial links, common language, a tradition of business and other interactions). Import tariffs are also low (or zero) between countries that negotiated trade agreements or other regulations reducing trade barriers.

Two factors are important determinants of R&D in this model. The first is the aggregate demand of a firm, or its market size. As in D'Aspremont and Jacquemin (1988), Goyal and Moraga-González (2001) and more recently König et al. (2014a), we consider the cost of R&D to be fixed. Instead, the returns to R&D are larger the larger the aggregate demand.[7] As a result and consistently with much empirical evidence (Griliches, 1957; Gustavsson et al., 1999; Acemoglu and Linn, 2004), firm's incentives to innovate increase in its market size. The latter, in turn, is determined by the number of markets where the firm sells its good and the level of competition in each market. The second factor is the fact that competition in R&D takes place *before* competition in a product market. As emphasized by Brander and Spencer (1983), when R&D is chosen before the associated output is produced, imperfectly competitive firms use R&D for strategic purposes rather than simply to minimize costs. They have higher incentives to reduce their marginal costs through R&D investment as this increases their own and reduces each of their rivals' output levels, and the larger the number of rivals, the stronger this effect.

In asymmetric trade networks firms are heterogeneous in both their aggregate demand and the level of competition they face. The main challenge is then to determine how this heterogeneity translates into firms' R&D decisions. Note that the joint action of the two driving forces for R&D is not immediately straightforward. On the one hand, a trade link provides an access to another market, which amplifies the aggregate demand of a firm and thereby increases its incentives for R&D (a positive *scale* effect). On the other hand, it also opens the domestic market of a firm to another competitor, which (i) reduces its domestic market share and thus reduces R&D (a negative *market size* effect of competition), but also (ii) intensifies the firm's strategic incentives for cost reduction and thus increases R&D (a positive *strategic* effect of competition). Moreover, the strength of the described effects depends on the number of trade partner's own links, as it determines the extent of both changes – in firm's market size and in the level of competition. In fact, as trade partner's own links only add to competition faced by a firm in the trade partner's market (without offering access to their market), their effect on R&D of the firm reveals the sign of the *overall* competition effect. This sign turns out to be negative. Thus, in asymmetric trade networks, R&D of a firm with many trade links may be higher as a result of a larger scale effect or lower as a result of higher competition.

We consider two large classes of trade network structures. In the spotlight of our analysis is the class of asymmetric, *hub-and-spoke* networks, where some countries (hubs) have a relatively large number of trade partners whereas other countries (spokes) have only a few partners. We use such networks to approximate the core-periphery structure common in the actual trade networks.[8] For simplicity, we focus on networks where all hub nodes are the same and all spoke nodes are the same, so that each network can be characterized by just four parameters: the number of trade partners of a hub, number of trade partners of a spoke, share of hubs among trade partners of a hub, and share of spokes among trade partners of a spoke. A variation in the first two parameters allows addressing the effects of asymmetry in countries' trade

[7] In contrast to this model, D'Aspremont and Jacquemin (1988), Goyal and Moraga-González (2001) and König et al. (2014a) focus on the role of R&D collaboration and spillovers between firms and assume that all firms compete in one market, either in both their choices, R&D and output, or only in output.

[8] See Figure 1 and references in footnote 1 to the literature that describes trade networks as core-periphery or hub-and-spoke in structure.

involvement. A variation in the last two allows studying the effects of the exact pattern of asymmetry, that is, how for a given degree of asymmetry, the composition of partners with high and low trade involvement matters for firms' incentives to innovate. The results of our analysis for the hub-and-spoke networks are then compared with the benchmark case of symmetric structures. In a symmetric network all countries have the same number of trade partners. For example, in the symmetric *complete* network any country is linked with every other.

The primary result of this paper is that the trade network asymmetry promotes R&D and productivity of a hub firm and hinders those of a spoke. Comparing hub-and-spoke and symmetric networks, we find that R&D investments are highest in a hub, lowest in a spoke and intermediate at a firm in a symmetric network. Furthermore, the larger the degree of network asymmetry, the larger the difference between R&D spendings of a hub and a spoke. We also find that a larger trade exposure of country's trade partners has a negative effect on firm's incentives to innovate, which reveals that the overall competition effect of trade on R&D in our model is negative. In particular, for any given degree of network asymmetry, the larger the share of hubs among trade partners of a country (hub or spoke), the lower its R&D.

Given this latter finding about the negative overall effect of competition, the observed effects of asymmetry are intuitive. R&D of a hub is larger than R&D of a firm in the symmetric network because even when they have access to the same number of foreign markets, the competition faced by a hub in each of these markets is lower than the competition faced by a firm in the symmetric network.[9] If on top of that the number of foreign markets of a hub is larger, then the positive scale effect of trade increases the difference between R&D of a hub and R&D of a firm in the symmetric network even further. Conversely for spokes, given the same number of foreign markets, a spoke is exposed to higher foreign competition than a firm in the symmetric network. Thus, in any hub-and-spoke network, R&D of a hub is larger than R&D of a spoke, while R&D of a firm in a symmetric network is in-between the two. Moreover, the difference in R&D of hubs and spokes becomes larger when either their market size differences increase – if the number of directly accessible markets of a hub increases or the number of directly accessible markets of a spoke declines, – or when their competition differences increase – if the share of spokes among hub's trade partners increases or the opposite occurs at a spoke.

We then examine the welfare implications of trade in the symmetric and star networks, the latter being the simplest type of the hub-and-spoke structure. We find that for the same number of direct trade partners of a hub in the star and a country in the symmetric network, the highest firm's profit and total surplus are achieved in the hub, while the highest consumer surplus is attained in a country of the symmetric network. A spoke exhibits the lowest levels of consumer surplus and total surplus and either the lowest or intermediate profit. Furthermore, the larger the degree of asymmetry in the star network, associated with a larger number of hub's trade partners, the larger the welfare gaps between countries. However, at the aggregate level the benefits of trade are always highest in a symmetric network: the symmetric *complete* network delivers the highest aggregate consumer surplus and total surplus, while the symmetric *empty* network is best for the aggregate profits.

Given the focus of the paper on the role of trade network asymmetry, in the baseline model we consider

[9]This is because some of the hub's foreign markets are spokes, which trade with only a few countries.

the network itself as *exogenous* and focus on the comparative static effects of a change in the relative number of country's trade partners on firms' innovation and countries' welfare.[10] The assumption of network exogeneity is necessary for the purposes of our study as in a setting with identical countries, asymmetries in countries' trade relations do not emerge endogenously. This has been demonstrated earlier in the network formation literature that abstracts from R&D (Goyal and Joshi, 2006; Furusawa and Konishi, 2007; Mauleon et al., 2010) and is also confirmed in our network stability analysis, where we show that depending on the definition of welfare, stable networks tend to be complete, empty or consist of a set of one or more isolated countries and a complete component.[11]

We also show that our main findings regarding the effects of trade network asymmetry on R&D are robust to a number of model modifications. These include relaxing the assumption of linear demand, allowing for cross-country differences in market size and cost structure, assuming the existence of R&D spillovers, and modelling the trade network asymmetry by a nested split graph. We find that for a reasonable extent of these modifications, a larger exposure to trade through direct trade links promotes R&D, and that hubs do more and spokes do less R&D than a firm in the symmetric network.

The rest of the paper is organized as follows. In the next section we discuss the closely related literature. In the following section, we describe the baseline model and the determinants of firms' incentives for R&D. Subsequently, we turn to the results of the equilibrium analysis for the case of hub-and-spoke and symmetric trade networks and we compare the findings. We then present the results of the welfare analysis and endogenous network formation. Finally, we consider a number of model extensions. The last section presents the conclusions. The proofs are provided in the Appendix and Supplementary Appendix.

2. Related literature

This paper is related to the literature on the effects of trade on firms' innovation incentives and/or productivity at the firm level. Theoretical studies identify different channels for these effects: the improved allocation of resources through specialization in multi-product firms (Grossman and Helpman, 1991; Eckel and Neary, 2010), the knowledge spillovers effect (Rivera-Batiz and Romer, 1991; Grossman and Helpman, 1991), the increased profitability of lower unit-cost technology due to access to a larger market (Yeaple, 2005; Atkenson and Burstein, 2010; Van Long et al., 2011), the pro-competitive effect of trade openness (Aghion et al., 2005; Impullitti and Licandro, 2013), and others.[12]

Among these studies the most closely related to our paper are oligopoly models of intra-industry trade between countries that are the same or similar in their endowments and technologies.[13] This literature is not large. Early contributions include Jensen and Thursby (1986, 1987), more recent developments are Impullitti and Licandro (2013), Haaland and Kind (2008), Van Long et al. (2011), and Dewit and Leahy

[10] We show that this enables the comparison of a large variety of complex network structures.

[11] Trade network asymmetries are likely to emerge in a setting where countries are *a priori* different in their market size and/or firms' marginal production costs. Consistently with Pires (2012), countries that are larger and/or more productive should be more involved in the international trade.

[12] In addition, the "new" trade literature with increasing returns in production (Krugman, 1979, 1980; Helpman, 1981) and the firm heterogeneity literature (Melitz, 2003; Melitz and Ottaviano, 2008; Arkolakis et al., 2014) take the firm-level productivity as exogenous and address the effects of trade on productivity at the *industry* level.

[13] Similarity in endowments and technologies sets aside the "comparative advantage" explanation of trade asserted in the traditional trade literature (the Heckscher-Ohlin and Ricardian models).

(2015). These studies provide the rationale for the impact of trade on firms' innovation incentives and for the effect of R&D subsidies, focusing on a setting with just two countries – home and foreign – or on a setting with more than two countries but such that all countries are absolutely symmetric (including the symmetry in firms' market size). A common assumption in this literature is that firms from all countries trade either in a single "world market", where the demand for good and competition between firms are increased compared to their autarky levels, or that they trade in separate, "segmented markets" but so that *all* firms have access to *all* markets and compete with each other. Clearly, such approach does not allow investigating the effects of asymmetry in countries' trade relations, which is the focus of this paper.[14] In addition, Pires (2012) analyzes a two-country trade model with asymmetric markets. However, the market size differences of firms in this model are imposed by assumption rather than implied by differences in their exposure to trade. Therefore, the focus of the paper is also different from the one in our paper. It is not on the impact of trade and asymmetries in trade on firms' R&D but in some sense, the other way round: Pires (2012) explores how (assumed) market size differences and the implied differences in firms' R&D affect the amount of firms' export.[15]

In terms of modelling approach, our paper combines the framework of the oligopolistic models of trade where trade relations between countries are represented by a network (Goyal and Joshi, 2006; Mauleon et al., 2010) and the framework of the models on R&D collaboration in oligopoly (D'Aspremont and Jacquemin, 1988; Goyal and Moraga-Gonz*á*lez, 2001; König et al. (2014a)). In contrast to the former, which focuses on network formation and efficiency of the trade networks, we are interested in R&D and the effects of a given network structure on firms' incentives to innovate.[16] In contrast to the latter, which studies R&D collaboration between firms that compete in a single market (either in both R&D and output, or only in output), we consider a model where firms compete in multiple markets and the number of competitors in each market is determined by the number of its trade links. This means, in particular, that each firm i makes not two but $n_i + 2$ decisions, choosing the level of R&D investment and production quantities for the domestic and n_i foreign markets.[17]

Finally, our paper is also related to the literature on trade agreements and political economy of trade. This literature examines the conditions that determine welfare gains of regional/preferential agreements between countries (see survey in Feenstra (2004, Chapters 6 and 9)), the economic rationale and consequences of different trade rules embodied in the GATT and the WTO (Krishna and Krueger, 1995; Bagwell and Staiger, 1997, 2002), and the incentives for countries to join regional trade agreements versus multilateral agreements (Bhagwati, 1993; McLaren, 2002; Baldwin, 1995). This literature, while rich and diverse, overlooks the question of firm innovation and productivity and the difference in those across different types of trade agreements.

[14]There is also a substantial literature on trade under oligopoly that does not address R&D, but examines motives for trade, gains from trade, etc. Classic references include Brander (1981), Brander and Krugman (1983), Venables (1985), Dixit and Grossman (1986), Yomogida (2008), Neary (2003, 2009), and Eckel and Neary (2010).

[15]In an extension (section 7.2) we consider a model, where in addition to firms' market size differences emerging from asymmetries in their exposure to trade, countries themselves are also different in size: larger countries, by assumption, have more consumers and generate higher demand for firms that sell in these countries.

[16]Network formation in this setting (with R&D) is addressed in section 6.

[17]König et al. (2014a) considers R&D collaboration between firms located in multiple markets, but there is no trade between them as each firm produces output only for its own market. Also, R&D and output decisions in this model are made simultaneously, which eliminates the "strategic" role of R&D investments and allows deriving R&D in arbitrary networks.

3. Basic model

We consider a setting with N countries, where at least some of the countries are involved in intra-industry trade with others, as represented by links in the trade network. In each country there is a single firm producing some homogeneous good that it can sell in the domestic market and in each of the *directly linked* foreign markets. Given a configuration of trade links, firms compete in different markets by first choosing their cost-reducing R&D and then output levels. In this model we examine the effects of the trade network structure on firms' R&D incentives. We now introduce some terminology and provide a formal description of the trade network, the economy, the two-stage game between firms and the equilibrium notion.

3.1. Trade network

Trade relations between countries are modeled as a network in which nodes represent countries and links indicate the pairs of countries between which tariffs and other trade costs are sufficiently low.[18] For simplicity, we suppose that the low trade costs between linked countries are, in fact, zero and high trade costs are trade prohibitive by being larger than the highest possible market price ($T > a$, see eq. (1)). Thus, only the countries that are directly linked in the network can trade, in which case they offer each other a free access to their domestic market.[19]

For any $i \in 1 : N$, N_i denotes the set of countries with whom i has a trade link in the network. These are *direct trade partners* of i. Let $n_i = |N_i|$. Similarly, N_i^2 denotes the set of direct trade partners of direct trade partners of i that are different from i itself. We call countries in N_i^2 *two-links-away trade partners* of i. Note that some countries can be simultaneously i's direct and two-links-away trade partners.

3.2. Demand and cost structure

Each country has one firm producing some homogeneous good that can be sold in the domestic market and in the markets of its direct trade partners. This gives rise to oligopolistic market structure in all countries.[20] Given the focus of the paper on the role of the trade network asymmetry, we consider the countries as identical in all but their position in the network, and we address the role of cross-country differences in market size and marginal costs in an extension (section 7.2).

Let us denote the output of firm i sold in country j by y_{ij}. The total output of firm i is then $y_i = \sum_{j \in N_i \cup \{i\}} y_{ij}$, while the total output sold in country j is $\sum_{k \in N_j \cup \{j\}} y_{kj}$. All firms selling their good in country j face an identical inverse linear demand given by:[21]

$$p_j = a - b \sum_{k \in N_j \cup \{j\}} y_{kj}, \tag{1}$$

[18] For example, countries for which trade barriers are low due to trade agreements or geographic proximity or historically established relations are connected by the link.

[19] The same representation of trade network is proposed in the network formation model of Goyal and Joshi (2006). In footnotes and in the Supplementary Appendix we show that most of our results continue to be valid when unit trade costs between linked countries are set at a positive level τ.

