Upstream and downstream horizontal R&D networks*

Dusanee Kesavayuth[†]

Vasileios Zikos[‡]

Abstract

The existing literature on R&D networks has focused on networks among firms who compete in the product market (downstream networks). This article develops the literature by casting the analysis in the context of a vertically related industry, where both downstream firms and their upstream suppliers can form horizontal R&D networks.

Our analysis suggests that economic factors, such as within-network R&D spillovers, may be the driving forces behind the equilibrium network formations. Moreover, the equilibrium upstream R&D network may have the same architecture as the downstream R&D network or may differ from it. Interestingly, we find that stable networks can be socially optimal, but only in the case where their architectures differ across market tiers.

Keywords: Networks, R&D collaboration, input suppliers.

JEL Classification: L13, J50.

*Particular appreciation is expressed to an anonymous referee for very helpful comments.

[†]School of Economics, University of the Thai Chamber of Commerce, 126/1 Vibhavadee-Rangsit Road, Dindaeng, Bangkok, 10400, Thailand. Email: dusanee_kes@utcc.ac.th

[‡]Corresponding author: Department of Economics, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom, Email: V.Zikos@surrey.ac.uk; and Research Institute for Policy Evaluation and Design, University of the Thai Chamber of Commerce, 126/1 Vibhavadee-Rangsit Road, Dindaeng, Bangkok, 10400, Thailand, Email: V.Zikos@riped.utcc.ac.th.

1 Introduction

The incentives for R&D cooperation among competing firms have been studied extensively in the literature. The main message is that, in the absence of R&D cooperation, research activity creates involuntary knowledge spillovers. The creation of such spillovers – which contribute positively to the R&D stock of rival firms – imply that innovating firms cannot appropriate fully the returns from R&D. This suggests that R&D cooperation can help to internalize spillovers. A generic finding is that sufficiently large spillovers make R&D cooperation worthwhile and thereby expand both R&D spending and social welfare (see e.g. d’Aspremont and Jacquemin, 1988; Kamien *et al.*, 1992; Suzumura, 1992; and Belderbos *et al.*, 2004, for empirical evidence).¹

During the 1980s and throughout the 1990s, we witnessed a substantial increase in the number of R&D alliances. The upsurge in R&D alliances reflects that non-equity forms of collaboration, such as R&D networks, are steadily becoming more popular relative to equity forms, such as research joint ventures (RJVs hereafter).² This empirical pattern has led to the so-called “age of alliance capitalism” (Dunning, 1995; Narula and Duysters, 2004), where hi-tech companies engage in a variety of research projects to share know-how and enhance technological capabilities. A related observation is that in many industries the “locus of innovation” is not so much the firm (i.e. a single entity) but a network of R&D alliances where the firm is embedded (Powell, Koput and Smith-Doerr, 1996).

The growth of R&D partnerships through networks is also reflected in the development of a new strand of literature, distinct from that of RJVs.³ The first study to investigate the impact of product-market competition on R&D network formation is that of Goyal and Moraga-González (2001). In their pioneering work, they considered a three-stage game: in stage one, firms choose their bilateral collaborative links, prior to undertaking their R&D investments in stage two, and then competing in a Cournot fashion (stage 3). The focus of the analysis is on the relationships between market competition, R&D incentives and network architecture. The findings suggest that individual incentives to form collaborations are likely to be excessive

¹Empirical work has also explored the determinants of R&D cooperation, focusing mainly on the role of firm size and R&D intensity (Kaizer, 2002; Leiponen, 2001; Veugelers, 1997).

²For example, Hagedoorn (2002) reports that, in fast-growing innovative industries like computers, telecommunications and pharmaceuticals, non-equity R&D partnerships reached a total share of more than 90% in all R&D partnerships. This upward trend reflects that non-equity partnerships allow for greater flexibility relative to more traditional forms of inter-firm collaboration – and thereby allow firms to adapt more effectively to an environment characterised by rapid technological change and uncertainty.

³Closer in spirit to the network approach is the “RJV competition” model proposed by Kamien *et al.* (1992), which is an exception to the norm of R&D co-operation.

from a collective viewpoint. Recently, this seminal contribution has been extended in a number of directions (see e.g. Deroian and Gannon, 2006; Song and Vannetelbosch, 2007; Mauleon *et al.*, 2008; Westbrock, 2010; Zikos, 2010; Zirulia, 2011; Zu *et al.*, 2011). However, the existing literature has mainly concentrated on R&D networks in the context of a one-tier industry, where firms compete in the product market.⁴

We develop this literature by casting the analysis in the context of a vertically related industry, and by allowing not only downstream but also upstream firms to form horizontal R&D networks. We analyze the firms' network formation decisions at both market tiers simultaneously, because the upstream R&D network may have an impact on the "stability" of the downstream network (and vice versa). Intuitively, a more successful upstream firm (through its R&D network) can transform its downstream counterpart into a more aggressive competitor. At the same time, a more successful downstream firm, who benefits from its horizontal collaborations with other firms, can secure greater profit for its upstream supplier. We address the following questions: Which network architectures will emerge endogenously at the upstream and downstream market tier of a vertically related industry? Do equilibrium networks maximize the aggregate level of effective R&D, industry profits and/or social welfare?

A natural way to examine which R&D network architectures will emerge endogenously is to adopt Jackson and Wolinsky's (1996) concept of pairwise stability. This concept allows at most a pair of firms to alter the network structure at a time. We also enrich the network formation process by adopting the concept of strong stability developed by Jackson and Van de Nouweland (2005), which allows any coalition of firms to deviate between alternative network formations.

In the context of a model consisting of three upstream and three downstream firms, we show that, under certain conditions, different industry structures can be "stable" as upstream and/or downstream spillovers vary. Specifically, if R&D spillovers within-the-upstream network are sufficiently large while R&D spillovers within-the-downstream network are sufficiently small, then downstream firms as well as their corresponding upstream suppliers may form horizontal R&D networks which are partially connected. A partial network architecture is asymmetric in that it includes two of the firms (at each market tier) but excludes the third. Yet if R&D spillovers within-the-upstream network are sufficiently small, then more R&D links will be established within the industry (to offset the lower degree of spillovers): that is, both the downstream firms

⁴A notable exception is Mauleon, Sempere-Monerris and Vannetelbosch (2008).

and their upstream suppliers will opt for complete R&D networks. Finally, when upstream spillovers are sufficiently large but downstream spillovers are intermediate, then the equilibrium upstream network is likely to be different from the downstream network. Specifically, we show that a partial upstream network might coexist with a complete downstream network. We may conclude that R&D spillovers, both within the upstream and downstream R&D network, play an important, yet complex role, in explaining the firms' network formation decisions.

Closest in spirit to our approach is the article by Mauleon, Sempere-Monerris and Vanetelbosch (2008) – hereafter MSV – who extend and enrich the existing literature by studying network formation in the presence of firm-level labour unions.⁵ The authors show that, as long as each firm settles its own wage, the partial R&D network arises as a strongly stable architecture,⁶ whereas the complete R&D network emerges when all the relevant bargaining power rests with the unions. This implies that stronger unions may promote the formation of R&D networks. Like MSV, we also cast the analysis in the context of a vertically related industry, but focus instead on the network formation decisions of both downstream firms and their upstream suppliers (who represent labour unions in MSV).