[20] The same setting with a single firm per country is considered in Goyal and Joshi (2006), Chen and Joshi (2010) and Mauleon et al. (2010). Note, however, that all model predictions would stay qualitatively the same if the number of domestic firms in each country was scaled up to $K > 1$ as long as each firm's market share remains positive in every market.

[21] In section 7.1 we explore the effects of concave demand functions.

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

Each firm has a constant marginal cost of production $\gamma > 0$. It can reduce it by investing in process R&D, which is itself costly and adds to firm's fixed costs. Let x_i denote the R&D effort of firm i. Then the (linear) production cost function is given by:

$$c(y_i, x_i) = (\gamma - x_i) y_i, \tag{2}$$

where $0 \leq x_i \leq \gamma \ \forall i \in 1 : N$. The R&D cost function is quadratic and given by[22]

$$z(x_i) = \delta x_i^2 \tag{3}$$

for some $\delta > 0$. Thus, when firms choose their innovation efforts, they face a trade-off between investing more in R&D and achieving lower marginal costs at the expense of higher fixed costs, and vice versa. However, firms with a larger overall market (domestic and foreign) can cover their fixed costs of innovation more easily due to increasing returns in production. The straightforward implication of this is that the overall market size of a firm, that is, its aggregate demand on the market is an important determinant of firm's incentives to innovate.

The demand and cost structure described above give rise to the following profit function of firm i:

$$\pi_i = \sum_{j \in N_i \cup \{i\}} \left(a - b y_{ij} - b \sum_{k \in N_j \cup \{j\}, k \neq i} y_{kj} \right) y_{ij} - (\gamma - x_i) y_i - \delta x_i^2. \tag{4}$$

It is equal to the total revenue collected by the firm in its domestic and foreign markets minus the costs of overall production and R&D.

3.3. Two-stage game

Firms choose their level of R&D and the subsequent production plan via interaction in a two-stage non-cooperative game. At the first stage firms simultaneously choose their R&D efforts, which determines their marginal cost of production. Given this cost, at the second stage firms compete in Cournot fashion and simultaneously choose their production quantities for the domestic market and for the markets of their direct trade partners.

Note that the two-stage nature of decision making in this game means that R&D investments chosen at the first stage are used for strategic purposes rather than simply to minimize costs. Higher R&D allows firms to increase their own and reduce each of their competitors' output levels, and the larger the number of competitors the stronger this effect.[23] Thus, competition does not only affect firm's incentives to innovate via its impact on firm's market size (negative *market size* effect of competition on R&D). It also affects these incentives directly by intensifying firm's strategic incentives for marginal cost reduction (positive *strategic* effect of competition on R&D). This makes the level of competition another important determinant of firm's R&D in our model.

The levels and nature of competition, in turn, are determined by the configuration of trade links and are quite specific in this game. First, observe that firms compete with each other not in one but in

[22] Quadratic cost of R&D implies diminishing returns to scale in innovation, which finds some support in the empirical literature (e. g. Fung (2002)).

[23] See Brander and Spencer (1983) for the detailed analysis of these strategic considerations in firms' R&D choice.

several separate markets. Second, since only directly linked countries trade, a 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 interaction does not mean, of course, that firms located further away from i do not affect its R&D and production choices. As soon as the trade network is connected, these firms affect the decisions of i *indirectly*, through the impact they have on R&D and production choices of their own trade partners and trade partners of their partners, etc. Therefore, the entire network and its precise structure matter.

3.4. Equilibrium

We use the subgame perfect Nash equilibrium as a solution concept for the game. We find it by backward induction and provide the details of derivations in the Appendix. First, we observe that the profit function of each firm is concave in firm's own choice variables – production quantities at the second stage of the game and R&D effort at the first stage.[24] Second, we show that the solution of the system of (linear) first-order optimality conditions at each stage exists and is interior as long as certain restrictions on parameters hold. Namely, as soon as the demand in each market, governed by parameter a, is sufficiently high relative to the marginal production cost γ (Assumption 1), all production quantities y_{ij} and R&D investments x_i of all firms are strictly positive. And as soon as R&D is sufficiently costly, due to a high enough value of δ (Assumption 2), the amount of R&D investments will not exceed the upper threshold of γ.

Assumption 1 $a > \gamma\left(1 + \max_{i\in 1:N} n_i\right)$.

Assumption 2 $\delta > \frac{1}{\gamma b} \max\limits_{i\in N} \sum\limits_{j\in N_i\cup\{i\}} \frac{n_j+1}{(n_j+2)^2}\left(\gamma n_j + a\right)$.

Thus, under these assumptions, the system of the first-order optimality conditions at each stage determines the equilibrium production quantities and R&D efforts of firms, where all production quantities and R&D efforts are strictly positive and R&D does not exceed γ.[25] In what follows we will assume that Assumptions 1 and 2 hold.

We also show that the Nash-Cournot equilibrium of the second stage is always unique, while the equilibrium of the first stage is either unique or unique for all but a few values of parameter δ. In the Appendix we demonstrate that the system of the first-order conditions at the R&D stage can be represented in the matrix form as $\left(\delta\mathbf{I} - \frac{1}{b}\mathbf{B}\right)\cdot\mathbf{x} = \frac{1}{b}\mathbf{u}$, where $\mathbf{I}$ is the identity matrix, while matrix $\mathbf{B}$ and vector $\mathbf{u}$ are composed of functions of n_i for all $i \in 1:N$. Then as soon as δ is different from each of the eigenvalues of matrix $\frac{1}{b}\mathbf{B}$, the matrix $\left(\delta\mathbf{I} - \frac{1}{b}\mathbf{B}\right)$ is invertible, and the system of the first-order conditions has a unique solution. This, for example, is *always* the case when all eigenvalues of $\frac{1}{b}\mathbf{B}$ are negative or some are positive but not large enough to satisfy Assumption 2. For simplicity, in the following we will focus on such generic values of δ under which the solution is unique.[26]

[24] At the first stage the concavity is ensured when parameter δ is high enough, which follows from Assumptions 1 and 2.
[25] In the Appendix we also show that under Assumptions 1 and 2, the equilibrium profits of all firms are strictly positive.
[26] Otherwise, the R&D equilibrium that we discuss is one of many but it is still a reasonable choice: it represents the unique *symmetric* equilibrium, where firms with the same position in the network exert identical R&D effort.

The equilibrium has two notable properties. First, the equilibrium output of firm i for any country $j \in N_i \cup \{i\}$, that is, i's share of market j, is increasing in firm's own R&D effort and decreasing in R&D efforts of i's rivals in market j. Second, the equilibrium R&D efforts of firm i and its direct and two-links-away trade partners are *strategic substitutes* from i's perspective. Intuitively, by exerting higher R&D efforts, firm i's rivals capture larger market shares, and this reduces returns to R&D for firm i.

Finally, we note that our focus on specific, hub-and-spoke and symmetric networks in the subsequent analysis is explained, on the one hand, by our interest in the effects of the trade network asymmetry, that are well captured in this setting, and on the other hand, by the complexity of the (network-dependent) coefficients of matrix $\mathbf{B}$ and vector $\mathbf{u}$, that makes the analysis in general networks infeasible.

4. Results

In this section, we derive the equilibrium R&D efforts of firms in hub-and-spoke and symmetric trade networks. Given the two driving forces for R&D – firm's market size and the level of competition it faces, – the main challenge is to determine how an asymmetry in countries' exposure to trade, and the associated differences in firms' overall market size and competition, translate into R&D differences. As larger exposure to trade also means higher level of competition faced by a firm, the positive *scale* effect of access to a greater market can be dominated by the negative *market size* effect of competition, or reinforced by its positive *strategic* effect.[27] The strength of each effect is determined not only by country's own and its trade partners' position in the network, but also by a broader network structure, so that minor differences even within a class of asymmetric networks (such as due to differences in trade partners' composition) lead to different incentives to innovate. In what follows we investigate these effects.

4.1. Asymmetric trade networks

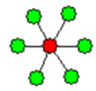
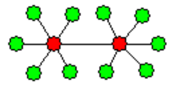
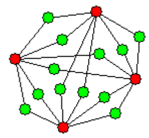
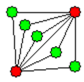
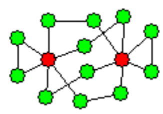
We approximate the core-periphery tendency in real-world trade networks by an asymmetric, hub-and-spoke structure.[28] It involves two types of countries: *hubs*, that have a relatively large number of direct trade partners, and *spokes*, that have only a few partners. For simplicity, all hubs are assumed to be the same and all spokes are the same, too, which allows describing the network by just four parameters: n_h, the number of direct trade partners of a hub; n_s, the number of direct trade partners of a spoke; ψ, the share of hubs among direct trade partners of a hub; and φ, the share of spokes among direct trade partners of a spoke. Asymmetry of the network is captured by considering $1 \leq n_s < n_h$, and the larger the difference between n_h and n_s, the larger the degree of asymmetry. The values of ψ and φ determine the composition of countries' direct trade partners, that is, the exact pattern of asymmetry. We consider $0 \leq \psi, \varphi < 1$, where $\varphi = \psi = 0$ represents the case in which hubs trade *exclusively* with spokes and vice versa.[29] Clearly, not all combinations of the four parameters are feasible but those that are feasible form

[27] In fact, the negative market size effect of competition is itself a result of two opposite effects (where the negative component prevails): the negative market share effect and positive markups effect. The latter increases firm's overall demand by means of a reduction in price markups.

[28] In an extension (section 7.4), we consider an alternative way of modelling an asymmetric trade network as a nested split graph.

[29] The examples of $\varphi = \psi = 0$ are Type 1 and 3 networks in Table 1. We also note that setting $n_s = n_h = n$ eliminates the difference between hubs and spokes and turns the network into a symmetric network of degree n (ψ and φ are meaningless in this case), while setting $\varphi = \psi = 1$ effectively splits the network into two symmetric components of degree n_s and n_h.

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

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

Remark: Red nodes indicate hubs, green nodes indicate spokes.

a rich set of different hub-and-spoke architectures. Some examples are presented in Table 1, where Types 1 - 5 of the hub-and-spoke network differ either in their degree of network asymmetry (difference between n_h and n_s) or in the pattern of asymmetry (values of ψ and φ).

Though hub-and-spoke networks offer only a simplistic description of actual trade networks (cf. Figure 1), they capture the key feature of asymmetry in countries' exposure to trade, while keeping the analysis tractable. In trade policy, hub-and-spoke networks can be viewed as a representation of regional/preferential type of trade. When signed by members of the WTO, regional trade agreements signify a major departure from the basic WTO principle of non-discrimination, according to which all WTO countries are obliged to grant each other unconditionally any benefit or privilege affecting custom duties and charges on equal, non-discriminatory basis. By contrast, in regional trade agreements (customs unions and free-trade areas), countries within the agreement are treated more favorably than those outside: import tariffs are completely eliminated between the members of the agreement, but kept on imports from the rest of the world. Regional trade agreements have become prevalent in the last two decades, with some countries being parties to several agreements. This results in the network where different regional trade agreements "overlap", forming the hub-and-spoke structure of the type considered here.

In what follows we first derive the equilibrium R&D investments of hub and spoke firms. These can be found as the unique solution of the system of the first-order conditions (12) (see Appendix). In equilibrium, all hub firms exert identical R&D effort x_h^* and all spoke firms exert identical R&D effort x_s^*, presented in

(14). With this solution in hand, we then perform comparative statics to examine the impact on R&D of a change in each of the four parameters describing the hub-and-spoke network.

Our main findings can be summarized as follows. First, a larger degree of asymmetry in the trade network, associated with an increase in n_h or a decrease in n_s or both, leads to a larger disparity in innovation efforts of hubs and spokes. While for a hub, the larger the asymmetry, the larger the equilibrium R&D, for a spoke the opposite is true, at least when certain conditions hold. Moreover, for a given degree of asymmetry, R&D of both a hub and a spoke increases in the share of spokes among their direct trade partners. Formally, these findings are stated below.

Proposition 1 (hub-and-spoke network). *Consider hub-and-spoke trade networks, where $n_s < n_h \leq \bar{n}$ for some $\bar{n} > 1$. There exists $\Delta > 0$ such that for any $\delta \geq \Delta$ and for any $n_s < n_h < \bar{n}$ and $0 \leq \psi, \varphi < 1$, the following statements are fulfilled:*

1. *the equilibrium R&D effort x_h^* of a hub is monotonically increasing in the number of hub's direct trade partners, n_h, and monotonically decreasing in the number of spoke's direct trade partners, n_s;*
2. *the equilibrium R&D effort x_s^* of a spoke is monotonically decreasing in the number of hub's direct trade partners, n_h;*
3. *the equilibrium R&D effort x_s^* of a spoke is monotonically increasing in the number of spoke's direct trade partners, n_s, if at least one of the conditions holds:*
   - *(a) the share of other spokes among direct trade partners is at least 1/3: $\varphi \geq \frac{1}{3}$,*
   - *(b) the gap between n_h and n_s is relatively small: $n_h \leq n_s^2$, that is, $1 < \frac{n_h}{n_s} \leq n_s$;*
4. *the equilibrium R&D efforts of both a hub and a spoke are monotonically increasing in the share of spokes among their direct trade partners: x_h^* is monotonically decreasing in ψ, and x_s^* is monotonically increasing in φ.*

Proposition 1 implies that the larger the number of directly accessible markets, the higher the incentives for R&D (parts 1. and 3.), but the larger the number of competitors in these markets (two-links-away trade partners), the lower these incentives (parts 1., 2. and 4.). In fact, the latter suggests that the overall effect of competition on R&D, revealed since only the number of firm's competitors increases, while the number of accessible markets remains the same, is negative. That is, the negative market size reducing component of the competition effect outweighs its positive strategic component.[30] Still, the positive scale effect of trade between any *directly* linked countries is strong enough to outweigh the negative competition effect: this is always true for hubs, and in cases (a), (b) for spokes.[31]

Given these observations about the scale and competition effects of trade in hub-and-spoke networks, the results of Proposition 1 are intuitive. For a hub, a larger asymmetry is associated with a larger number

[30] Alternatively, this can be demonstrated in a simple model where N firms compete in a single market of a fixed size, by first choosing R&D and then output for that one market. There it is easy to show that equilibrium R&D is decreasing in N.

[31] In Supplementary Appendix we further investigate the impact of direct and two-links-away trade partners on R&D of a firm in a *generic* network under the assumption of *small local effects*. Consistent with Proposition 1, we find that in a generic network, new direct trade partners tend to increase R&D of a firm, and this effect is stronger, the smaller the number of competitors in the new markets.

of directly accessible markets (higher n_h) and lower number of competitors at least in some of these markets (lower n_s). For a spoke, the implications of asymmetry are the opposite. Moreover, for any given n_h and n_s, the larger the share of spokes among direct trade partners of a country (hub or spoke), the lower the foreign competition.

It remains to understand conditions (a) and (b) which ensure that an increase in n_s promotes R&D of a spoke.[32] Recall that the specification of a hub-and-spoke trade network in this model is such that an increase in the number of spoke's direct trade partners n_s is associated with an increase in the number of *both* types of partners – hubs and spokes. Then since the market share that can be gained in a hub is "small" – smaller than the market share to be gained in a spoke, an increase in spoke's foreign market share due to access to new markets may actually be smaller than a decrease in its domestic market share due to increased competition. That is, the positive scale effect of an increase in n_s on spoke's market size and R&D may be dominated by the negative competition effect.[33] Conditions (a) and (b) ensure that this would not be the case if either (a) hubs represent only a relatively small share of direct trade partners of a spoke, or (b) the number n_s of competitors in a spoke's market is comparable to n_h, so that the loss in the domestic market share of a spoke does not exceed the gain in a new hub's market.

The results of Proposition 1 can be employed to rank R&D efforts of firms in different types of hub-and-spoke networks. For example, Corollary 1 describes the comparisons that can be made with respect to hub-and-spoke networks of Table 1. Here we denote by x^*_{hi} the R&D of a hub and by x^*_{si} the R&D of a spoke in Type i of the hub-and-spoke structure, where $i \in 1:5$.

Corollary 1. *Consider Types 1–5 of the hub-and-spoke trade network. Suppose that (i) n_h is the same across all types, (ii) n_s is the same across all types where $n_s > 1$ (Types 3, 4 and 5), and (iii) ψ is the same across all types where $\psi > 0$ (Types 2 and 4). Then firms' equilibrium R&D efforts in Types 1–5 of the hub-and-spoke structure can be ranked as follows:*[34]

$$x^*_{h1} > x^*_{h3} > x^*_{h4}, \quad x^*_{h1} > x^*_{h2} > x^*_{h4}, \quad \textit{and} \quad x^*_{s5} > x^*_{s3} > x^*_{s1}, \quad x^*_{s4} > x^*_{s2}.$$

Note that amongst all hub-and-spoke networks, a star (Type 1 network) is the one where hub enjoys the lowest competition in its foreign markets. Therefore, for a fixed number of a hub's direct trade partners, the hub of a star invests in R&D most. As the number of rivals in a hub's foreign markets increases, R&D of the hub declines. This is the case when either the number of a spoke's direct trade partners, n_s, increases (Type 3 network), or the share of hubs among direct trade partners, ψ, grows (Type 2 network), or both changes in n_s and ψ happen simultaneously (Type 4 network).For spokes, the situation is reversed. In a star (Type 1 network) each spoke has access to a single foreign market. Then given a fixed number of a hub's direct trade partners, the market size and R&D of a spoke in the star are smaller than in other hub-and-spoke networks. As the number of direct trade partners of a spoke, n_s, increases (Type 3

[32]In a model where trade costs between the linked countries are not zero but τ per unit of export, another condition is that the trade costs of firms are sufficiently high (to restrict the amount of exports from new trade partners): $\tau \geq \frac{1-3\varphi}{3(1-2\varphi)}(a-\gamma)$. Note that this condition is only meaningful when $\varphi < \frac{1}{3}$, i.e., when (a) does not hold.

[33]This outcome seems to be rather rare though. For example, by calculating the model for the star network under various parameter assumptions, we find that initiating trade with the hub decreases R&D of a spoke only when the number of competitors in the hub's market (other spokes) is above 100.

[34]The last two inequalities, $x^*_{s3} > x^*_{s1}$ and $x^*_{s4} > x^*_{s2}$, require in addition, that at least one of two conditions (a), (b) of Proposition 1 holds, under which x^*_s is increasing in n_s.

network), its market and R&D expand, and they expand even further if the share of spokes among direct trade partners, φ , grows (Type 5 network).

To further examine the effects of asymmetry in the trade network, in the next section we compare our results for hub-and-spoke networks with those for a symmetric network, where all countries have the same number of direct trade partners. This will also allow us to demonstrate that in any hub-and-spoke network R&D of a hub is strictly larger than R&D of a spoke, as the former turns out to be larger and the latter – smaller than R&D of a firm in the symmetric network.

4.2. Symmetric trade networks. Comparison with asymmetric networks

In symmetric, or *regular* trade networks, each country has the same number n of direct trade partners. n is sometimes called the *degree* of a symmetric network. When $n = N - 1$, every country has a trade link with every other country, and the network is called *complete.*

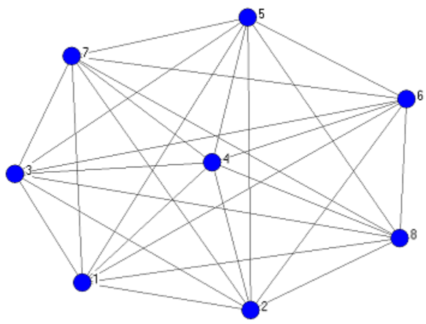


Figure 2: Complete network with 8 countries

The complete network can be thought of as representing multilateral trade between countries as it satisfies two fundamental principles of the GATT: "reciprocity" and the "most favoured nation" principle of non-discrimination.[35] Clearly, when all countries are linked with each other and tariffs are zero on all links, both principles apply.

In a symmetric network, all countries are identical, and the unique solution of the first-order conditions at the R&D stage of the game is such that $x_i^* = x^*$ for all $i \in 1 : N$. That is, the equilibrium R&D investments of all firms are the same and equal to

$$x^*(n) = \frac{a - \gamma}{-1 + \delta b\left(1 + \frac{1}{n+1}\right)^2}. \tag{5}$$

This is clearly increasing in n, which implies that firms' incentives to innovate become stronger as the number of a country's direct trade partners increases.[36]

Proposition 2 (symmetric network). *In a symmetric network of degree n, where $n < \bar{n}$ for some $\bar{n} \geq 1$, firm's equilibrium R&D effort x^* is monotonically increasing in n for any $n < \bar{n}$.*

[35] The former implies that each country agrees to reduce its trade barriers in return for a reciprocal reduction by another, while the latter states that all countries in the multilateral trade system should be treated equally, that is, tariffs imposed by a country on imports from *any* other country in the system must be the same.

[36] When tariffs between the linked countries are $\tau > 0$, it is easy to show that $x^*(n) = \frac{a-\gamma-\frac{n}{n+1}\tau}{-1+\delta b\left(1+\frac{1}{n+1}\right)^2}$. This is also monotonically increasing in n.

Thus, even though higher n means not only access to a larger number of foreign markets but also higher competition in each country, the total effect promotes R&D of every firm. In fact, it is the positive component of the competition effect – the strategic marginal cost reduction – that is responsible for the R&D rise.[37] The other two effects – the negative market size effect associated with increased competition and the positive scale effect associated with access to a new market – exactly offset each other: in a symmetric network, as new links are formed, the reduction in the domestic and foreign market shares suffered by each firm is exactly compensated by the participation in the new market.[38]

Now, bringing the results of our equilibrium analysis in this and previous section together, we can compare R&D of firms in symmetric and hub-and-spoke trade networks. The following proposition states that in any hub-and-spoke network, R&D of a hub is larger than R&D of a spoke. Moreover, hubs do more and spokes do less R&D than a firm in the symmetric network, even when the number of direct trade partners of a hub (resp., spoke) is the same as in the symmetric network.

Proposition 3 (comparison of symmetric and hub-and-spoke networks). *Consider a hub-and-spoke network defined by parameters $0 \leq \psi, \varphi < 1$ and $1 \leq n_s < n_h$, and any symmetric trade networks of degree n_s and n_h. There exists $\Delta > 0$ such that for any $\delta \geq \Delta$, R&D of firms in hub-and-spoke and symmetric networks can be ranked as follows:*

$$x_h^* > x^*(n_h) > x^*(n_s) > x_s^*.$$

The proof is based on the observation that a symmetric network of degree n_h can be regarded as a hub-and-spoke network "composed only of hubs", that is, where n_s in the hub-and-spoke network has increased to become equal to n_h. Similarly, a symmetric network of degree n_s can be regarded as a hub-and-spoke network "composed only of spokes", where n_h has decreased to become equal to n_s. Then inequalities $x_h^* > x^*(n_h)$ and $x^*(n_s) > x_s^*$ follow immediately from parts 1. and 2. of Proposition 1 about the negative effect of larger n_s on x_h^* and larger n_h on x_s^*. The last, "connecting" inequality $x^*(n_h) > x^*(n_s)$ is implied by Proposition 2.[39]

The next proposition combines the results of Proposition 3 and Corollary 1 and provides the ranking of equilibrium R&D efforts of firms in different types of hub-and-spoke networks (see Table 1) and in the symmetric networks.

Proposition 4 (extended comparison). *Consider Types 1–5 of the hub-and-spoke trade network. Suppose that (i) n_h is the same across all types, (ii) n_s is the same across all types where $n_s > 1$ (Types 3, 4 and 5), and (iii) ψ is the same across all types where $\psi > 0$ (Types 2 and 4). Then firms' equilibrium R&D efforts in Types 1–5 of the hub-and-spoke network and in the symmetric network can be ranked as*

[37] To be more precise, the positive markups reducing component of the competition effect contributes to that, too. See footnote 27.

[38] Note that by contrast, in asymmetric, hub-and-spoke networks, the negative market size effect of competition is generally *not* offset by the positive scale effect.

[39] The intuition is, again, suggested by the negative competition effect of firm's two-links-away trade partners in a hub-and-spoke network. While in a symmetric network of degree n_h, the number of firm's competitors is n_h in *each* of its foreign markets, in a hub-and-spoke network, the number of hub's competitors is n_h only in ψn_h of its foreign markets and smaller in the rest. Conversely for a spoke, the number of its competitors in the foreign markets is larger than for a firm in a symmetric network of degree n_s. Thus, for the same number of direct trade partners, a hub is exposed to lower and spoke to higher competition than a firm in the symmetric network. This leads to corresponding differences in R&D.

follows:

$$x^*_{h1} > x^*_{h3} > x^*_{h4} > x^*(n_h) > x^*(n_s) > x^*_{s5} > x^*_{s3} > x^*_{s1}$$

and

$$x^*_{h1} > x^*_{h2} > x^*_{h4} > x^*(n_h) > x^*(n_s) > x^*_{s4} > x^*_{s2}.$$

The first sequence of inequalities is demonstrated by Figure 3, where R&D is shown as a function of n_h.[40] R&D is depicted in red for a hub (highest in a hub of the star), in green for a spoke (lowest in a spoke of the star) and in blue for a firm in the symmetric network of degree n_h.

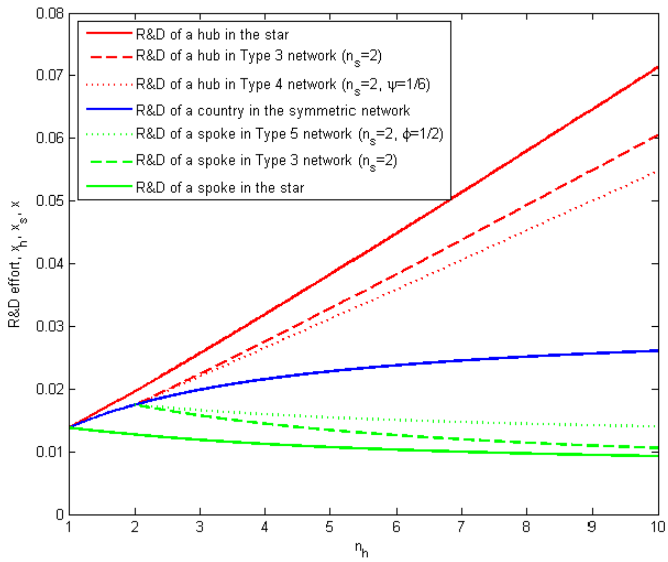


Figure 3: Equilibrium R&D in a symmetric and hub-and-spoke trade networks as a function of n_h.

We also compare aggregate R&D of the same total number of countries in the complete trade network and in the simple star. We find that even though R&D of the hub in a star is higher than R&D of a single country in the symmetric network, aggregate R&D is lower in the star (see Figure 8).

5. Welfare analysis

To complement the analysis of the effects of trade network asymmetry on R&D, in this section we compare the *welfare* implications of trade within a symmetric network and within a star, the simplest type of the hub-and-spoke structure. A higher degree of asymmetry in the star is associated with a larger number of spokes (hub's direct trade partners). We consider four different measures of welfare in a country: consumer surplus, domestic firm's profit, total surplus and production cost.[41] Firm's profit, π_i, and production cost, c_i, were defined in section 3.2, while consumer surplus, CS_i, is given by $CS_i = \frac{1}{2b}(a - p_i)^2$ due to linearity of the demand function, and total surplus is $W_i = \pi_i + CS_i$.

[40] Figure 7 in the Appendix demonstrates this sequence as a function of n_s.

[41] In Supplementary Appendix we show how the results of this analysis change with the introduction of positive import tariffs between the linked countries.

5.1. Effects of new trade links and asymmetry

Starting from the case of an asymmetric, star network, we find that as the number of hub's direct trade partners, n_h, increases, the profit, total surplus and production costs rise in a hub but decline in a spoke. Consumer surplus increases in both types of countries but it increases at a higher rate in a hub.[42] Thus, according to all measures of welfare, a higher degree of asymmetry in the star network widens the gap between the hub and the spokes. And even though the *aggregate* welfare in the star is shown to increase, the benefits of larger asymmetry (and star size) are mostly reaped by the hub.

Proposition 5 (welfare in a star). *In any star network where the number of hub's direct trade partners is $n_h \geq 2$, as n_h increases, firm's profit, production cost and total surplus increase in a hub but decline in a spoke, whereas consumer surplus increases in both types of countries. The aggregate profit, production cost, consumer surplus and total surplus in the star all increase in n_h.*[43]

For the hub an access to a new spoke market leads to a large expansion in its overall production, not only at the extensive margin but also due to larger market shares it gains in *all* countries as a result of higher R&D/competitiveness. Then even though hub's marginal cost declines, its total production cost increases. Also, hub's profit grows despite the mounting production costs and lower market prices. Moreover, a lower price in the hub benefits the consumers. As a result, the total surplus of the hub improves due to an increase in both, firm's profit and consumer surplus. By contrast, in a spoke economy only consumer surplus is increasing in n_h as a result of stronger competition with the hub. The overall market size of a spoke shrinks, leading to lower firm's profit, total surplus and production cost, where the latter declines even with the marginal cost rising (because of R&D cuts).

In a symmetric trade network, the welfare changes associated with a larger number of direct trade partners n are similar to those at the hub in a star. However, trade with a new partner in a symmetric trade network leads to a much smaller expansion of a firm's aggregate demand compared to that of a hub. These still ensure that the total production cost, consumer surplus and total surplus in each country increase in n.[44] But firm's profit declines as larger aggregate demand does not make up for the increase in total production cost and lower prices. Thus, differently from the hub, where both consumer surplus and hub's profit contribute to the increase in total surplus, in a symmetric network, the total surplus improves due to an increase in consumer surplus only.