As well as having theoretical significance, we suggest that the present analysis is of empirical value in light of the observed proliferation of R&D alliances in vertically related industries. The upsurge in R&D alliances is perhaps most obvious in hi-tech industries such as computers, pharmaceuticals and telecommunications. For instance, in the computer industry, firms specialize in different market layers, as it is rather difficult for individual firms to develop technological capabilities by relying solely on internal research (Cloudt *et al.*, 2006). Within this industry, upstream firms are active in different fields such as microprocessors (e.g. Intel, Motorola, Texas Instruments, AMD), software (e.g. IBM, Microsoft, Sun Microsystems, Oracle) and telecommunication technologies (e.g. Ericsson, AT&T, Siemens). Cloudt *et al.* (2006), Palmberg and Martikainen (2003), among others, identified 121 newly formed R&D partnerships by Intel, Motorola, Texas Instruments and AMD during the period 1990-1999. Yet R&D partnerships are common not only between upstream but also between downstream firms such as personal computer manufacturers (e.g. Compaq, Dell, Sony, Hewlett-Packard).⁷ This body of empirical

⁵We note that labour unions can be thought of as being upstream firms in the present setting.

⁶MSV qualify this result by showing that the partial network emerges as long as within-network spillovers are sufficiently large.

⁷Needless to say, R&D collaborations are not only horizontal but also vertical. For vertical R&D collaborations see, for example, Attalah (2002) for a theoretical framework; and Cassiman and Veugelers (2002) for empirical

evidence is an additional motivation for our article.

The article is structured as follows. Section 2 presents our model. Section 3 studies the upstream and downstream firms' decisions to form horizontal R&D networks. Section 4 considers the potential implications of the stable network formations, focusing on aggregate effective R&D, industry profits and social welfare. Section 5 discusses various aspects of our results, particularly their relation to the literature and certain assumptions of our model. The last section concludes the article.

2 The model

We carry out our analysis in a modified version of the R&D network formation model proposed by MSV. The key differences with our model are the following. First, we postulate that *both* the downstream firms and their upstream suppliers (labour unions in MSV) undertake process R&D investments. Second, we study simultaneously the stability of the upstream and downstream R&D networks.⁸

Setting. Consider an industry consisting of three upstream and three downstream firms denoted by U_i and D_i , $i = 1, 2, 3$, respectively (see Figure 1, left panel).⁹ One can think of the upstream firms as being input suppliers and the downstream firms as being final good manufacturers. Each upstream firm U_i maintains an exclusive relation with one of the downstream firms D_i .¹⁰ Each downstream firm buys an input from its upstream supplier at a unit price w_i , and transforms it to the final product. The downstream marginal cost is initially constant at $\bar{k}$; while each upstream firm faces an initial marginal cost $\bar{c}$, where $0 \leq \bar{c} + \bar{k} < a$. One unit of input produces exactly one unit of output, which is sold in the retail market under the (inverse) demand function:

$$p = a - \sum_{i=1}^3 q_i, \quad (1)$$

evidence.

⁸This allows us to capture the potential interaction between the firms' network formation decisions at the two market tiers.

⁹This is the smallest number of firms that allows us to study asymmetric networks tractably; indeed, Goyal and Moraga-González (2001), MSV, among others, note that a general examination of horizontal asymmetric networks would be especially challenging.

¹⁰Exclusive relations are a common feature of the Japanese automobile industry. In that context, automakers and suppliers of auto parts undertake large fixed investments, thereby increasing their switching costs. Though we return to this issue in section 5, we note here that such high-commitment relationships are very likely to "continue indefinitely" (Helper and Levine, 1992, p. 563).

where p is the retail price and q_i is the output of downstream firm i ($i = 1, 2, 3$).

Collaboration networks. In an upstream and downstream triopoly, four distinct R&D networks may arise at each market tier – see Figure 1 (right panel). In the empty network (g^e), there are no collaborative links between firms; while in the complete network (g^c) each firm has a link with the other two firms. In the partial network (g^p), there is only one link, creating an insider/outsider pattern. Finally, in the star network (g^s), there is a hub firm which is directly linked with the other two, spoke firms; in turn, the spokes are indirectly linked with each other via the hub.¹¹ We shall write $ij \in g$ to represent the link between firms i and j in a network g . Let $g + ij$ denote the new network when firms i and j add a link to network g ; and $g - ij$ the resulting network after i and j sever their link.¹²

Figure 1: Industry Structure (left panel) and Network Structures (right panel)

Marginal costs and R&D investments. By investing x_i^2 and e_i^2 in process R&D, firm U_i and D_i , respectively, can attain unit production costs $\bar{c} - x_i$ and $\bar{k} + w_i - e_i$, where x_i and e_i denote a firm's R&D output (e.g. d' Aspremont and Jacquemin, 1988). Note that the R&D cost function reflects diminishing returns to the level of R&D investment/output, x_i (e_i , respectively).¹³

Upstream and downstream firms can reduce their production costs further by forming collaborative links. Such links allow firms to access the R&D outputs of other horizontally related

¹¹Note that the partial and star networks are asymmetric architectures in that some of the firms maintain more links than others.

¹²Like the existing literature on R&D networks (e.g. Goyal and Moraga-González, 2001; Deroian and Gannon, 2006; Song and Vannetelbosch, 2007; MSV), we assume that the formation of collaboration links is costless. Goyal and Joshi (2003) provide related work which looks at the effects of linking costs on the network architecture between oligopoly firms. They do not endogenize R&D efforts so the level of cost reduction is exogenous as well.

¹³This is a special case of the quadratic R&D cost function (say) $\Gamma(x_i) = \gamma x_i^2$, where $\gamma > 0$ denotes the efficiency of the R&D technology. Clearly, the higher γ the lower is the level of technology efficiency. For tractability, we set $\gamma = 1$ which ensures nonnegativity of all variables (see e.g. MSV; Goyal and Moraga-González, 2001).

firms. Let the subscript u denote an upstream R&D network and the subscript d a downstream R&D network. Following MSV – and given a network profile (g_u^n, g_d^n) , where $n = c, p, s, e$ – the marginal cost of firm U_i and D_i , respectively, is:

$$c_{U_i}(g_u^n, g_d^n) = \bar{c} - x_i - \beta \left[\frac{x_j}{t(ij)} + \frac{x_k}{t(ik)} \right], \quad (2)$$

$$c_{D_i}(g_u^n, g_d^n) = \bar{k} + w_i - e_i - \theta \left[\frac{e_j}{t(ij)} + \frac{e_k}{t(ik)} \right], \quad i \neq j \neq k, \quad i, j, k \in \{1, 2, 3\}. \quad (3)$$

In eq. (2) and (3), $\beta \in (0, 1]$ and $\theta \in (0, 1]$ denote the rate of knowledge transmission within an upstream and downstream R&D network, respectively, i.e. within-network R&D spillovers.¹⁴ Within-network spillovers depend on the “distance” between collaborating firms, where $t(ij)$ refers to the distance between a pair of firms i and j in terms of the number of links in the shortest path between them. Following again MSV, we set $t(ij) = \infty$ to denote the absence of a path between firms i and j .¹⁵

From eq. (2) and (3), the “effective” R&D output of firm U_i and D_i , respectively, is:

$$X_{U_i} \equiv x_i + \beta \left[\frac{x_j}{t(ij)} + \frac{x_k}{t(ik)} \right], \quad (4)$$

$$X_{D_i} \equiv e_i + \theta \left[\frac{e_j}{t(ij)} + \frac{e_k}{t(ik)} \right]. \quad (5)$$

This represents the overall reduction in a firm’s marginal cost as a result of R&D. It consists of firm i ’s own R&D output, x_i (respectively, e_i), and the sum of the R&D outputs that firm i can access through collaborative links with other horizontally related firms.¹⁶ As eq. (4) and (5) suggest, firm i can access only a proportion β (respectively, θ) of its partners’ R&D outputs.