Proposition 6 (welfare in a symmetric network). *In any symmetric network of degree $n \geq 0$, as n increases, firm's production cost, consumer surplus and total surplus increase in each country, whereas firm's profit decreases. The aggregate production cost, consumer surplus and total surplus in the symmetric network increase in n. The aggregate profit decreases in n if the number of countries is fixed, but in the complete network of degree $n \geq 1$, as n increases, the aggregate profit increases.*[45]

We now present the comparison of welfare levels in a hub, spoke and a country in a symmetric network,

[42] The latter is implied by Proposition 7.
[43] Results for the production cost require that R&D cost parameter, δ, is higher than required by Assumption 2.
[44] As in the hub, the production cost increases despite the improvement in the marginal cost.
[45] Results for the production cost and aggregate profit in the complete network require that R&D cost parameter, δ, is higher than required by Assumption 2.

where the number of direct trade partners of a hub and a country in the symmetric network is the same. The next proposition and Figure 4 assert that the highest firm's profit and total surplus are achieved in the hub, while the highest consumer surplus is attained in a country of the symmetric network. A spoke exhibits the lowest levels of consumer surplus and total surplus and either the lowest or intermediate profit. In what follows we use subscripts h and s for the welfare measures in a hub and in a spoke, respectively, and no subscript for a country in the symmetric network.

Proposition 7 (comparison of symmetric and star networks). *Consider a symmetric network of degree n and a star with n spokes. For any $n \geq 2$, the firm's profit, consumer surplus and total surplus in a hub, spoke and a country in the symmetric network can be ranked as follows:*

$$\pi_h(n) > \pi(n) > \pi_s(n) \quad \forall 2 \leq n \leq 3 \quad \text{and} \quad \pi_h(n) > \pi_s(n) > \pi(n) \quad \forall n \geq 4,$$

$$CS(n) > CS_h(n) > CS_s(n),$$

$$W_h(n) > W(n) > W_s(n).$$

Moreover, as n increases, the differences in profit, consumer surplus and total surplus described by these inequalities become larger (in case of the difference between π_s and π this holds at $n \geq 4$).

In a hub, the highest level of the total surplus, $W_h(n)$, results from the highest profit as the level of the consumer surplus is actually higher in the symmetric network.[46] In a spoke, the profit is second highest at any $n \geq 4$, and the lowest total surplus is a result of the lowest consumer surplus.[47] Furthermore, as all welfare differences between countries increase in n, a larger degree of asymmetry in a star network leads to a larger divergence in profits, consumer surplus and total surplus not only between a hub and a spoke but also between a country in the star (hub or spoke) and a country in the symmetric network.

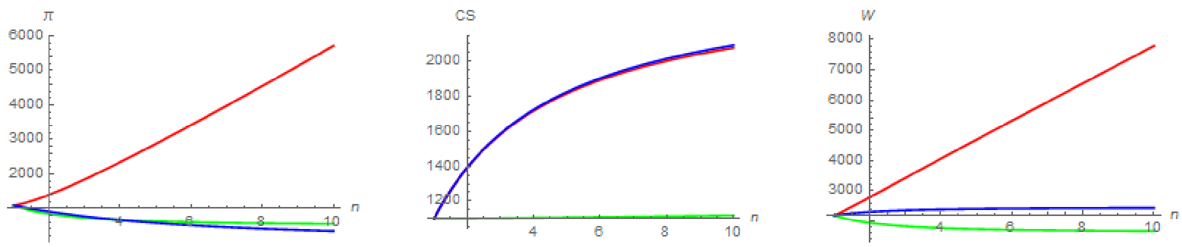


Figure 4: Firm's profit, consumer surplus and total surplus in a symmetric network (blue) and star network (red in a hub, green in a spoke).

5.2. Efficiency in the class of symmetric and star networks

Let us now consider the implications of the welfare analysis at the aggregate level to study the efficiency of trade networks within the class of symmetric networks and stars. The result on aggregate welfare in Proposition 5 implies that the larger the star network, the more efficient it is according to all measures of welfare apart from the total production cost, which is smallest when $n_h = 2$. For the class of symmetric

[46] As Figure 4 shows, the profit of the hub is much larger than the profit of a firm in the symmetric network for any $n \geq 2$.

[47] These results find support in earlier studies. For example, Baldwin (2004), Kowalczyk and Wonnacott (1992), Deltas et al. (2006), Lloyd and Maclaren (2004), and De Benedictis et al. (2005) find that the total surplus and income levels of spokes are lower than those of hubs and of countries in the complete network.

networks Proposition 6 implies that for a given, fixed number of countries N, the unique efficient network is complete ($n = N - 1$) when welfare is measured in terms of consumer surplus or total surplus, and it is empty ($n = 0$) when welfare is measured by firms' profits or production costs. Also, the larger the number of countries in the efficient (complete or empty) network, the higher the aggregate consumer surplus, total surplus and profit.

Now, comparing the efficiency of symmetric networks and stars, we find that for the same total number of countries, the benefits of trade are highest in a symmetric network. Namely, if welfare is measured by consumer surplus or total surplus, it is the symmetric, complete network that delivers the best outcome to the set of N countries, while if welfare is measured by profits, the empty network is the best.[48] Thus, the network that is efficient in the class of symmetric networks is also efficient in the class of symmetric networks and stars.

Proposition 8 (efficiency). *Consider a class of symmetric networks and stars. If welfare is measured in terms of consumer surplus or total surplus, then for any fixed number of countries $N \geq 3$, the unique efficient network is complete, while in terms of profits the unique efficient network is empty.*[49]

In the proof we show that for the same total number of countries, $W_{star} < W_{complete}$ and $\pi_{star} < \pi_{empty}$. The inequality for consumer surplus, $CS_{star} < CS_{complete}$, follows immediately from Proposition 7.[50] We note that in view of our findings in section 6, the efficient networks, – complete and empty, – turn out to be pairwise stable. But there exist other pairwise stable networks that are not efficient, revealing the common discrepancy between stability and efficiency in network formation games.

In section A-3 of the Supplementary Appendix we also address the question of a *socially optimal* level of R&D expenditures and *first-best* R&D. The former refers to R&D that maximizes each country's consumer surplus or total surplus, instead of firm's profit. We show that in either case, the socially optimal R&D is higher than the profit maximizing one. The latter refers to the level of R&D that maximizes the *joint* profit of all firms or *joint* consumer surplus or total surplus of all countries. We find that for any country i, R&D of its direct and two-links-away trade partners imposes negative externalities on i's profit and total surplus but positive externalities on i's consumer surplus.[51] In case of profits and total surplus optimization, internalizing the negative externalities leads to lower R&D of all firms and strictly improves the profits and total surplus of all countries. In case of consumer surplus optimization, R&D of each firm is maximal, i.e., $x_i = \gamma$, under both decentralized and centrally made decisions, so that there is no efficiency loss due to decentralization.

6. Trade network stability

So far we have taken a trade network as exogenous. Suppose now that prior to market interactions between firms in our baseline model, a government in each country has an opportunity to form *pairwise* trade links

[48] The highest total profit in the empty network is achieved due to aggregation of profits of N countries: a single-country profit in the empty network is lower than in a hub but higher than in a spoke.

[49] In the proof, the inequality for total surplus, $W_{star} < W_{complete}$, with $N = 3$ and $N = 4$ requires a slightly stronger condition on δ than in Assumption 2: $\delta \geq \frac{1}{b} \cdot 5$.

[50] In addition, one can show that $\pi_{complete} < \pi_{star}$ for any $N \geq 3$ (for $N \geq 5$ this follows from Proposition 7).

[51] It is easy to show that CS_i is increasing in R&D of i's direct trade partners, while both π_i and W_i are decreasing in R&D of its direct and two-links-away trade partners (for W_i this holds at least in case of symmetric and star networks).

with other countries. The question is which network structures will be stable and how it depends on the objective that is pursued at the network formation stage. We assume that each government seeks to maximize its country's welfare, where three main definitions of welfare are used: the domestic firm's profit, π_i, consumer surplus, CS_i, and total surplus, W_i.

We employ a relatively weak notion of network stability borrowed from Jackson and Wolinsky (1996). It is based on the idea that any trade link is formed bilaterally, upon consent of both involved countries, but can be severed unilaterally. To define it formally, let us say that if countries i and j are connected by a link in the trade network g, then $ij \in g$, and if i and j are not linked, then $ij \notin g$. Networks obtained by adding or deleting a link ij to/from network g are denoted by $g + ij$ and $g - ij$, respectively. Given this notation and given the welfare function $S_i \in \{\pi_i, CS_i, W_i\}$ of each country i, the network g is called *pairwise stable* if (i) for all $ij \in g$, $S_i(g) \geq S_i(g - ij)$ and $S_j(g) \geq S_j(g - ij)$, and (ii) for all $ij \notin g$, if $S_i(g) < S_i(g + ij)$, then $S_j(g) > S_j(g + ij)$. That is, in a stable network, no country can benefit from deleting one of its trade links, and no pair of countries can benefit from forming a link.

Below we present some general findings on network stability. Essentially, we show that depending on the definition of welfare, stable networks tend to be complete, empty or consist of a set of one or more isolated countries and a complete component. Similar findings are reported in the trade network formation model of Goyal and Joshi (2006), although the absence of R&D decisions in that model allows for a more complete characterization of stable outcomes. An asymmetric network, such as star, is not stable for any measure of welfare as any two spokes have an incentive to form a link. This is the reason why in the baseline model of this paper, focusing on the effects of trade network asymmetry, the network structure is taken as exogenous.

First, we state a "positive" result, asserting the stability of certain networks.

Proposition 9 (stable networks). *The following statements hold:*

1. *For any welfare definition, – in terms of domestic firm's profit, consumer surplus or total surplus, – and for any number of countries $N \geq 3$, the complete network is stable.*[52]

2. *If welfare in each country is equal to the domestic firm's profit or total surplus, and $N \geq 4$, then the network that consists of two components, – one with $N - 1$ countries and complete, and the other with a single country, – is stable. It is not stable if welfare is equal to the consumer surplus.*

3. *If welfare in each country is equal to the domestic firm's profit, then the empty network and the network that consists of $k > 1$ singleton components and one complete component with $N - k \geq 3$ countries, are stable. These networks and other networks with more than one singleton component are not stable if welfare is equal to the consumer surplus or total surplus.*

The proof that the complete network is stable relies on the observation that with any welfare definition no country can gain by deleting a trade link. When welfare is measured by the domestic firm's profit or total surplus, the network with one singleton component and one complete component of size $N - 1 \geq 3$

[52]In fact, if welfare is equal to consumer surplus or total surplus, this also holds at $N = 2$. With profits, a network with two linked countries is not stable, as each firm benefits from deleting a link.

is stable because the isolated country is better off in autarky. Indeed, when an isolated country forms a trade link with a country in the complete component, the overall profit of its erstwhile monopoly firm declines due to increased domestic competition and only a small profit gain in a competitive foreign market. Therefore, even though the increased domestic competition also raises consumer surplus, the total surplus drops below the autarky level. Moreover, if social welfare in each country is given by profits, the number of singleton components in a stable network can be larger than one because profits of each autarkic firm decline not only from forming a link with a country in the complete component but also from forming a link with another isolated country. For the same reason the empty network is also stable when link formation is guided by the domestic firm's profit considerations. If, instead, the government cares about consumer surplus or total surplus, then the empty network and, more generally, any network with more than one singleton component is not stable, because forming a trade link between two autarkic countries increases both countries' welfare.

The results of Proposition 9 are analogous to those in Goyal and Joshi (2006). However, owing to a simpler formulation of the welfare function in their setting, which only depends on the number of country's direct and two-links-away trade partners but not on their R&D, Goyal and Joshi (2006) can also prove that the other networks are not stable. In our model, other stable networks may exist, but what we can show is that the networks described in Proposition 9 are the only networks that are stable for *all* $N \geq 3$. This follows from observing that in case of three or four countries, no other stable networks exist: when $N = 3$, the complete and empty networks are the only networks that are stable under different measures of welfare, and when $N = 4$, these are the complete, empty and the network that consists of two components – a singleton and the complete component with three countries.[53]

Finally, an important "negative" result is that with any measure of welfare, an asymmetric, star network is not stable. Intuitively and in line with the previous network formation literature, in a setting with identical countries, asymmetries in countries' trade relations are unlikely to emerge.

Proposition 10. *For any welfare definition, – in terms of domestic firm's profit, consumer surplus or total surplus, – and for any number of countries $N \geq 3$, the star network is not stable.*

In the proof we show that this has to do with the fact that any pair of spokes in the star have an incentive to form a link.

7. Extensions

In this section, we report the results of a number of extensions of our baseline model. First, we allow for a more general, non-linear market demand function. Second, we extend our model to cross-country differences in market size and marginal costs. Third, we explicitly account for the possibility of R&D spillovers between firms. Finally, we present a different way of modelling asymmetric trade networks by nested split graphs.[54] We show that for a moderate extent of these modifications, the basic conclusions of our baseline model remain the same. The detailed derivations and proofs can be found in the Supplementary Appendix.

[53] The case of $N = 3$ is straightforward in view of the results presented here, while the proof for $N = 4$, together with the illustration of relevant network structures, is provided in the Supplementary Appendix.

[54] In Supplementary Appendix we also consider the model with positive trade costs between the linked countries.

7.1. Non-linear demand

One important concern is that our main results, regarding the effects of trade links and network asymmetry, depend critically on linearity of the market demand function. In this section we relax the linearity assumption and consider the inverse market demand given by $p(Q_i) = a - Q_i^\beta$ for $\beta \geq 1$, where $Q_i = \sum_{j \in N_i \cup \{i\}} y_{ji}$ is the total quantity sold in market i. $\beta \geq 1$ guarantees that the inverse demand is downward-sloping and concave in each country. The linear model obtains as a special case when $\beta = 1$.

In this more general setting we find that though the equilibrium at the R&D-choice stage might not be unique, the *symmetric* equilibrium, where R&D of all firms in identical network positions are the same, has the same properties as in our baseline model. Namely, R&D of a firm in a symmetric network of degree n is increasing in n, while R&D in a star with n_h spokes is increasing in n_h for the hub and decreasing in n_h for a spoke. Thus, our basic finding, that a larger asymmetry in the star increases the gap between R&D investments of a hub and a spoke, continues to hold with concave demand functions.[55]

Proposition 11 (effects of n and n_h). *Consider a symmetric network of degree n and a star with n_h spokes. Suppose inverse demands are downward-sloping and concave in each country, given by $p(Q_i) = a - Q_i^\beta$ with $\beta \geq 1$. Then in a symmetric network, firm's equilibrium R&D, x^*, is increasing in n. Also, in a star, there exists $\Delta > 0$ such that for any $\delta \geq \Delta$, the equilibrium R&D of the hub, x_h^*, is increasing in n_h, while the equilibrium R&D of a spoke, x_s^*, is decreasing in n_h.*

7.2. Differences in market size and cost structure

In the baseline model we assumed that all countries were identical in all but their position in the network. In particular, the size of each country's market and the cost structure of each firm are the same across countries. In this section we examine the role of this symmetry assumption.

We parametrize differences in market size of the countries in terms of different values of the demand parameter a, and we capture differences in firms' costs by considering different values of the marginal cost γ. To keep the analysis tractable, we will suppose that in asymmetric, hub-and-spoke networks, differences in market size and domestic firm's cost exist only between a hub and a spoke country, but these differences can, in general, be of any sign and value. Let a_h, γ_h denote the market size and firm's marginal cost of any hub, and a_s, γ_s denote the market size and marginal cost of any spoke. We start the analysis by solving our model once again for firms' equilibrium output levels and R&D. We then focus on comparative statics. As before, our main concern is the effects of new trade links and network asymmetry on R&D of hubs and spokes and how those compare with R&D in symmetric networks.