Profits. For a given network profile, (g_u^n, g_d^n) , the profits of an upstream firm U_i and a downstream firm D_i are, respectively:

$$\pi_{U_i}(g_u^n, g_d^n) = [w_i(g_u^n, g_d^n) - c_{U_i}(g_u^n, g_d^n)] q_i(g_u^n, g_d^n) - [x_i(g_u^n, g_d^n)]^2; \text{ and} \quad (6)$$

$$\pi_{D_i}(g_u^n, g_d^n) = [p(g_u^n, g_d^n) - c_{D_i}(g_u^n, g_d^n)] q_i(g_u^n, g_d^n) - [e_i(g_u^n, g_d^n)]^2. \quad (7)$$

¹⁴We thus allow spillovers at the two market tiers *not* to be necessarily of the same size. We note that potential differences in the size of within-network spillovers can result from various sources, such as absorptive capacity and the efficiency of communication channels between collaborating firms (Attalah, 2002).

¹⁵Note that if firms i and j are directly linked, then $t(ij) = 1$.

¹⁶For example, in an upstream complete network (say), $X_{U_i} = x_i + \beta(x_j + x_k)$, $i \neq j \neq k$, $i, j, k \in \{1, 2, 3\}$.

The first term to the right of eq. (6) captures U_i 's wholesale profit. Wholesale profit is the product of the sales volume (q_i) and the relevant wholesale profit margin. The wholesale profit margin is the difference between the input price (w_i) that an upstream firm charges and its marginal cost (c_{U_i}). In turn, both the input price and marginal cost depend on the industry structure, (g_u^n, g_d^n) , as well as the position of trading partners U_i and D_i within it. Likewise, eq. (7) reflects D_i 's retail profit, which is the product of its sales volume and retail profit margin. The retail profit margin is the difference between the retail price (p) and the downstream marginal cost (c_{D_i}).

Timing of events. Upstream and downstream firms play a four-stage game. In *stage one*, the upstream and downstream firms choose simultaneously their collaborative links to form horizontal R&D networks. The collection of pairwise links between the upstream (downstream) firms defines an upstream (downstream) horizontal R&D network, as shown in Figure 1 (right panel). In *stage two*, the upstream and downstream firms choose simultaneously and independently their R&D investments (x_i and e_i , respectively). In *stage three*, the upstream firms set simultaneously their wholesale quantities, resulting in input prices $w_i \geq 0$. In *stage four*, the downstream firms choose their output levels (q_i).

The timing above reflects that the selection of collaborative links is a long-run and strategic decision for an upstream and a downstream firm. This is motivated by the empirical observation that firms ask for “strong commitment” from their partners (in terms of involvement and resources) in order to establish R&D alliances (Hagedoorn, 2002, p. 479).¹⁷ In addition, the timing above which is standard in the R&D network literature captures that the choice of the R&D investments is longer-run decision than the exact level of wholesale prices. This is because R&D activity is inherently uncertain, so it may require a relatively long time to come into fruition; while input prices can be changed more easily and more often (perhaps responding to small changes in market conditions).

Notation. We shall use the following notation throughout the article. Let the superscripts h and s denote, respectively, the hub and spoke firms in a star network (g^s); and let the superscript

¹⁷It is worth noting that, by asking for “strong commitment”, firms try to limit a potential failure of R&D alliances. The possibility that an R&D alliance fails may be related either with the highly uncertain nature of R&D activity or with strategic reasons such as an incentive for a firm to terminate an agreement after it has benefited by more compared to its research partners (Narula and Hagedoorn, 1999). In spite of this possibility, as Narula and Hagedoorn (2004, p. 202) point out, R&D alliances “stand out in terms of their effectiveness” compared to other types of alliances (e.g. sales and marketing alliances).

l refer to a linked firm in the partial network (g^p) .

3 Main analysis

We solve the game backwards from stage 4 to stage 2. We then turn to the first stage for which we obtain the set of “stable” networks. To this end we use two well-established equilibrium concepts – “pairwise stability” and “strong stability”.

3.1 Pairwise stability

A simple way to analyze which network architectures are likely to emerge in the present setting is to consider the concept of pairwise stability. Following Jackson and Wolinsky (1996), we say that a network is *pairwise stable* if no firm has an incentive to delete unilaterally one of its links and no pair of firms want to add a new link between them (with one benefiting strictly and the other at least weakly).

Because there are 4 network structures that can possibly emerge at each market tier, there are 16 qualitatively different industry structures in the present setting. To pin down the pairwise stable industry structures we proceed as follows. We take as given the network structure at one of the market tiers, the downstream (say), and ask what network structures will endogenously emerge between the upstream firms.¹⁸ We then turn to study what R&D networks will arise between the downstream firms for a given network between the upstream firms. Finally, to determine the equilibrium R&D networks at both market tiers simultaneously, we note that the network profile (g_u^n, g_d^n) , where $n = c, p, s, e$, is “stable” if and only if the R&D network at one market tier is a best response to the R&D network at the other market tier.

We now characterize the set of pairwise stable networks. This tells us about the upstream and downstream firms’ incentives to form collaborative links. The following lemma summarizes our findings.

Lemma 1 *In the parameter space (β, θ) , the following industry structures emerge endogenously as pairwise stable:*

- (i) (g_u^c, g_d^c) for all parameter configurations.
- (ii) $(g_u^p(ij), g_d^p(ij))$ if β is sufficiently large and θ is sufficiently small.

¹⁸For example, if we ‘fix’ the downstream R&D network to the complete network (say), then upstream firms can opt for a complete, partial, star or empty network.

(iii) (g_u^p, g_d^c) if β is sufficiently large.

Figure 2 shows the pairwise stable industry structures in the present setting. In particular, the industry structure (g_u^c, g_d^c) emerges for all values of β and θ ; $(g_u^p(ij), g_d^p(ij))$ emerges in the region to the right of curve C_2 and below curve C_1 ; and (g_u^p, g_d^c) emerges in the region to the right of the C_3 curve.¹⁹

Part (i) of the lemma asserts that at both market tiers – upstream and downstream – a complete R&D network is pairwise stable. Intuitively, in the star network, the spoke firms are in a weaker competitive position vis-à-vis the hub firm. Therefore, given a complete R&D network at a market tier, a firm at the other market tier will not unilaterally sever a link to become a spoke in the star network.

Figure 2: Pairwise stable industry structures

Part (ii) of the lemma states that, at both market tiers, a partial R&D network between firms 1 and 2, say, is pairwise stable. The stability of the partial network hinges on the competitive advantage of the linked firms relative to the isolated (outsider) firm. This competitive advantage means that neither of the linked firms will unilaterally sever their link to form the empty network, given a partial network at the other market tier. Likewise, even though the isolated firm benefits by forming a link with an insider, linked firm (to become a spoke in the star), it is the case that none of the insiders have an incentive to form such a link (to become the hub in the star). As lemma 1 suggests, an insider firm will not form this link provided that spillovers β within the upstream R&D network are sufficiently large; while spillovers θ within the downstream R&D network are sufficiently small.

¹⁹We note that the C_1 , C_2 and C_3 curves are the set of (β, θ) values that solve the equations $\pi_D^h(g_u^p, g_d^s) = \pi_D^l(g_u^p, g_d^p)$, $\pi_U^h(g_u^s, g_d^p) = \pi_U^l(g_u^p, g_d^p)$ and $\pi_U^h(g_u^s, g_d^c) = \pi_U^l(g_u^p, g_d^c)$, respectively.

The intuition behind the need for sufficiently large upstream and sufficiently small downstream spillovers can be explained as follows. Greater upstream spillovers β imply that the competitive advantage of the linked firms is more pronounced. To put it differently, the insiders are ‘strong’ while the outsider is ‘weak’ when β is large. Therefore, the linked firms will have no incentive to offer a link to the isolated firm.

The competitive advantage of the upstream linked firms is transferred to their downstream counterparts through lower input prices.²⁰ As lemma 1 (ii) suggests, the downstream counterparts of the upstream linked firms will form a partial R&D network as well. Interestingly, they will do so even though spillovers θ within the downstream R&D network are sufficiently small. The reason is that the insider downstream firms are relatively aggressive in product market competition as they face lower input prices than the outsider firm. Therefore, they have no incentive to expand their partial R&D network. Consequently, only one link is established at the downstream market tier, and an insider/outsider formation results.

The most interesting result, though, is part (iii) of the lemma as it suggests that an asymmetric industry structure will be pairwise stable. In particular, a partial upstream network will coexist with a complete downstream network if spillovers β within the upstream R&D network are sufficiently large. This industry structure arises for two primary reasons. First, in the partial network, the upstream linked firms have no incentives to form a link with their isolated counterpart if within-network spillovers β are sufficiently large. This is so because the competitive advantage of the linked firms is relatively pronounced when β is large. Second, the upstream isolated firm does not suffer a lot (even though β is large), given that its downstream counterpart maintains an R&D link with both its rivals. Putting this last observation slightly differently, the additional downstream link helps to compensate for the absence of an upstream link, thereby increasing the overall profit of this vertical chain with an isolated upstream firm.

3.2 Strong stability

The concept of pairwise stability permits deviations only by a pair of firms at a time. This suggests that if we enrich the network formation process to encompass deviations by a coalition of firms, then it may no longer be the case that the same network architectures will materialize in equilibrium. Indeed, it may well be the case that a pairwise stable network is no longer

²⁰We note that forming an upstream (horizontal) R&D link, *ceteris paribus*, has the effect of raising input quantities and, thus, reducing input prices.

strongly stable.²¹ Following Jackson and Van de Nouweland (2005), we say that a network is *strongly stable* if it survives all possible changes in the number of its links by any coalition of firms – because at least one firm in the coalition would lose from the proposed group deviation. This constitutes then a refinement of the set of pairwise stable networks. The final network architectures of our network formation game are put forward in the following proposition.

Proposition 1 *In the parameter space (β, θ) , the following industry structures emerge endogenously as strongly stable:*

- (i) (g_u^c, g_d^c) if β is sufficiently small.
- (ii) $(g_u^p(ij), g_d^p(ij))$ if β is sufficiently large and θ is sufficiently small.
- (iii) (g_u^p, g_d^c) if β is sufficiently large and θ is intermediate.

Figure 3 illustrates the content of proposition 1. More specifically, the industry structure (g_u^c, g_d^c) arises in the region to the left of curve C_4 ; $(g_u^p(ij), g_d^p(ij))$ arises in the region below curve C_1 and to the right of curve C_2 ; and (g_u^p, g_d^c) arises in the region to the right of the C_3 curve and between curves C_5 and C_6 .²²

Part (i) of the proposition can be explained as follows. Consider first a complete upstream network, given a complete network at the downstream market tier. Because strong stability is a refinement of pairwise stability, there are two possible deviations from the complete network. More specifically, the three upstream firms will not jointly deviate to the empty network. However, a coalition of two upstream firms has incentives to sever its links with the third firm in order to form the partial network. As explained in the previous section (3.1), in the partial network, the linked firms enjoy a substantial cost advantage over their rival. This cost advantage of the linked firms becomes more pronounced as within-network spillovers β increase. As a result, the partial network destabilizes the complete network when spillovers are large. Therefore, the upstream firms will opt for a complete network only if within-network spillovers β are sufficiently small, given a complete network at the downstream market tier. In contrast, given a complete network at the upstream market tier, there will be no coalitional deviation by the downstream firms to either the partial or the empty network.

²¹ Pairwise stability can be seen as a necessary condition for stability (see Jackson and Wolinsky, 1996; Goyal and Moraga-González, 2001).

²² We note that the curve C_4 is the set of (β, θ) values that solve the equation $\pi_U(g_u^c, g_d^c) = \pi_U(g_u^p, g_d^c)$; while the C_5 and C_6 curves are the set of (β, θ) values that solve $\pi_D(g_u^p, g_d^c) = \pi_D(g_u^p, g_d^p)$.

Figure 3: Strongly stable industry structures

Given this, a profile of R&D networks (i.e. industry structure) emerges endogenously if and only if the R&D network at one market tier is a best response to the R&D network at the other market tier. Thus, a complete network at both market tiers will be a strongly stable architecture provided that within-the-upstream network spillovers β are sufficiently low, as part (i) of proposition 1 reports.

Part (ii) of the proposition states that, at both market tiers, the partial R&D network between firms 1 and 2, say, is strongly stable. This suggests that the two stability concepts provide identical predictions regarding the equilibrium industry structure in this case. As explained in the previous section on pairwise stable networks, the emergence of the partial network reflects two factors. First, the competitive strength of the insider upstream firms increases with a rise in the degree of spillovers within the network. This means that the insiders will have no incentives to expand their partial R&D network. Second, the competitive advantage of the insider upstream firms is transferred to their downstream counterparts through lower input prices. In turn, the corresponding downstream firms will also form a partial R&D network in order to retain this increased competitive strength. Because the downstream firms are ‘strong’ enough in product market competition, they will form this partial R&D network even though within-the downstream network spillovers θ are relatively low.

Part (iii) of the proposition suggests that a partial upstream network might coexist with a complete downstream network. In particular, this asymmetric industry structure arises if within-the-upstream network spillovers β are sufficiently large; while within-the-downstream network spillovers θ are intermediate. In the previous section (3.1), we saw that for this industry

structure to emerge, there was only a requirement on the size of spillovers β .

The intuition can be explained as follows. We first note that, given the R&D network at the downstream market tier, the upstream firms will not deviate from the partial network. However, it appears that, given the upstream R&D network, the downstream firms will force a deviation from the complete to the partial network if spillovers θ are sufficiently *large* or *small*. Recall that because the upstream firms 1 and 2, say, opt for a partial network, their downstream counterparts benefit from the ensuing input price reductions. In turn, the lower input prices increase the competitive strength of the downstream firms, 1 and 2. It turns out that if spillovers θ within the downstream network are sufficiently large, these downstream firms will jointly sever their links with the third firm in order to form a partial network. By doing so, they can retain their competitive advantage in product market competition over their rival.