7.2.1 Effects of direct and two-links-away trade partners

Note that with asymmetric market sizes and costs, the fact that $n_h > n_s$, does not, in general, guarantee that a hub has a larger overall market or, when it does, that it benefits from it since hubs can be much less efficient than spokes, i.e., $\gamma_h > \gamma_s$. Indeed, we find that the effect of direct trade links on R&D of any firm (hub or spoke) is now certain to be positive only when the firm's marginal cost is not higher (or not much

[55] Given the complexity of the involved expressions, the result for the star is derived numerically for a broad range of parameters consistent with Assumptions 1 and 2 and any $0 \leq x_h, x_s \leq \gamma$.

higher) than the marginal cost of its trade partners and when the size of a new foreign market relative to its number of competitors, is sufficiently large. For example, for a hub, R&D is increasing in the number of its direct trade partners, n_h, as long as γ_h is lower (or not much higher) than γ_s, and also, – in case when the share of spokes among hub's direct trade partners is high (ψ is low), – as long as the market size of a spoke, a_s, is large enough relative to a_h, and/or the number of competitors in a spoke's market, n_s, is small enough relative to that in a hub, n_h. The latter ensures that an increase in hub's aggregate demand due to a new foreign market is sufficiently large relative to a loss in its domestic market share due to the increased competition. On the other hand, the effect of two-links-away trade partners on R&D of either a hub or a spoke is always negative irrespective of the market sizes and costs. This suggests, as before, that competition tends to hinder firm's innovation. The (lengthy) formal statement of these comparative statics effects is relegated to the Supplementary Appendix. Proposition 1 obtains as its special case.

The described findings imply that in any hub-and-spoke network, a larger degree of asymmetry associated with an increase in n_h leads to a lower R&D of a spoke and higher R&D of a hub, where the latter holds at least under the mentioned conditions. Similarly, a larger degree of asymmetry associated with a decrease in n_s leads to a higher R&D of a hub and lower R&D of a spoke, where the latter is ensured by another set of conditions, symmetric to those that we described for the hub. Now, the difference in the sufficient conditions means that if in a given hub-and-spoke network, asymmetry increases due to both changes – an increase in n_h and decrease in n_s, – the effects on R&D of both a hub and a spoke are *a priori* not clear as it may happen that only one of the two sets of conditions is satisfied. What is evident, however, is that for a small enough difference in γ_h and γ_s, both sets of conditions are likely to hold.

7.2.2 Comparison with symmetric networks

We now turn to the central comparison in this paper – between symmetric and asymmetric networks and between hubs and spokes in a given asymmetric network. Remarkably, the former holds just as in the baseline model: in any hub-and-spoke network, R&D of a hub is larger and R&D of a spoke is lower than in a symmetric network, keeping the market size, cost efficiency and the number of direct trade partners of a hub (resp., spoke) the same as in the symmetric network. Furthermore, whenever $a_h - \gamma_h$ is large enough relative to $a_s - \gamma_s$, – for which it is sufficient, for example, that $a_h \geq a_s$ and $\gamma_h \leq \gamma_s$, – R&D of a hub is guaranteed to be larger than R&D of a spoke (and R&D in symmetric networks is in-between the two). In what follows, we will denote by $x^*(n, a, \gamma)$ the equilibrium R&D of a firm in a symmetric network of degree n, where each country's market size is a and firm's marginal cost is γ.

Proposition 12 (comparison of hub-and-spoke and symmetric networks). *Consider a hub-and-spoke network defined by parameters $0 \leq \psi, \varphi < 1$ and $1 \leq n_s < n_h$, with market size and firm's marginal cost equal to a_h, γ_h in a hub and a_s, γ_s in a spoke. Also, consider two symmetric trade networks with network degree, market size and firm's marginal cost equal to n_s, a_s, γ_s in the first and n_h, a_h, γ_h in the second. Then there exists $\Delta > 0$ such that for any $\delta \geq \Delta$, the following relation between R&D of a firm in a hub (spoke) and a firm in a symmetric network of the same degree, market size and marginal cost holds:*

$$x_h^* > x^*(n_h, a_h, \gamma_h) \quad \text{and} \quad x^*(n_s, a_s, \gamma_s) > x_s^*.$$

Moreover, if $(a_h - \gamma_h)/(a_s - \gamma_s) > \upsilon(n_h, n_s)$*, where* $\upsilon(n_h, n_s) = \frac{(1+n_s)^2(-(1+n_h)^2+b\delta(2+n_h)^2)}{(1+n_h)^2(-(1+n_s)^2+b\delta(2+n_s)^2)} < 1$*, then it holds that*

$$x_h^* > x^*(n_h, a_h, \gamma_h) > x^*(n_s, a_s, \gamma_s) > x_s^*.$$

Alternatively, R&D of a hub is larger than R&D of a spoke, $x_h^* > x_s^*$*, under a combination of two other sufficient conditions:*

1. *either (i)* $a_h = a_s$ *or (ii)* $\psi + \varphi < 1 - \frac{1}{n_h}$ *and* $a_h/a_s \leq \frac{(n_h+2)^2(n_s+1)}{(n_s+2)^2(n_h+1)}$ *or (iii)* $\psi + \varphi > 1 - \frac{1}{n_h}$ *and* $a_h/a_s \geq \frac{(n_h+2)^2(n_s+1)}{(n_s+2)^2(n_h+1)}$ *; and*

2. $\gamma_h/\gamma_s < \omega(n_h, n_s, \varphi, \psi)$*, where* $\omega(n_h, n_s, \varphi, \psi) < 1$*.*

The main part of the proof employs the same argument as in Proposition 3. A symmetric network of degree n_h can be regarded as a hub-and-spoke network in which n_s has increased to become equal to n_h, and similarly, a symmetric network of degree n_s can be regarded as a hub-and-spoke network in which n_h has decreased to become equal to n_s. Then inequalities $x_h^* > x^*(n_h, a_h, \gamma_h)$ and $x^*(n_s, a_s, \gamma_s) > x_s^*$ follow immediately from our finding that R&D of a hub is decreasing in n_s and R&D of a spoke is decreasing in n_h. Next, we observe that in a symmetric network, both a larger degree and larger value of $a - \gamma$ lead to higher R&D of a firm (see eq. (5)). Then as long as $a_h - \gamma_h \geq a_s - \gamma_s$, the "connecting" inequality in Proposition 12, between R&D in two symmetric networks of degree n_h and n_s, also holds. More generally, given (5), it holds when $(a_h - \gamma_h)/(-1 + \delta b(1 + \frac{1}{n_h+1})^2) > (a_s - \gamma_s)/(-1 + \delta b(1 + \frac{1}{n_s+1})^2)$, which leads to the exact condition on $(a_h - \gamma_h)/(a_s - \gamma_s)$. Under this condition we obtain the ranking of R&D in hub-and-spoke and symmetric networks analogous to the one in Proposition 3.[56]

Finally, the two alternative sufficient conditions for R&D of a hub to be larger than R&D of a spoke obtain from a direct evaluation of $x_h^* - x_s^*$. Note that these conditions allow for $a_h < a_s$. The intuition is as follows. When $\psi + \varphi$ is sufficiently close to one, each hub has a large share of other hubs among its direct trade partners and/or each spoke is linked mostly to spokes. Then R&D of a hub is larger than R&D of a spoke as soon as the market size of a hub, a_h, is large enough relative to that of a spoke, a_s, and/or the number of competitors in a hub, n_h, is not too large relative to that in a spoke, n_s.[57] Instead, when $\psi + \varphi$ is not so large, a substantial share of hub's trade partners are spokes and vice versa, and then the market of a spoke should be relatively large and/or sufficiently less competitive than the market of a hub. This indicates, as before, that a larger market has positive and stronger competition negative effect on R&D of a firm. Moreover, in both cases hubs should be more efficient than spokes.

7.3. R&D spillovers

As another extension of our model, we consider a possibility of R&D spillovers between directly linked countries. Indeed, such a possibility is supported by some empirical research which finds that international trade is an important conduit for technology transfers (Acharya and Keller, 2009). We model R&D

[56] The intuition is again suggested by the negative competition effect on R&D of firm's two-links-away trade partners in a hub-and-spoke network: for the same number of direct trade partners (as well as market size and marginal cost), a hub is exposed to lower and spoke to higher competition than a firm in the symmetric network.

[57] Note that $\frac{(n_h+2)^2(n_s+1)}{(n_s+2)^2(n_h+1)}$ is increasing in n_h and decreasing in n_s.

spillovers by assuming that the total cost reduction for each firm stems not only from its own R&D effort but also from the research knowledge of its direct trade partners, which is either fully or partially absorbed. This means that the cost of producing the amount y_i by firm i is now given by

$$c(y_i, x_i, \{x_j\}_{j \in N_i}) = (\gamma - x_i - \rho \sum_{j \in N_i} x_j) y_i, \tag{6}$$

where $\rho \in (0, 1]$ reflects the level of spillovers, or the marginal cost reduction due to trade partner's effort.[58]

In this setting, where individual R&D has positive spillovers on the costs of rivals, it is natural to expect that incentives to innovate will be lower. Indeed, each firm's R&D now helps its direct trade partners gain larger market shares, while its own market share is increased by a lesser extent. This reduces the marginal returns to investing in R&D at any given number of direct trade links, and may also lower or even reverse a positive impact on R&D of adding new links. On the other hand, just as own R&D of firm i lowers marginal costs of its direct trade partners, their R&D lowers the marginal cost of i. This makes i relatively more competitive and helps to expand its market, which fosters innovation. Therefore, direct trade partners (or adding a new direct trade partner) may, in fact, give an extra boost to firm's incentives for R&D. Moreover, the higher the level of spillovers ρ is, the stronger the described effects should be.

Our findings appear to be consistent with the negative effect of spillovers on R&D, or more precisely, we find that the negative component of the spillovers effect prevails. First, in all considered types of networks R&D of each firm is reduced compared to the case without spillovers and this reduction is larger at higher ρ. Second, the effects of new direct trade links tend to be positive either at any level of spillovers – in case of a hub, – or at low and medium spillovers, – in case of a spoke and a firm in a symmetric network. At last, in the class of considered networks and when ρ is not too high, R&D of all firms can be ranked as before, with hub's R&D being higher and spoke's – lower than in a symmetric network.

We start the analysis by solving the model with the new cost functions. As in the baseline model, both stages of the game result in linear first-order conditions that produce the unique, interior solution as long as a and δ are sufficiently large (Assumptions 1 and 2). At the second, output-choice stage, the production quantities of firm i are given by:

$$y_{ii} = \frac{1}{b(n_i+2)} \left(a - \gamma + (n_i+1)(x_i + \rho \sum_{j \in N_i} x_j) - \sum_{j \in N_i} (x_j + \rho \sum_{k \in N_j} x_k) \right), \tag{7}$$

$$y_{ij} = \frac{1}{b(n_j+2)} \left(a - \gamma + (n_j+1)(x_i + \rho \sum_{j' \in N_i} x_{j'}) - \sum_{k \in N_j \cup \{j\}, k \neq i} (x_k + \rho \sum_{k' \in N_k} x_{k'}) \right), \ \forall j \in N_i. \tag{8}$$

Observe that, as before, x_i has a positive effect on i's market shares in the domestic and foreign markets, though this effect is now weaker due to x_i's simultaneous positive impact on market shares of its rivals: these are all other firms trading in market i and those of the firms trading in market $j \in N_i$ that are the direct trade partners of i (for example, firm j itself).[59] This weaker effect of x_i on i's production quantities reveals the first, negative effect of spillovers on i's incentives to innovate. On the other hand, R&D of

[58] This way of modelling R&D spillovers is common in the literature on R&D collaboration (D'Aspremont and Jacquemin, 1988; Goyal and Moraga-González, 2001; König et al., 2014a).

[59] Indeed, the effect of x_i on y_{ii} is positive because $n_i + 1 > \rho n_i$ for any $\rho \in (0, 1]$; similarly, the effect of x_i on y_{ij} is *guaranteed* to be positive whenever $n_j + 1 > \rho n_j$, which is also true for any ρ.

i's direct trade partners, $\sum_{j\in N_i} x_j$, now tends to have a positive effect on i's domestic and also foreign market shares: the effect on y_{ii} is only certain to be negative when spillovers are low ($\rho(n_i+1) < 1$), while the effect on y_{ij} is always positive unless these direct trade partners are also two- and three-links-away trade partners of i. This positive effect of R&D of direct trade partners of i on its market shares when ρ is sufficiently high reveals the second, positive effect of spillovers on i's incentives to innovate.

In addition, the production quantities of firm i for each market are now also affected by R&D of the firms that do not themselves trade in these markets but that affect the competitiveness of those firms that do. Namely, y_{ii} is affected by R&D of i's two-links-away trade partners and y_{ij} is influenced by R&D of its direct and three-links-away trade partners. This influence of three-links-away trade partners on i's market shares and profits introduces a new difficulty into our analysis. Recall that in the baseline model, the profit of each firm at the first, R&D stage is fully determined by R&D of i and its direct and two-links-away trade partners. Then *irrespective of the network structure* it is certain that firm i is *never* at a distance of one link from itself ($i \notin N_i$) and *always* at a distance of two links from itself ($i \in N_j$ for any $j \in N_i$). It is, therefore, easy to keep track of the "locations" of x_i in the profit function, which is important for deriving the optimality conditions. With R&D of three-links-away trade partners in the profit function, it is *generally* impossible to say whether i is at a distance of three links from itself or not: it depends on the network structure. For this reason, in the rest of this section we restrict our attention to the complete network as a representative of symmetric structures and Type 3 hub-and-spoke network (with $n_h > n_s \geq 1$ and $\varphi = \psi = 0$), one example of which was presented in Table 1, as a representative of asymmetric structures. The class of Type 3 networks includes a star as a special case when $n_s = 1$.

7.3.1 Effects of ρ and trade links

As before, we study the dependence of each firm's equilibrium R&D on the number of trade links and network asymmetry. We start, however, by observing that for any given number of trade links and network asymmetry, the overall effect of spillovers on R&D is negative. In line with the intuition that spillovers reduce the marginal returns to investing in R&D, all firms in the complete and Type 3 hub-and-spoke networks exert lower R&D efforts in the presence of spillovers. Moreover, the stronger the spillovers, the lower the R&D.

Proposition 13 **(effects of ρ).** *Consider a symmetric, complete network of degree n and Type 3 hub-and-spoke network with $n_h > n_s \geq 1$ and $\varphi = \psi = 0$. The equilibrium R&D of a firm in the complete network is decreasing in the level of spillovers ρ for any $\rho \in (0, 1]$. Also, in Type 3 hub-and-spoke network, there exists $\Delta > 0$ such that for any $\delta \geq \Delta$, R&D of both a hub and a spoke is decreasing in ρ for any $\rho \in (0, 1]$.*

We further find that an increase in the number of direct trade partners still has a positive effect on R&D of each firm, though in case of a firm in the complete network and in case of a spoke, this is certain to hold only when spillovers are medium and low. Also, in a spoke, another sufficient condition (similar to the one in the baseline model) is in place: the number of competitors in a hub's market, n_h, should be not very high compared to the number of competitors in a spoke's own market, n_s, to make sure that spoke's overall demand increases rather than decreases when a new link is formed. Furthermore, competition from two-links-away trade partners lowers R&D of either a hub or a spoke irrespective of the level of spillovers. Thus, in line with our earlier findings, for a broad range of spillover levels, a larger degree of asymmetry in the hub-and-spoke network leads to a larger difference in R&D of hubs and spokes.