Furthermore, the downstream firms 1 and 2 will also deviate from the complete to the partial network as long as θ is sufficiently small. The reason is that small within-network spillovers mean that the downstream firms 1 and 2 do not enjoy a substantial access to the R&D results of the third downstream firm. Because firms 1 and 2 already secure their inputs at a lower cost than the third firm, proposition 1 implies that they will find it profitable to break both their links with this firm. Therefore, compared to the concept of pairwise stability, the coexistence of a partial upstream network and a complete downstream network becomes less likely and emerges only if β is sufficiently large and θ is intermediate (rather than for any θ value).

Together, lemma 1 and proposition 1 seem to suggest that within-network upstream spillovers are more important than downstream spillovers in determining the equilibrium industry structures. For example, part (i) of the proposition requires a qualification only on the size of upstream spillovers to pin down the strongly stable industry structure. Likewise, part (ii) of the proposition suggests that a partial downstream network – given a partial upstream network – is likely to emerge when downstream spillovers are small; but an additional requirement is that upstream spillovers are large. Of course, a task for future empirical work is a thorough testing of this theoretical prediction that seems to be relevant in the present setting.

4 Further analysis

In this section we consider some aspects of aggregate performance, focusing first on the aggregate level of effective R&D. Evaluating the different networks in terms of aggregate effective R&D is

important because more R&D implies lower costs and therefore higher input/output quantities. The resulting decrease in product prices may also benefit consumers.

By comparing the aggregate level of effective R&D under each strongly stable industry structure against the other possible industry structures, we can state the following proposition.

Proposition 2 (i) *The industry structure (g_u^p, g_d^c) maximizes the aggregate level of effective R&D when it emerges as strongly stable.* (ii) *In contrast, the other two industry structures, (g_u^c, g_d^c) and $(g_u^p(ij), g_d^p(ij))$, may lead to a lower aggregate level of effective R&D compared to industry structures with fewer collaborative links.*

An asymmetric industry structure – a partial upstream network and a complete downstream network – is desirable in terms of aggregate effective R&D; in contrast, the other two, symmetric, structures are never optimal. As proposition 2 suggests, these industry structures are actually dominated by industry structures that contain a smaller number of collaborative links. For instance, we find that an empty network at both market tiers generates higher aggregate effective R&D than the corresponding industry structure where complete networks are strongly stable.

We now consider industry profits. We say that an industry structure is *strongly efficient* if it secures at least as high an aggregate level of profits as any other industry structure; that is, $\sum_{i=1}^3 [(\pi_{U_i} + \pi_{D_i})(g_u^n, g_d^n)] \geq \sum_{i=1}^3 [(\pi_{U_i} + \pi_{D_i})(g_u^n, g_d^n)']$ for any other industry structure $(g_u^n, g_d^n)'$, where $n = c, p, s, e$. We note that the strongly efficient industry structures are not easily characterized in the present setting as it proves rather difficult to provide a profit ranking of all possible industry structures.²³ Instead, we examine whether there are parameter configurations for which the strongly stable industry structures can maximize industry profits – and thus are strongly efficient. The following proposition summarizes our findings.

Proposition 3 *Neither of the strongly stable industry structures is strongly efficient.*

Proposition 3 implies that individual and collective interests for R&D collaboration do never coincide. It is worth noting that such misalignment is particularly severe when either complete or partial networks arise at both market tiers, i.e. (g_u^c, g_d^c) and $(g_u^p(ij), g_d^p(ij))$. In both cases, it appears that a fairly wide variety of industry structures can secure higher aggregate profits.²⁴

²³ Recall that there are 16 possible industry structures in the present setting.

²⁴ For example, the industry structure (g_u^c, g_d^c) – within the range of β and θ values where it is strongly stable – is outperformed by: (g_u^s, g_d^c) for all β and θ ; (g_u^c, g_d^s) if θ is large; (g_u^s, g_d^s) if β is small and θ is large. Likewise, the industry structure (g_u^p, g_d^p) performs worse than: (g_u^c, g_d^c) unless β is large and θ is low; (g_u^s, g_d^c) for all β and θ ; (g_u^p, g_d^e) for all β and θ .

However, when the partial upstream network and the complete downstream network are strongly stable, then ‘only’ one industry structure performs better in terms of aggregate profits – the star upstream network and the complete downstream network, (g_u^s, g_d^c) .

The divergence between individual and collective interests seems particularly pronounced in the present setting. For this reason, we would like to explore this result further by examining social welfare under the strongly stable industry structures. We shall define social welfare in the usual way, as the sum of consumer surplus, upstream and downstream firms’ profits. Social welfare under an industry structure (g_u^n, g_d^n) is thus given by:

$$W(g_u^n, g_d^n) = \frac{Q^2(g_u^n, g_d^n)}{2} + \sum_{i=1}^3 \pi_{U_i}(g_u^n, g_d^n) + \sum_{i=1}^3 \pi_{D_i}(g_u^n, g_d^n), \quad (8)$$

where $Q(g_u^n, g_d^n) = \sum_{i=1}^3 q_i(g_u^n, g_d^n)$. To compute social welfare under the different networks, we substitute into (8) the equilibrium outcomes for output and firm profits.

Proposition 4 *(i) If β is sufficiently large, then the industry structure (g_u^p, g_d^c) maximizes social welfare when it emerges as strongly stable. (ii) Neither the industry structure (g_u^c, g_d^c) nor the industry structure $(g_u^p(ij), g_d^p(ij))$ is welfare-maximizing.*

The result above shows that only one industry structure can be socially optimal in the present setting. In particular, if within-the-upstream network spillovers are sufficiently large, then the industry structure consisting of an upstream partial network and a complete downstream network is socially desirable relative to any other industry structure. In contrast, we find that, when spillovers are sufficiently small, this industry structure is socially dominated by the upstream star network and the complete downstream network, (g_u^s, g_d^c) . The intuition can be explained as follows. The upstream partial network and the complete downstream network secure a higher aggregate level of effective R&D and, thus, consumer surplus than any other industry structure (recall proposition 2). However, the industry structure consisting of an upstream star network and a complete downstream network, (g_u^s, g_d^c) , leads to higher aggregate profits. It turns out that the increase in aggregate profits under (g_u^s, g_d^c) outweighs the corresponding decrease in consumer surplus when spillovers, β , are small. Therefore, social welfare is maximized under (g_u^p, g_d^c) so long as β is sufficiently large.

5 Discussion

The aim of this section is to discuss both the relation of our results to the literature and certain assumptions of the model. We first consider the performance of the stable network formations in terms aggregate effective R&D investment. Our analysis here complements Song and Vannetelbosch (2007), who consider a model of international R&D collaboration among three firms located in different countries. The authors find – in line with us – that stable networks do not perform well in terms of aggregate effective R&D.²⁵ Taking the next step, the authors also show that a government policy in the form of R&D subsidies increases effective R&D investment. In the present article, we find that, an asymmetric industry structure within a two-tier setting – a partial upstream network and a complete downstream network – produces the highest aggregate level of effective R&D when it emerges as strongly stable.

We now consider the relationship between strongly stable, industry-profit maximizing and/or welfare-maximizing networks. Taken together, propositions 1, 3 and 4 imply that, in the pursuit of their private interests, the downstream firms and their upstream suppliers cannot collectively achieve a profit-maximizing outcome but, under certain conditions, may achieve a welfare-maximizing outcome when the upstream partial network and the complete downstream network emerge endogenously. We note that other authors have reported similar conclusions regarding a potential divergence between individual and collective incentives for R&D collaboration. For instance, Goyal and Moraga-González (2001) do so in an one-tier setting when firms are located in the same country; Song and Vannetelbosch (2007) do so when firms are located in different countries; and MSV (2008) do so when firms settle their own wages.