Proposition 14 (effects of n, n_h and n_s). *Consider a symmetric, complete network of degree n and Type 3 hub-and-spoke network with $n_h > n_s \geq 1$ and $\varphi = \psi = 0$. In the complete network, the equilibrium R&D of a firm, x^*, is increasing in n as long as $\rho \leq 2/3$. Also, in Type 3 hub-and-spoke network, there exists $\Delta > 0$ such that for any $\delta \geq \Delta$ and for any $n_h > n_s \geq 1$, the following statements are fulfilled:*

1. *the equilibrium R&D effort x_h^* of a hub is increasing in the number of hub's direct trade partners, n_h, and decreasing in the number of spoke's direct trade partners, n_s, for any $\rho \in (0, 1]$;*

2. *the equilibrium R&D effort x_s^* of a spoke is decreasing in the number of hub's direct trade partners, n_h, for any $\rho \in (0, 1]$;*

3. *the equilibrium R&D effort x_s^* of a spoke is increasing in the number of spoke's direct trade partners, n_s, if at least one of the conditions holds:*[60]

   (a) $n_s = 1$ and either $n_h \leq 9$ or both $9 < n_h \leq 23$ and $\rho < \frac{23+23n_h-n_h^2}{31+4n_h+n_h^2}$ are true,

   (b) $n_s = 2$ and either $n_h \leq 27$ or both $n_h = 28$ and $\rho < 7/8$ are true,

   (c) $n_s \geq 3$ and $n_h \leq 6n_s + n_s^2 + 8$.

The intuition for these results is similar to the one for Proposition 1, but due to the adverse effects of spillovers on R&D, it does not hold when ρ is high. For example, it is easy to show that in the complete network, the effect of new trade links on R&D becomes negative when ρ is close to one. Essentially, when spillovers are strong, their deterring influence on firm's incentives to innovate associated with a new trade partner prevails over the positive effects due to the market expansion. Similarly, in a spoke, as a new link is added, R&D is only guaranteed to increase when spillovers are not too high (and n_h is not much larger than n_s). This is, however, not the case in a hub, where the positive effect of market expansion is strong enough to outweigh the negative influence of spillovers even when they are high.

7.3.2 Comparison of hub-and-spoke and symmetric networks

Finally, since all the comparative statics above holds as before at low and medium ρ, the key ranking of R&D in the complete and Type 3 hub-and-spoke networks remains the same, at least in a lower range of spillovers. Proposition 15 establishes this result.

Proposition 15 (comparison of hub-and-spoke and symmetric networks). *Consider a symmetric, complete network of degree n and Type 3 hub-and-spoke network with $n_h > n_s \geq 1$ and $\varphi = \psi = 0$. There exists $\Delta > 0$ such that for any $\delta \geq \Delta$, the following relation between R&D of a firm in a hub (spoke) and a firm in the complete network of the same degree holds:*

$$x_h^* > x^*(n_h) \quad \text{and} \quad x^*(n_s) > x_s^*,$$

[60]The sufficient condition for all restrictions on n_h is that $n_h \leq n_s^2$, as in Proposition 1.

where the latter is true at least as long as $\rho < \frac{n_h^2 - n_s^2 + n_s n_h^2 - n_s^2 n_h}{4 n_s n_h + n_s n_h^2 - n_s^2 - 4}$.[61] *Moreover, if* $\rho < \min\left\{\frac{2}{3}, \frac{n_h^2 - n_s^2 + n_s n_h^2 - n_s^2 n_h}{4 n_s n_h + n_s n_h^2 - n_s^2 - 4}\right\}$, *then it holds that*

$$x_h^* > x^*(n_h) > x^*(n_s) > x_s^*.$$

Thus, at least at low and intermediate spillovers, R&D of a hub is larger than R&D of a spoke, while intermediate levels are exhibited by a firm in the complete network. Figure 5 demonstrates this result and also compares R&D with and without spillovers.

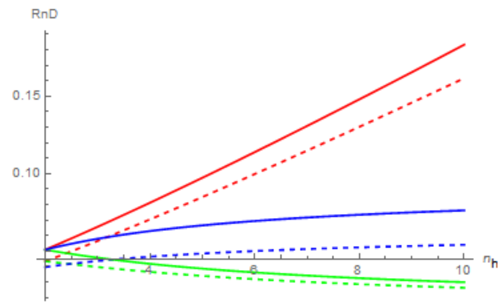


Figure 5: R&D as a function of n_h in a hub (red), spoke (green) and complete network (blue) at $\rho = 0$ (solid) and $\rho = 1/3$ (dashed).

7.4. Nested split graph representation of asymmetric trade networks

In the baseline model we approximated the core-periphery nature of the real-world trade networks by hub-and-spoke structures. In this section we extend our analysis to *nested split graphs*, which according to a recent study by König et al. (2014), capture the same core-periphery feature well. By definition (Mahadev and Peled, 1995), the nodes of a nested split graph can be partitioned into a set of nodes that are all connected among each other (dominating set) and sets of nodes that are disconnected among each other (independent sets). Moreover, the neighbourhoods of the nodes are nested. To keep the analysis tractable, in what follows we will focus on simple nested split graphs with just two independent sets S_1, S_2 and two partition subsets of the dominating set H_1, H_2. The degrees of nodes within each subset are the same but distinct across the subsets. In this case the formal definition imposes that the neighbourhoods $\mathcal{N}_i$ of nodes are nested in the following sense:

$$\begin{aligned}
\forall i \in S_1 \quad \mathcal{N}_i &= H_2, \\
\forall i \in S_2 \quad \mathcal{N}_i &= H_1 \cup H_2, \\
\forall i \in H_1 \quad \mathcal{N}_i &= S_2 \cup H_1 \cup H_2 \setminus \{i\}, \\
\forall i \in H_2 \quad \mathcal{N}_i &= S_1 \cup S_2 \cup H_1 \cup H_2 \setminus \{i\}.
\end{aligned}$$

Figure 6 illustrates this type of structure, where much of the notation is borrowed from König et al. (2014). The nodes in the dominating set (within the black frame) induce a complete network, while the nodes in the independent sets (within the gray frame) induce an empty network.

Let us denote by n_{s1}, n_{s2}, n_{h1} and n_{h2} the degrees of nodes within each of the sets S_1, S_2, H_1 and H_2, respectively. By definition, $n_{h2} > n_{h1} > n_{s2} > n_{s1}$. Thus, we obtain a trade network with countries

[61] For example, at $n_s = 2$ and $n_h = 6$, as on the picture in Table 1, this means $\rho < 5/7$.

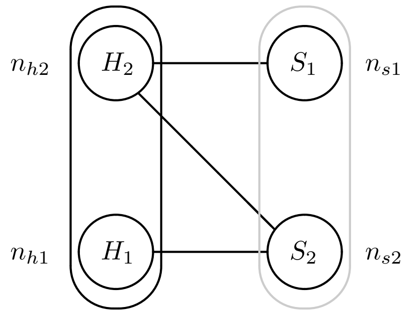


Figure 6: Representation of a nested split graph with four distinct positive degrees. A line between two sets indicates that every node in one set is linked to every node in the other. The black frame indicates the dominating set, and the nodes in the independent sets are included in the gray frame. Next to each set, the degree of the nodes in the set is indicated.

of four different degrees. Countries with the highest degrees, in sets H_2 and H_1, can be regarded as hubs of the trade network (or the core), while the other countries, in S_2 and S_1, are spokes.[62]

We solve our model for the case of such a nested split network and examine the dependence of R&D on firm's position in it. As before, the unique equilibrium is symmetric in the sense that firms' R&D are only distinct across the sets S_1, S_2, H_1 and H_2, but identical within each set. Those can be found from the system of four linear first-order conditions. Comparing these four distinct R&D levels, we obtain the results that are consistent with the insights for the hub-and-spoke networks. A larger exposure to trade by means of direct trade links translates into larger R&D expenditures as long as the market share gained in the foreign markets is not lower than the market share lost domestically due to the competition with the foreign firms. The latter appears to be a concern only when comparing R&D of firms in S_1 and S_2. While a firm in S_2 has access to a larger number of foreign markets (H_1 in addition to H_2), a competition in these markets is rather harsh (firms in H_1 compete with all other firms in H_1 and H_2). Thus, having access to these additional markets would only promote R&D of a firm in S_2 (beyond R&D in S_1) if the number of competitors in each of the H_1's markets, n_{h1}, is not much higher than the number of competitors in the domestic market, n_{s2}. Recall that a similar condition was also in place to guarantee that R&D of a spoke in a hub-and-spoke network increases in n_s (Proposition 1). The intuition for the other comparisons is straightforward: overall market access is higher and competition in the foreign markets is lower for firms in H_2 compared to H_1 and for firms in H_1 compared to S_2. This leads to $x^*_{h2} > x^*_{h1} > x^*_{s2} > x^*_{s1}$, where x^*_{s1}, x^*_{s2}, x^*_{h1} and x^*_{h2} denote the equilibrium R&D of firms from each of the four sets.

Proposition 16 (comparison of R&D in S_1, S_2, H_1 and H_2). *Consider an asymmetric trade network represented by a nested split graph with two independent sets of countries S_1, S_2 and two partition subsets of the dominating set H_1, H_2, where $n_{h2} > n_{h1} > n_{s2} > n_{s1}$. There exists $\Delta > 0$ such that for any $\delta \geq \Delta$, R&D of all firms can be ranked as follows:*

$$x^*_{h2} > x^*_{h1} > x^*_{s2} > x^*_{s1},$$

where the last inequality holds at least as long as $n_{h1} \leq \frac{9}{2} n_{s2} + 2$.

[62]Note that in a special case where sets S_1 and H_1 are empty this nested split graph becomes a special case of our hub-and-spoke network, such that spokes in S_2 are linked only with hubs ($\varphi = 0$, $n_s = |H_2|$) and hubs in H_2 are linked with spokes and among themselves ($\psi > 0$, $n_h = |H_2| + |S_2| - 1$).

Thus, the main insights of our analysis, – that the trade network asymmetry generates higher R&D at firms in more connected countries and that the larger the difference in countries' connectivities, the larger the difference in R&D, – remain valid if we model asymmetric trade networks by nested split graphs.

8. Conclusions, policy implications and discussion

This paper develops a model of intra-industry trade with firm-level productivity improvements via R&D. It focuses on the effects of trade network asymmetry on firms' innovation incentives and countries' welfare. Overall, the trade network asymmetry promotes R&D, productivity and welfare of a hub and hinders those of a spoke. First, we find that in any hub-and-spoke network R&D investment of a hub is larger than R&D of a spoke, while R&D of a firm in a symmetric network is in-between the two, even if the number of trade partners of a hub (resp., spoke) is the same as in the symmetric network. Second, the larger the degree of network asymmetry, the larger the difference between R&D spendings of a hub and a spoke. We show that the driving force behind these results is the difference in the aggregate demand and level of competition faced by firms in different countries, which in turn is generated by the differences in the interaction of the scale and competition effects of trade.

As for the welfare, we find that for the same number of direct trade partners of a hub in the star and a country in the symmetric network, firm's profit and total surplus are highest in the hub, while consumer surplus is highest in the symmetric network. A spoke exhibits the lowest levels of consumer surplus and total surplus and either the lowest or intermediate profit. Furthermore, an increase in the degree of asymmetry of the star network (due to an expansion in the number of hub's foreign markets) increases the welfare gaps between a hub and a spoke, while an expansion of the symmetric network improves each country's welfare, except profits.

In a number of extensions we verify that for a range of modifications, the main insights from our baseline model continue to hold in a setting with concave inverse demand functions, cross-country differences in market size and firms' marginal costs, R&D spillovers between directly linked countries and the nested split graph representation of the trade network asymmetry. For example, in all of these extensions, R&D of a firm tends to increase in the number of own trade links, at least as long as certain conditions on countries' relative market sizes and costs hold and as long as R&D spillovers are not too high. Also, with cross-country differences in market size and cost structure, we obtain that whenever $a_h - \gamma_h$ is large enough relative to $a_s - \gamma_s$, R&D of a hub is guaranteed to be larger than R&D of a spoke and R&D in symmetric networks is in-between the two. The same ranking of R&D in a hub, spoke and a symmetric network holds in a setting with R&D spillovers, provided that they are not too strong.

The findings of the paper suggest some policy implications. First, interpreting the hub-and-spoke network as a trade network that emerges in the process of regional/preferential trade liberalization, and the symmetric *complete* network as a result of multilateral trade liberalization, we conclude that R&D and welfare gains of regionalism versus those of multilateralism depend heavily on the relative number of regional trade agreements signed by countries. If a country signs a relatively large number of regional trade agreements and thus becomes a hub in the trade network, then its R&D/productivity and many measures of welfare are higher than R&D/productivity and welfare of a country in the multilateral trade system. On the other hand, a country that is involved in a relatively small number of regional trade agreements derives lower R&D and welfare gains than a country in the multilateral system. This implies that from the perspective of a small economy, which can only become a spoke in the regional trade system, the prospects for productivity improvements and welfare gains are generally better in the multilateral trade system than in the regional system. In contrast, for hubs the regional alternative is more attractive. Furthermore, the finding that opening to trade with new countries in the symmetric trade network promotes R&D and welfare of every country implies that an expansion of the WTO benefits all member states. Differently, in asymmetric regional trade systems, an expansion mostly benefits those countries that are immediately involved in a new trade agreement.

At last, considering the results of the paper in application to the inter-regional trade within one country, we obtain that regions where businesses are better connected to markets in other parts of the country outperform their more isolated neighbours, both in terms of welfare and firm productivity. This points towards the importance of regional trade and business integration and provides new insights into the reasons for large productivity and wealth gaps between regions in many countries. Similarly, interpreting asymmetry of the trade network more generally as asymmetry in firms' market coverage, the implications of our analysis are that firms that sell their product in a larger number of markets, – for example, by attracting consumers through online trade on multiple platforms, – or produce a good that appeals to a larger number of consumers due to being more central in the product space (a mass product versus niche product), should have more incentives to invest in R&D and exhibit higher productivity.

References

[1] Acemoglu, D., and J. Linn. 2004. "Market Size in Innovation: Theory and Evidence from the Pharmaceutical Industry." *The Quatrly Journal of Economics*, 119(3): 1049–1090.

[2] Acharya, R., and W., Keller. 2009. "Technology Transfer through Imports." *Canadian Journal of Economics*, 42(4): 1411–1448.

[3] Aghion, P., Bloom N., Blundell R., Griffith R., and P. Howitt. 2005. "Competition and Innovation: An Inverted-U relationship." *The Quatrly Journal of Economics*, 120(2): 701-728.

[4] Alba, J.D., Hur, J. and D. Park. 2008. "Effects of Hub-and-Spoke Free Trade Agreements on Trade: Panel Data Analysis", *ADB Economics Working Paper Series No. 127.*

[5] Alvarez, R., and R. Lopez. 2005. "Exporting and Performance: Evidence from Chilean Plants." *Canadian Journal of Economics*, 38(4): 1384-1400.