As a caveat to our conclusions above, we note that an important assumption of the model is that upstream and downstream firms are locked into exclusive relations. This assumption can be justified by assuming that, prior to their network formation decisions, the two parties have undertaken relationship-specific investments (see Symeonidis, 2008). Such investments, which would prevent the two parties from breaking up, are a common feature of the Japanese automobile industry, where automakers often engage in high-commitment relationships with their suppliers.²⁶ In this context, both parties undertake large fixed investments, such as investments

²⁵In particular, Song and Vannetelbosch (2007) demonstrate that the stable R&D networks – a complete and a partial network – generate a lower aggregate level of effective R&D than the empty network. In the present setting, we also confirm that the empty network at both market tiers outperforms the corresponding complete networks in terms of aggregate effective R&D.

²⁶As Helper and Levine (1992) note, U.S. automakers have also moved progressively towards long-term rela-

on flexible automation, information flow mechanisms and quality control training (Helper and Levine, 1992).

On the other hand, as Narula and Dysters (2004, p. 207) point out, “firms seek partnerships in response to similar moves made by other firms in the same industry, not always because there are sound economic rationale in doing so, but in imitation of their competitors”.²⁷ In turn, this could be a reason behind a potential failure of R&D alliances, as some partners might appear dishonest by terminating an agreement after they have appropriated important technologies (Narula and Hagedoorn, 1999).²⁸ In that sense, relationships between downstream firms and their upstream suppliers might be longer term than horizontal R&D collaborations and, as such, they tend to increase switching costs and create “lock-in”. Indeed, Helper and Levine (1992, p. 563) point out that in the context of the Japanese automobile industry: “As long as the supplier continues to meet the automaker’s expectations, the supplier can count on the relationship continuing indefinitely.”

We next turn to discuss whether the downstream firms and their upstream suppliers have incentives for vertical integration in the present setting. To understand this, we note that vertical integration creates an efficiency effect. That is, it eliminates the double marginalization problem and thereby transforms the vertically integrated unit into a more aggressive competitor in the retail market. Similarly, investments in cost reducing R&D and/or R&D collaboration imply an efficiency-enhancing effect, which also tends to expand the output base of the collaborating firms. Notice the presence of complementarities between greater output and lower costs: more output makes the benefit from lower costs more pronounced, and lower costs make output increases more valuable.²⁹ Therefore, due to a larger output base, lower marginal cost firms (as a result of R&D collaboration) will find it more profitable to vertically integrate compared to their non-collaborating counterparts. We conclude that horizontal R&D networks are likely to strengthen firms’ incentives for vertical integration.³⁰

tionships with their suppliers, thereby enhancing their overall efficiency.

²⁷This statement reflects the so-called follow-my-leader strategy, an idea originating in Knickerbocker (1973).

²⁸Narula and Hagedoorn (1999), Podolny and Page (1998), among others, point out that failing R&D alliances are a common empirical phenomenon. It has been further documented that R&D alliances may not meet the partners’ expectations.

²⁹Buehler and Schmutzler (2008) examine the incentives for vertical integration in the presence of endogenous cost-reducing investments by downstream firms. In a model where vertical integration entails a fixed cost, the authors show that the incentives for integration are ambiguous and depend on the market size and the efficiency of the R&D technology.

³⁰Vertical integration of collaborating firms may also work towards expanding their market dominance over their non-collaborating counterparts. Such a situation of market dominance seems to be prevalent in this setting particularly when, under certain conditions, downstream firms and their upstream suppliers opt for establishing

6 Conclusion

Over the last thirty years, we witnessed a substantial increase in the number of R&D collaborations through networks. Such networks are often observed in vertically related industries. In that context, both downstream firms and their upstream suppliers form horizontal collaborative links to pool R&D results with other firms. However, the existing literature has mainly focused on R&D networks in the context of a one-tier industry, where firms compete in the product market. In the present article we develop the literature by studying the endogenous formation of horizontal R&D networks at the upstream and downstream market tier of a vertically related industry. Because the upstream R&D network may have an impact on the stability of the downstream network (and vice versa), we have considered the situation in which R&D networks are determined at both market tiers simultaneously.

Our analysis suggests that economic factors, such as within-network R&D spillovers, may be the driving forces behind the equilibrium network formations. We have found that, under certain conditions, downstream firms and their corresponding upstream suppliers may either form partial or complete R&D networks. Moreover, we have identified the circumstances in which the equilibrium upstream R&D network is likely to be different from the downstream network. That is, a partial upstream network might coexist with a complete downstream network as long as R&D spillovers within the upstream network are sufficiently large; while spillovers within the downstream network are intermediate.

We have also examined the implications of the stable networks formations for aggregate effective R&D, industry profits and social welfare. Our analysis suggests that, in the pursuit of their private interests, the downstream firms and their upstream suppliers cannot collectively achieve a profit-maximizing outcome. In spite of this negative effect, we have found that, under certain conditions, both an effective R&D-maximizing and a welfare-maximizing outcome can be attained but only under the partial upstream and the complete downstream R&D network.

The potential divergence between private and collective interests for R&D collaboration implies that there is room for public policy. As a general policy prescription, our analysis suggests that the *structure* of the upstream and the downstream network might be as important for designing public policy as the *extent* of within-network R&D spillovers. Further developments in this area could consider more general demand and cost structures, informational asymmetries

partial R&D networks (that exclude both an upstream and a downstream firm).

and alternative forms of wholesale and retail competition. These extensions which are beyond the scope of the present paper are promising avenues for future research.

7 Appendix

Proof of proposition 1. Because strong stability is a refinement of pairwise stability, from lemma 1, there are three candidates for strongly stable industry structures: (i) (g_u^c, g_d^c) for all parameter configurations; (ii) $(g_u^p(ij), g_d^p(ij))$ if β is sufficiently large and θ is sufficiently low; and (iii) (g_u^p, g_d^c) if β is sufficiently large and θ is intermediate. We consider first (g_u^c, g_d^c) and focus on g_u^c , given g_d^c . There are two possible deviations from g_u^c . More specifically, the three upstream firms will not jointly deviate to the empty network, because $\pi_U(g_u^c, g_d^c) > \pi_U(g_u^e, g_d^c)$. A coalitional deviation to the partial network, where two of the upstream firms in the complete network sever their links with the third firm, can be ruled out as long as $\pi_U(g_u^c, g_d^c) > \pi_U(g_u^p, g_d^c)$ – that is, as long as β is sufficiently small. To show this, we calculate $\Delta\pi_1 \equiv \pi_U(g_u^c, g_d^c) - \pi_U^l(g_u^p, g_d^c)$. Let curve C_4 in Figure 3 be the set of (β, θ) values that solve the equation $\pi_U(g_u^c, g_d^c) = \pi_U^l(g_u^p, g_d^c)$. We note that $\lim_{\beta \rightarrow 0+} \Delta\pi_1 > 0$ for all $\theta \in (0, 1]$; and $\lim_{\beta \rightarrow 1-} \Delta\pi_1 < 0$ for all $\theta \in (0, 1]$. Therefore, there exist critical values of β , such that $\pi_U(g_u^c, g_d^c) - \pi_U^l(g_u^p, g_d^c) > 0$ if β is sufficiently small (i.e. in the region to the left of curve C_4 in Figure 3); while $\pi_U(g_u^c, g_d^c) - \pi_U^l(g_u^p, g_d^c) < 0$ if β is sufficiently large.

Further, we note that, given a complete network at the upstream market tier (g_u^c) , there will be no coalitional deviation by the downstream firms to either the partial network (because $\pi_D(g_u^c, g_d^c) > \pi_D^l(g_u^c, g_d^p)$) or the empty network (because $\pi_D(g_u^c, g_d^c) > \pi_D(g_u^c, g_d^e)$). Given this, a profile of R&D networks (i.e. industry structure) emerges endogenously if and only if the R&D network at one market tier is a best response to the R&D network at the other market tier. Thus, (g_u^c, g_d^c) will be a strongly stable industry structure provided that β is sufficiently small (i.e. in the region to the left of curve C_4 in Figure 3).

Next, we consider $(g_u^p(ij), g_d^p(ij))$. In this case, it is easy to show that, given a partial R&D network at a market tier, the linked firms in the partial network at the other market tier will not jointly deviate to the complete network, because $\pi_U^l(g_u^p, g_d^p) > \pi_U(g_u^c, g_d^p)$ and $\pi_D^l(g_u^p, g_d^p) > \pi_D(g_u^p, g_d^c)$, respectively.

Finally, we show that (g_u^p, g_d^c) is strongly stable if β is sufficiently large and θ is intermediate.

We first note that, given the R&D network at the downstream market tier (i.e. g_d^c), the upstream firms will not jointly deviate from the partial network to the complete network, because $\pi_U^l(g_u^p, g_d^c) > \pi_U(g_u^c, g_d^c)$. However, given the upstream R&D network (i.e. g_u^p), the downstream firms will force a deviation from the complete to the partial network if spillovers θ are sufficiently large or small. To see this, we calculate $\Delta\pi_2 \equiv \pi_D(g_u^p, g_d^c) - \pi_D^l(g_u^p, g_d^p)$. Let curves C_5 and C_6 in Figure 3 be the set of (β, θ) values that solve the equation $\pi_D(g_u^p, g_d^c) = \pi_D^l(g_u^p, g_d^p)$. We note that $\lim_{\theta \rightarrow 0+} \Delta\pi_2 < 0$ for all $\beta \in (0, 1]$; $\lim_{\theta \rightarrow 1-} \Delta\pi_2 < 0$ for all $\beta \in (0.05, 1]$; and $\lim_{\theta \rightarrow 0.5} \Delta\pi_2 > 0$ for all $\beta \in (0, 1]$; see Figure 3. Therefore, there exist critical values of θ , such that $\pi_D(g_u^p, g_d^c) - \pi_D^l(g_u^p, g_d^p) < 0$ if θ is sufficiently small or large; and $\pi_D(g_u^p, g_d^c) - \pi_D^l(g_u^p, g_d^p) > 0$, otherwise (i.e. in the region between the curves C_5 and C_6 in Figure 3).

From lemma 1, we know that (g_u^p, g_d^c) is pairwise stable if β is sufficiently large. Given this, a profile of R&D networks (i.e. industry structure) emerges endogenously if and only if the R&D network at one market tier is a best response to the R&D network at the other market tier. It follows immediately that (g_u^p, g_d^c) will be a strongly stable industry structure provided that β is sufficiently large and θ is intermediate (i.e. in the region to the right of curve C_3 and between curves C_5 and C_6). Q.E.D.

Proof of proposition 2. We consider the region of (β, θ) values where the industry structures (g_u^c, g_d^c) , $(g_u^p(ij), g_d^p(ij))$ and (g_u^p, g_d^c) are strongly stable. From Figure 3 note that the coordinates identifying the area where (g_u^c, g_d^c) is strongly stable are $(0, 0)$, $(0.27, 0)$, $(0.31, 1)$ and $(0, 1)$; while the relevant coordinates for the industry structures (g_u^p, g_d^c) and $(g_u^p(ij), g_d^p(ij))$ are, respectively, $(0.89, 0.31)$, $(1, 0.32)$, $(1, 0.69)$, $(0.91, 0.69)$, and $(0.97, 0)$, $(1, 0)$, $(1, 0.18)$, $(0.96, 0.18)$.

(i) The result follows by comparing $X(g_u^p, g_d^c)$ against the level of aggregate effective R&D in all other industry structures. (ii) Consider the industry structure (g_u^c, g_d^c) . The result can be established by comparing $X(g_u^c, g_d^c)$ with the aggregate level of effective R&D in an industry structure characterized by a smaller number of links, (g_u^e, g_d^e) , say. Let $\Delta X \equiv X(g_u^c, g_d^c) - X(g_u^e, g_d^e)$. We note that $\Delta X > 0$ when $\beta \rightarrow 0$ and $\theta \rightarrow 0$; $\Delta X > 0$ when $\beta \rightarrow 0.27$ and $\theta \rightarrow 0$; $\Delta X > 0$ when $\beta \rightarrow 0.31$ and $\theta \rightarrow 1$; and $\Delta X < 0$ when $\beta \rightarrow 0$ and $\theta = 1$. Thus, there exist critical values of β and θ , such that $X(g_u^c, g_d^c) < X(g_u^e, g_d^e)$ if β is sufficiently small and θ is not too small; while $X(g_u^c, g_d^c) > X(g_u^e, g_d^e)$, otherwise. Next, we consider the industry structure (g_u^p, g_d^p) . Again, to establish the result it suffices to compare $X(g_u^p, g_d^p)$ with the level of aggregate effective R&D in an industry structure characterized by fewer links, (g_u^p, g_d^e) , say.

This implies that $X(g_u^p, g_d^e) > X(g_u^p, g_d^p)$, which holds for all configurations of the parameters. Q.E.D.

Proof of proposition 3. To prove the result, it suffices to show that, for each industry structure that emerges as strongly stable, there is (at least) one industry structure that leads to higher industry profits (i.e. the sum of the upstream and downstream firms' profits). To this end, we note that $\sum_{i=1}^3[(\pi_{U_i} + \pi_{D_i})(g_u^c, g_d^c)] < \sum_{i=1}^3[(\pi_{U_i} + \pi_{D_i})(g_u^s, g_d^c)]$ for all β and θ (within the range of values that (g_u^c, g_d^c) emerges as strongly stable); $\sum_{i=1}^3[(\pi_{U_i} + \pi_{D_i})(g_u^p, g_d^p)] < \sum_{i=1}^3[(\pi_{U_i} + \pi_{D_i})(g_u^s, g_d^c)]$ for all β and θ (in the region where (g_u^p, g_d^p) is strongly stable); and $\sum_{i=1}^3[(\pi_{U_i} + \pi_{D_i})(g_u^p, g_d^c)] < \sum_{i=1}^3[(\pi_{U_i} + \pi_{D_i})(g_u^s, g_d^c)]$ for all β and θ (in the region where (g_u^p, g_d^c) is strongly stable). Q.E.D.