[6] Arkolakis C., Ramondo, N., Rodriguez-Clare, A., and S. Yeaple. 2014. "Innovation and Production in the Global Economy", *NBER WP 18792*.

[7] Bagwell, K., and R. W. Staiger. 1997. "An Economic Theory of GATT." *American Economic Review,* 89 (1), 215–248.

[8] Bagwell, K. and R. W. Staiger. 2002. "The Economics of the World Trading System," Cambridge: MIT Press.

[9] Baldwin, R. E., 1995. "A Domino Theory of Regionalism," in Richard E. Baldwin, P. Haaparanta and J. Kiander, eds. Expending Membership in the European Union. Cambridge, UK: Cambridge university Press, 25-48.

[10] Baldwin, R. E. 2004. "The Spoke Trap: Hub-and-Spoke Regionalism in East Asia." *CNAEC Research Series 04-02*, Korean Institute for International Economic Policy.

[11] Baldwin, R. E. 2005. "Stepping Stones or Building Blocks? Regional and Multilateral Integration." in *Regional Economic Integration in a Global Framework*, ed. J. McKay, M. O. Armengol, and G. Pineau. European Central Bank, Frankfurt.

[12] Bernard, A. B., Jensen J. B., and P.K. Schott. 2006. "Falling Trade Costs, Heterogeneous Firms, and Industry Dynamics." *Journal of Monetary Economics*, 53: 917-937.

[13] Bernard, A. B., Redding S. J., and P.K. Schott. 2007. "Comparative Advantage and Heterogeneous Firms." *Review of Economic Staudies*, 74(1): 31-66.

[14] Bhagwati, J. 1993. *"Regionalism and Multilateralism: an Overview,"* in New Dimensions in Regional Integration, ed. Melo and Panagariya.

[15] Brander, J.A. 1981. *"Intra-industry trade in identical commodities",* Journal of International Economics, 11: 1-14.

[16] Brander, J.A. and P. Krugman. 1983. *"A reciprocal dumping model of international trade",* Journal of International Economics, 15: 313-321.

[17] Brander, J. A. and B. J. Spencer. 1983. *"Strategic Commitment with R&D: The Symmetric Case",* The Bell Journal of Economics, 14 (1): 225-235.

[18] Bustos, P. 2011. "Multilateral Trade Liberalization, Exports and Technology Upgrading: Evidence on the Impact of MERCOSUR on Argentinian Firms." *American Economic Review.*

[19] Chen, M.X. and S. Joshi. 2010. "Third-country effects on the formation of free trade agreements," *Journal of International Economics*, Elsevier, vol. 82(2): 238-248.

[20] Chong, S. J., and Hur, J. 2008. "Small Hubs, Large Spokes and Overlapping Free Trade Agreements." *The World Economy.* 31(12): 1625–1665.

[21] D'Aspremont, C., and A. Jacquemin. 1988. "Cooperative and Noncooperative R&D in Duopoly with Spillovers." *American Economic Review*, 78: 1133-1137.

[22] De la Torre, A., and M. R. Kelly. 1992. "The Regional Trade Arrangements." *IMF Occasional Paper*, 93, IMF, Washington, DC.

[23] De Benedictis, L., De Santis R., and C. Vicarelli. 2005. "Hub-and-Spoke or Else? Free Trade Agreements in the 'Enlarged' European Union." *ENERPI and ISAE.*

[24] De Benedictis, L. and L. Tajoli. 2011. "The World Trade Network." *The World Economy*, 34: 1417 – 1454.

[25] Deltas, G., Desmet K., and G. Facchini. 2006. "Hub-and-Spoke Free Trade Areas." *CEPR Discussion Paper No. 5960.*

[26] Dewit, G., and D. Leahy. 2015. "Strategic R&D Commitment and the Gains from Trade", manuscript.

[27] Eckel, C. and J. P. Neary. 2010. "Multi-Product Firms and Flexible Manufacturing in the Global Economy," *Review of Economic Studies*, 77(1): 188-217.

[28] Fagiolo, G., Reyes, J. and Schiavo, S. 2009. "World-Trade Web: Topological Properties, Dynamics, and Evolution." *Physical Review E* 79(3), 36115.

[29] Feenstra, R. 2004. "Advanced International Trade: Theory and Evidence," Princeton University Press, Princeton.

[30] Fung, M. 2002. "Technological Opportunity and Economies of Scale in Research Productivity: A Study on Three Global Industries," *Review of Industrial Organization*, 21, 419–436.

[31] Furusawa, T., and H. Konishi. 2007. "Free Trade Networks." *Journal of International Economics*, 72: 310-335.

[32] Goyal, S., and J. Moraga-González. 2001. "R&D Networks," *RAND Journal of Economics*, 32(4): 686-707.

[33] Goyal, S., and S. Joshi. 2006. "Bilateralism and Free Trade." *International Economic Review*, 47 (3): 749-778.

[34] Griliches, Z. 1957. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica*, 25: 501-522.

[35] Grossman, G. and E. Helpman. 1991. "Innovation and Growth in the Global Economy," The MIT Press.

[36] Gustavsson, P., Hansson, P., Lundberg, L. 1999. "Technology, Resource Endowments and International Competitiveness," *European Economic Review*, 43: 1501–1530.

[37] Haaland, J. I., and H. J. Kind. 2008. "R&D Policies, Trade and Process Innovation," *Journal of International Economics*, 74(1): 170-187.

[38] Helpman, E. 1981. "International Trade in the Presence of Product Differentiation, Economies of Scale, and Monopolistic Competition: A Chamberlin-Heckscher-Ohlin Approach." *Journal of International Economics*, 11(3): 305-340.

[39] Horaguchi, H. H. 2007. "Economic Analysis of Free Trade Agreements: Spaghetti Bowl Effect and a Paradox of Hub and Spoke Network," *Journal of economic integration*, 22(3): 664-683.
[40] Impullitti, G., and O. Licandro. 2013. "Trade, Firm Selection, and Innovation: The Competition Channel," *Discussion Papers 13/04*, University of Nottingham, School of Economics.
[41] Jackson, M. O., and A. Wolinsky. 1996. "A Strategic Model of Social and Economic Networks," *Journal of Economic Theory*, 71(1): 44-74.
[42] Jensen, R., and M. Thursby. 1986. "A Strategic Approach to the Product Life Cycle", *Journal of International Economics*, 21: 269-284.
[43] Jensen, R., and M. Thursby. 1987. "A Decision Theoretic Model of Innovation, Technology Transfer, and Trade", *The Review of Economic Studies*, 54(4): 631-647.
[44] Kali, R., and J. Reyes. 2007. "The Architecture of Globalization: A Network Approach to International Economic Integration", *Journal of International Business Studies*, 38: 595–620.
[45] Kowalczyk, C., and R. Wonnacott. 1991. "Substitute and Complement Trading Clubs." Dartmouth College, Department of Economics, working paper 91-16.
[46] Kowalczyk, C., and R. Wonnacott. 1992. "Hubs and Spokes, and Free Trade in the Americas," *NBER Working Paper 4198*.
[47] König, M., C. Tessone, and Y. Zenou. 2014. "Nestedness in Networks: A Theoretical Model and Some Applications," *Theoretical Economics*, 9, 695 – 752.
[48] König, M., Liu, X., and Y. Zenou. 2014a. "R&D Networks: Theory, Empirics and Policy Implications," *CEPR Discussion Paper*, No. DP9872.
[49] Krisha, K. and A. O. Krueger. 1995. "Implementing Free Trade Areas: Rules of Origin and Hidden Protection," in James Levinsohn, Alan Deardorff and Robert Stern, eds. New Directions in Trade Theory. Ann Arbor: University of Michigan Press.
[50] Krugman, P. R. 1979. "Increasing Returns, Monopolistic Competition, and International Trade," *Journal of International Economics,* 9 (4): 469-479.
[51] Krugman, P. R. 1980. "Scale Economies, Product Differentiation, and the Pattern of Trade," *American Economic Review,* 70 (5): 950-959.
[52] Lileeva A, and D. Trefler. 2010. "Does Improved Market Access Raise Plant-Level Productivity," *Quarterly Journal of Economics* 125(3): 1051-99.
[53] Lloyd, P. J., and D. Maclaren. 2004. "Gains and Losses from Regional Trading Agreements: A Survey." *The Economic Record*, 80(251): 445-467.
[54] Mahadev, N.V.R. and U. N. Peled. 1995. "Threshold Graphs and Related Topics", North Holland, Amsterdam.
[55] Mauleon, A., Song H., and V. Vannetelbosch. 2010. "Networks of Free Trade Agreements among Heterogeneous Countries," *Journal of Public Economic Theory*, 12, 471-500.
[56] McLaren, J., 2002, "A Theory of Insidious Regionalism," *Quarterly Journal of Economics*, 98(2): 571-608.
[57] Melitz, M. J. 2003. "The Impact of Trade on Intra-Industry Reallocations and Aggreate Industry Productivity." *Econometrica*, 71: 1695-1725.
[58] Melitz, M., and G., Ottaviano. 2008. "Market Size, Trade, and Productivity." Review of Economic Studies 75: 295-316.
[59] Neary, P. 2003. "Globalisation and Market Structure," *Journal of the European Economic Association,* 1(2-3): 245-271.
[60] Neary, P. 2009. "International Trade in General Oligopolistic Equilibrium," mimeo.
[61] Pires, A. J. G. 2012. "International Trade and Competitiveness." *Economic Theory*, 50: 727-763.
[62] Puga, D., and A. J. Venables. 1997. "Preferential Trade Arrangements and Industrial Location", *Journal of International Economics*, 43: 347-68.
[63] Rivera-Batiz, L., and P. Romer. 1991. "Economic Integration and Endogenous Growth." *The Quaterly Journal of Economics*, 106: 531-556.
[64] Saggi, K. 2006. "Preferential Trade Agreements and Multilateral Tariff Cooperation." *International Economic Review*, 47(1): 29–57.
[65] Topalova, P. *"Trade Liberalization and Firm Productivity: The Case of India,"* IMF Working Paper WP/04/28 (2004)
[66] Trefler, D. 2004. "The Long and Short of the Canada-U.S. Free Trade Agreement." *American Economic Review*, 94(4): 870-895.
[67] Van Long, N., Raff, H, and F. Stähler. 2011. "Innovation and Trade with Heterogeneous Firms", *Journal of International Economics*, 84(2): 149-159.
[68] Venables, A. J. 1985. "Trade and Trade Policy with Imperfect Competition: The Case of Identical Products and Free Entry." *Journal of International Economics*, 19: 1-19.
[69] Verhoogen, E. 2008. "Trade, Quality Upgrading and Wage Inequality in the Mexican Manufacturing Sector," *Quarterly Journal of Economics*, vol. 123, no. 2, pp. 489-530.
[70] Wonnacott, R. 1990. "U. S. Hub-and-Spoke Bilaterals and the Multilateral Trading System." *C. D. Howe Institute Commentary 23*.
[71] Wonnacott, R. 1991. "The Economics of Overlapping Free Trade Areas and the Mexican Challenge." C. D. Howe Institute and National Planning Association.
[72] Wonnacott, R. 1996. "Trade and Investment in a Hub-and-Spoke System versus a Free Trade Area." *World Economy*, 19: 237-252.
[73] Yeaple, S. R. 2005. "A Simple Model of Firm Heterogeneity, International Trade, and Wages." *Journal of International Economics*, 65: 1-20.
[74] Yang, Y. and S. Gupta. 2005. "Regional Trade Agreements in Africa: Past Performance and the Way Forward", *IMF Working Paper* (WP/05/36).

9. Appendix

Appendix A: Solving the two-stage game (section 3.4)

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

Stage 2: output choice At the second stage, each firm $i \in 1:N$ chooses a vector of profit maximizing production quantities $\{y_{ij}\}_{j\in N_i\cup\{i\}}$, given the vector of R&D efforts $\{x_i\}_{i\in 1:N}$. The profit of firm i, π_i, is given in (4) and can be written as:

$$\pi_i = \sum_{j\in N_i\cup\{i\}} \left(-by_{ij}^2 - by_{ij} \sum_{k\in N_j\cup\{j\},k\neq i} y_{kj} \right) + (a-\gamma+x_i)y_i - \delta x_i^2. \tag{9}$$

Note that function π_i is additively separable and linear-quadratic in output levels $\{y_{ij}\}_{j\in N_i\cup\{i\}}$ of firm i. Moreover, it's strictly concave in own production quantities since $b > 0$. Then the solution of the system of linear first-order conditions determines the equilibrium of the second stage as long as this solution is interior, that is, $y_{ij} > 0$ for any i and any $j \in N_i \cup \{i\}$. The unique solution of the system is given by

$$y_{ij} = \frac{1}{b(n_j+2)} \left(a - \gamma + (n_j+1)x_i - \sum_{k\in N_j\cup\{j\},k\neq i} x_k \right) \quad \forall i, j \in N_i \cup \{i\}. \tag{10}$$

All of these quantities are strictly positive as soon as the demand in each market, governed by parameter a, is sufficiently high relative to the marginal production cost γ:[63]

Assumption 1 $\quad a > \gamma\left(1 + \max_{i\in 1:N} n_i\right).$

Moreover, as we demonstrate below, when Assumption 1 holds, also the R&D investments of all firms are strictly positive.