Proof of proposition 4. (i) The industry structure (g_u^p, g_d^c) emerges as strongly stable when β is sufficiently large and θ is intermediate (note that the four coordinates indentifying this region are $(0.89, 0.31)$, $(1, 0.32)$, $(1, 0.69)$ and $(0.91, 0.69)$). Within this region of β and θ values, the result follows directly from comparing social welfare under (g_u^p, g_d^c) against the social welfare levels under the other possible industry structures. It is fairly easy to show that (g_u^p, g_d^c) dominates every other industry structure in terms of social welfare for all β and θ , except for the industry structure (g_u^s, g_d^c) . To this end, we calculate the difference $\Delta W \equiv W(g_u^p, g_d^c) - W(g_u^s, g_d^c)$. We note that $\Delta W < 0$ when $\beta \rightarrow 0.89$ and $\theta \rightarrow 0.31$; $\Delta W < 0$ when $\beta \rightarrow 0.91$ and $\theta \rightarrow 0.69$; $\Delta W > 0$ when $\beta \rightarrow 1$ and $\theta \rightarrow 0.32$; and $\Delta W > 0$ when $\beta \rightarrow 1$ and $\theta \rightarrow 0.69$. Thus, there exist critical values of β , such that $W(g_u^p, g_d^c) - W(g_u^s, g_d^c) < 0$ if β is sufficiently small; while $W(g_u^p, g_d^c) - W(g_u^s, g_d^c) > 0$ if β is sufficiently large.

(ii) To establish the result, it suffices to show that, for each of the industry structures (g_u^c, g_d^c) and (g_u^p, g_d^p) , there is (at least) one of the other possible industry structures in this setting that secures higher social welfare. That is, $W(g_u^c, g_d^c) < W(g_u^s, g_d^c)$ for all β and θ (in the region where (g_u^c, g_d^c) emerges as strongly stable); and $W(g_u^p, g_d^p) < W(g_u^s, g_d^c)$ for all β and θ (in the region where (g_u^p, g_d^p) emerges as strongly stable). Q.E.D.

References

- [1] d' Aspremont, C. and Jacquemin, A. (1988) "Cooperative and Noncooperative R&D in Duopoly with Spillovers," *American Economic Review*, 78, 1133- 37.

- [2] Atallah, G. (2002) “Vertical R&D spillovers, cooperation, market structure, and innovation,” *Economics of Innovation and New Technology*, 11, 179-209.
- [3] Belderbos, R., Carree, M., Diederer, B., Lokshin, B. and Veugelers, R. (2004) “Heterogeneity in R&D cooperation strategies,” *International Journal of Industrial Organization*, 22, 1237-1263.
- [4] Buehler, S. and Schmutzler, A. (2008) “Intimidating competitors – Endogenous vertical integration and downstream investment in successive oligopoly,” *International Journal of Industrial Organization*, 26, 247-265.
- [5] Cassiman, B. and Veugelers, R. (2002) “R&D cooperation and spillovers: some empirical evidence from Belgium,” *American Economic Review* 92, 1169-1184.
- [6] Cloudt, M., Hagedoorn, J. and Roijakkers, N. (2006) “Trends and patterns in inter-firm R&D networks in the global computer industry: a historical analysis of major developments during the period 1970-1999,” *Business History Review*, 80, 725-746.
- [7] Deroian, F. and Gannon, F. (2006) “Quality-improving alliances in differentiated oligopoly,” *International Journal of Industrial Organization*, 24(3), 629-637.
- [8] Dunning, J. (1995) “Reappraising the eclectic paradigm in the age of alliance capitalism,” *Journal of International Business Studies*, 26, 461-491.
- [9] Goyal, S. and Joshi, S. (2003) “Networks of Collaboration in Oligopoly”, *Games and Economic Behavior*, 43, 57-85.
- [10] Goyal, S. and Moraga-González, J.L. (2001) “R&D Networks,” *The RAND Journal of Economics*, 32(4), 686-707.
- [11] Hagedoorn, J. (2002) “Inter-firm R&D Partnerships: An Overview of Major Trends and Patterns since 1960,” *Research Policy*, 31, 477-492.
- [12] Helper, S. and Levine, D. (1992) “Long-Term Supplier Relations and Product-Market Structure,” *Journal of Law, Economics, & Organization*, 8, 561-581.
- [13] Jackson, M.O. and van den Nouweland, A. (2005) “Strongly Stable Networks,” *Games and Economic Behavior*, 51(2), 420-444.

- [14] Jackson, M.O. and Wolinsky, A. (1996) "A Strategic Model of Social and Economic Networks," *Journal of Economic Theory*, 71, 44-74.
- [15] Kaiser, U. (2002) "An empirical test of models explaining research expenditures and research cooperation: evidence for the German service sector," *International Journal of Industrial Organization*, 20, 747-774.
- [16] Kamien, M.I., Muller, E., and Zang, I. (1992) "Research Joint Ventures and R&D Cartels," *American Economic Review*, 85, 1293-1306.
- [17] Knickerbocker, F. (1973) "Oligopolistic Reaction and the Multinational Enterprise," Harvard University Press, Cambridge, MA.
- [18] Leiponen, A. (2001) "Why do firms not collaborate? The role of competencies and technological regimes," In: Kleinknecht, A., Mohnen, P. (Eds.), *Innovation and Firm Performance: Econometric Exploration of Survey Data*. Palgrave, pp. 253- 277.
- [19] Mauleon, A., Sempere-Monerris, J.J., and Vannetelbosch, V. (2008) "Networks of Knowledge among Unionized Firms," *Canadian Journal of Economics*, 41, 971-997.
- [20] Narula, R. and Duysters, G. (2004) "Globalisation and trends in international R&D alliances," *Journal of International Management*, 10, 199-218.
- [21] Narula, R. and Hagedoorn, J. (1999) "Innovating through strategic alliances: moving towards international partnerships and contractual agreements," *Technovation*, 19, 283-294.
- [22] Palmberg, C. and Martikainen, O. "The Economics of Strategic R&D Alliances – A Review with Focus on the ICT Sector." 21.11.2003.
- [23] Podolny, J.M. and Page, K.P. (1998) "Network Forms of Organization," *Annual Review of Sociology*, 24, 57-76.
- [24] Powell, W.W., Koput, K.W., and Smith-Doerr, L. (1996) "Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology," *Administrative Science Quarterly*, 41, 116-145.
- [25] Song, H. and Vannetelbosch, V. (2007) "International R&D Collaboration Networks," *The Manchester School*, 75(6), 742-766.

- [26] Suzumura, K. (1992) “Cooperative and noncooperative R&D in an oligopoly with spillovers,” *American Economic Review*, 82, 1307-1320.
- [27] Symeonidis, G. (2008) “Downstream competition, bargaining and welfare,” *Journal of Economics and Management Strategy*, 17, 247-270.
- [28] Veugelers, R. (1997) “Internal R&D expenditures and external technology sourcing,” *Research Policy*, 26, 303-315.
- [29] Westbrook, B. (2010) “Natural concentration in industrial research collaboration,” *The RAND Journal of Economics*, 41, 351-371.
- [30] Wolfram, S. (1999) “The Mathematica Book”, 4th ed. Cambridge University Press, Wolfram Media.
- [31] Zikos, V. (2010) “R&D Collaboration Networks in Mixed Oligopoly,” *Southern Economic Journal*, 77, 189-212.
- [32] Zirulia, L. (2011) “The role of spillovers in R&D network formation,” *Economics of Innovation and New Technology*, forthcoming.
- [33] Zu, L., Dong, B., Zhao, X. and Zhang, J. (2011) “International R&D Networks,” *Review of International Economics*, 19, 325-340.