Stage 1: R&D choice Incorporating the second-stage solution (10) into firm i's profit function (9), we obtain a function of R&D efforts of i and its direct and two-links away trade partners:

$$\begin{aligned} \pi_i \;=\; & \left[\frac{1}{b} \sum_{j\in N_i\cup\{i\}} \frac{(n_j+1)^2}{(n_j+2)^2} - \delta \right] x_i^2 + \frac{2}{b}(a-\gamma) \sum_{j\in N_i\cup\{i\}} \frac{n_j+1}{(n_j+2)^2} x_i - \\ & -\frac{2}{b} \sum_{j\in N_i} \left[\frac{n_i+1}{(n_i+2)^2} + \frac{n_j+1}{(n_j+2)^2} \right] x_i x_j - \frac{2}{b} \sum_{j\in N_i} \sum_{k\in N_j,k\neq i} \frac{n_j+1}{(n_j+2)^2} x_i x_k + f(\{x_k\}_{k\in N_i\cup N_i^2}), \end{aligned} \tag{11}$$

where $f(\{x_k\}_{k\in N_i\cup N_i^2})$ is a term independent of x_i.[64]

This profit function is linear-quadratic in firm i's own R&D effort x_i. It is strictly concave in x_i for sufficiently high values of the R&D cost parameter δ, $\delta > \frac{1}{b}\sum_{j\in N_i\cup\{i\}} \frac{(n_j+1)^2}{(n_j+2)^2}$. Then the vector of

[63] Note that under Assumption 1 and condition that $0 \le x_i \le \gamma$,

$$y_{ij} \ge \frac{1}{b(n_j+2)}(a - \gamma - n_j\gamma) = \frac{1}{b(n_j+2)}(a - (\gamma + \gamma n_j)) > 0 \quad \forall i \in 1:N \quad \forall j \in N_i \cup \{i\}.$$

Moreover, $x_k \le \gamma$ ensures that $\sum_{k\in N_j\cup\{j\}} y_{kj} < a/b$ (see demand specification in (1)):

$$\sum_{k\in N_j\cup\{j\}} y_{kj} = \frac{n_j+1}{b(n_j+2)}(a-\gamma) + \frac{1}{b(n_j+2)} \sum_{k\in N_j\cup\{j\}} x_k \le \frac{n_j+1}{b(n_j+2)} a < \frac{a}{b}.$$

[64] Simple algebra confirms that

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

equilibrium R&D efforts of all firms can be found as a solution of the system of linear first-order conditions, provided that this solution is interior, i.e., $0 < x_i < \gamma$:

$$\left[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}+\delta\right]x_i+\frac{1}{b}\sum_{j\in N_i}\left[\frac{n_i+1}{(n_i+2)^2}+\frac{n_j+1}{(n_j+2)^2}\right]x_j+\frac{1}{b}\sum_{j\in N_i}\sum_{k\in N_j,k\neq i}\frac{n_j+1}{(n_j+2)^2}x_k$$

$$=\frac{1}{b}(a-\gamma)\sum_{j\in N_i\cup\{i\}}\frac{n_j+1}{(n_j+2)^2}\quad i\in 1:N. \tag{12}$$

In matrix form, this system can be written as

$$\left(\delta\mathbf{I}-\frac{1}{b}\mathbf{B}\right)\cdot\mathbf{x}=\frac{1}{b}\mathbf{u}, \tag{13}$$

where $\mathbf{x}$ is a vector of R&D investments, $\mathbf{I}$ is the $N\times N$ identity matrix, vector $\mathbf{u}$ is composed of $(a-\gamma)\sum_{j\in N_i\cup\{i\}}\frac{n_j+1}{(n_j+2)^2}$ at each position i, and $N\times N$ matrix $\mathbf{B}$ is defined as follows. A diagonal element of $\mathbf{B}$ at position ii is equal to $\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}$, and an element at position ij for $i\neq j$ is either $-\left[\frac{n_i+1}{(n_i+2)^2}+\frac{n_j+1}{(n_j+2)^2}\right]$ if j is *only* a direct trade partner of i, or $-\sum_{j'\in N_i\cap N_j}\frac{n_{j'}+1}{(n_{j'}+2)^2}$ if j is *only* a two-links-away trade partner of i (via i's direct trade partners $j'\in N_i$), or the sum of the two if j is both, direct and two-links-away trade partner of i, or 0 if j is neither of the above.[65] The determinant of matrix $\left(\delta\mathbf{I}-\frac{1}{b}\mathbf{B}\right)$ is equal to the product of its eigenvalues, $(\delta-\nu_1)\cdot\ldots\cdot(\delta-\nu_N)$, where $\{\nu_i\}$ are the eigenvalues of matrix $\frac{1}{b}\mathbf{B}$.[66] Then it becomes apparent that as soon as $\delta\neq\nu_i$ for all i, the matrix $\left(\delta\mathbf{I}-\frac{1}{b}\mathbf{B}\right)$ is nonsingular, and the system of equations (13) has a unique solution. Without much loss of generality we focus on such values of δ. Then

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

Below we show that this solution is interior, i.e., $0<x_i^*<\gamma$ for any $i\in 1:N$, if not only Assumption 1 but also Assumption 2, requiring that R&D is sufficiently costly, holds. First, observe that since all coefficients multiplying the R&D efforts of firms on the left-hand side of (12) are positive (provided that the profit function is concave in x_i), the best-response function of firm i is decreasing in R&D efforts of its direct and two-links-away trade partners. That is, the efforts of firm i and its direct and two-links-away trade partners are *strategic substitutes* from i's perspective. Then $0<x_i^*<\gamma$ as soon as the best-response effort of a firm is greater than zero even when the efforts of its rivals are equal to γ, and that it remains below γ even when the efforts of its rivals are zero. The former is provided by Assumption 1 (and the condition on δ making sure that the profit function is concave), while the latter is ensured by

Assumption 2 $\quad \delta>\frac{1}{\gamma b}\max_{i\in N}\sum_{j\in N_i\cup\{i\}}\frac{n_j+1}{(n_j+2)^2}(\gamma n_j+a).$

Thus, if the demand for the good is sufficiently large relative to the production cost (Assumption 1) and R&D is sufficiently costly (Assumption 2), the returns to R&D are high enough to induce strictly positive R&D investments in all countries but not high enough for R&D to exceed the upper threshold of γ. Furthermore, Assumption 2 is also sufficient for the concavity of the profit function as it is stronger

[65]From this definition and the formula for profit in (11) it follows that matrix $\mathbf{B}$ captures the strength of local interactions between firm's own R&D decision and R&D decisions of its direct and two-links-away neighbours in determination of the firm's profit.

[66]All $\{\nu_i\}$'s are different real numbers as matrix $\frac{1}{b}\mathbf{B}$ is real and symmetric.

than $\delta > \frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}$, at least under Assumption 1. Thus, both assumptions together imply that the system of the first-order conditions (12) determines the equilibrium R&D investments and these investments are strictly interior for all firms.

Solution of the first-order conditions (12) *for a hub-and-spoke network:*

$$
\begin{aligned}
x_s &= -\frac{\begin{array}{c}\left((a-\gamma)\left(\frac{n_s(n_h+1)(\varphi-1)}{(n_h+2)^2}-\frac{n_s(n_s+1)\varphi}{(n_s+2)^2}\right)-\frac{(n_s+1)(a-\gamma)}{(n_s+2)^2}\right)\\ \left(-b\delta-\frac{(n_s+1)n_h(\psi-1)(n_s(\varphi-1)+1)}{(n_s+2)^2}-\frac{(n_s+1)^2n_h(\psi-1)}{(n_s+2)^2}-\frac{2n_h(n_h+1)\psi}{(n_h+2)^2}-\frac{n_h(n_h+1)\psi(n_h\psi-1)}{(n_h+2)^2}+\frac{(n_h+1)^2(n_h\psi+1)}{(n_h+2)^2}\right)+\\ n_s(1-\varphi)\left(\frac{n_s(n_s+1)\varphi}{(n_s+2)^2}+\frac{n_s+1}{(n_s+2)^2}+\frac{n_h(n_h+1)\psi}{(n_h+2)^2}+\frac{n_h+1}{(n_h+2)^2}\right)\left((a-\gamma)\left(\frac{(n_s+1)n_h(\psi-1)}{(n_s+2)^2}-\frac{n_h(n_h+1)\psi}{(n_h+2)^2}\right)-\frac{(n_h+1)(a-\gamma)}{(n_h+2)^2}\right)\end{array}}{\begin{array}{c}n_sn_h(1-\varphi)(1-\psi)\left(\frac{n_s(n_s+1)\varphi}{(n_s+2)^2}+\frac{n_s+1}{(n_s+2)^2}+\frac{n_h(n_h+1)\psi}{(n_h+2)^2}+\frac{n_h+1}{(n_h+2)^2}\right)^2-\\ \left(b\delta+\frac{n_s(n_h+1)(\varphi-1)(n_h(\psi-1)+1)}{(n_h+2)^2}+\frac{n_s(n_h+1)^2(\varphi-1)}{(n_h+2)^2}-\frac{(n_s+1)^2(n_s\varphi+1)}{(n_s+2)^2}+\frac{2n_s(n_s+1)\varphi}{(n_s+2)^2}+\frac{n_s(n_s+1)\varphi(n_s\varphi-1)}{(n_s+2)^2}\right)\\ \left(b\delta+\frac{(n_s+1)n_h(\psi-1)(n_s(\varphi-1)+1)}{(n_s+2)^2}+\frac{(n_s+1)^2n_h(\psi-1)}{(n_s+2)^2}+\frac{2n_h(n_h+1)\psi}{(n_h+2)^2}+\frac{n_h(n_h+1)\psi(n_h\psi-1)}{(n_h+2)^2}-\frac{(n_h+1)^2(n_h\psi+1)}{(n_h+2)^2}\right)\end{array}}\\
x_h &= \frac{\begin{array}{c}(a-\gamma)\left(\frac{n_s(n_s+1)\varphi}{(n_s+2)^2}-\frac{n_s(n_h+1)(\varphi-1)}{(n_h+2)^2}\right)+\frac{(n_s+1)(a-\gamma)}{(n_s+2)^2}-\\ x_s\left(b\delta+\frac{n_s(n_h+1)(\varphi-1)(n_h(\psi-1)+1)}{(n_h+2)^2}+\frac{n_s(n_h+1)^2(\varphi-1)}{(n_h+2)^2}-\frac{(n_s+1)^2(n_s\varphi+1)}{(n_s+2)^2}+\frac{2n_s(n_s+1)\varphi}{(n_s+2)^2}+\frac{n_s(n_s+1)\varphi(n_s\varphi-1)}{(n_s+2)^2}\right)\end{array}}{n_s(1-\varphi)\left(\frac{n_s(n_s+1)\varphi}{(n_s+2)^2}+\frac{n_s+1}{(n_s+2)^2}+\frac{n_h(n_h+1)\psi}{(n_h+2)^2}+\frac{n_h+1}{(n_h+2)^2}\right)}
\end{aligned} \tag{14}
$$

In a star ($n_s=1, \varphi=\psi=0$) this becomes:

$$
\begin{aligned}
x_s &= -\frac{\left(-\frac{(n_h+1)(a-\gamma)}{(n_h+2)^2}-\frac{2(a-\gamma)}{9}\right)\left(-b\delta+\frac{(n_h+1)^2}{(n_h+2)^2}+\frac{4n_h}{9}\right)+\left(\frac{n_h+1}{(n_h+2)^2}+\frac{2}{9}\right)\left(-\frac{2}{9}n_h(a-\gamma)-\frac{(n_h+1)(a-\gamma)}{(n_h+2)^2}\right)}{n_h\left(\frac{n_h+1}{(n_h+2)^2}+\frac{2}{9}\right)^2-\left(b\delta-\frac{(n_h+1)^2}{(n_h+2)^2}-\frac{4n_h}{9}\right)\left(b\delta-\frac{(n_h+1)^2}{(n_h+2)^2}-\frac{(1-n_h)(n_h+1)}{(n_h+2)^2}-\frac{4}{9}\right)}\\
x_h &= \frac{(a-\gamma)\left(3b\delta\left(2n_h^4+12n_h^3+33n_h^2+43n_h+18\right)-4n_h^4-48n_h^3-159n_h^2-170n_h-51\right)}{27b^2\delta^2(n_h+2)^3-3b\delta\left(4n_h^4+37n_h^3+126n_h^2+179n_h+86\right)+4n_h^4+48n_h^3+159n_h^2+170n_h+51}
\end{aligned} \tag{15}
$$

Positivity of the profit function under Assumptions 1 and 2:

The profit function in (11) can be written as:

$$
\begin{aligned}
\pi_i &= 2x_i^*\Bigg[\frac{1}{b}(a-\gamma)\sum_{j\in N_i}\frac{n_j+1}{(n_j+2)^2}+\frac{1}{b}(a-\gamma)\frac{n_i+1}{(n_i+2)^2}-\frac{1}{b}\sum_{j\in N_i}\left[\frac{n_i+1}{(n_i+2)^2}+\frac{n_j+1}{(n_j+2)^2}\right]x_j^*-\\
&- \frac{1}{b}\sum_{j\in N_i}\sum_{k\in N_j,k\neq i}\frac{n_j+1}{(n_j+2)^2}x_k^*\Bigg]-\left[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}+\delta\right]x_i^{*2}+f(\{x_k\}_{k\in N_i\cup N_i^2}).
\end{aligned}
$$

Given the first-order conditions (12), this reduces to:

$$
\begin{aligned}
\pi_i &= 2\left[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}+\delta\right]x_i^{*2}-\left[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}+\delta\right]x_i^{*2}+\\
&+ f(\{x_k\}_{k\in N_i\cup N_i^2})=\left[-\frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{(n_j+1)^2}{(n_j+2)^2}+\delta\right]x_i^{*2}+\\
&+ \frac{1}{b}\sum_{j\in N_i\cup\{i\}}\frac{1}{(n_j+2)^2}\left(a-\gamma-\sum_{k\in N_j\cup\{j\},k\neq i}x_k^*\right)^2.
\end{aligned}
$$

It is easy to see that this expression is strictly positive whenever Assumptions 1 and 2 hold.

Appendix B: Figures

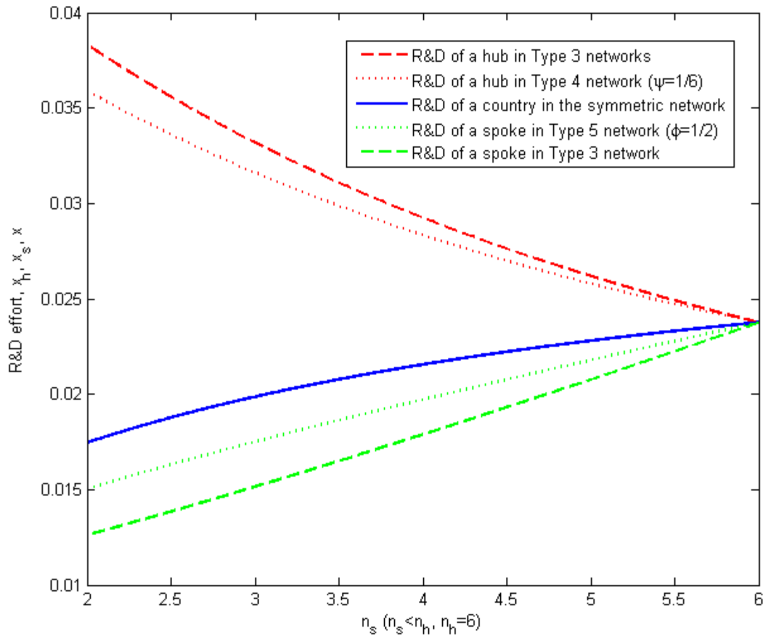


Figure 7: Equilibrium R&D in a symmetric and hub-and-spoke trade networks as a function of n_s.

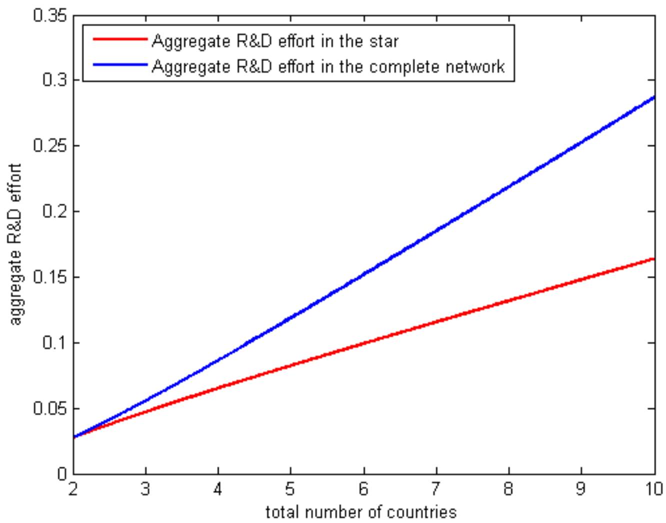


Figure 8: Aggregate equilibrium R&D in the star and in the complete trade network.