# COOPERATIVE R&D WITH DIFFERENTIATED PRODUCTS IN VERTICALLY RELATED INDUSTRIES

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## Abstract

*This paper studies the impact of cooperative R&D on innovation, welfare, and profitability in vertically related industries with differentiated products. The model incorporates two vertically related industries, with horizontal spillovers within industries and vertical spillovers between them. Upstream firms produce a homogeneous intermediate good, while downstream firms provide differentiated products. Three types of R&D cooperation are studied: no cooperation, horizontal cooperation, and vertical cooperation. The comparison of cooperation settings in terms of R&D and profitability shows that although vertical cooperation yields higher innovation and welfare, it may lead to over–investment in R&D.*


**Keywords:** vertical spillovers, horizontal spillovers, product differentiation, R&D cooperation

**JEL:** L13, O32

## 1. Introduction

The importance of industry clustering for innovation and the economic performance of industrialized countries due to access to knowledge spillovers has been largely stressed recently by the theoretical and empirical literature (Gilbert et al. 2008). Although the theoretical literature concludes that potential gains to cooperation are higher than no cooperation when horizontal spillovers are sufficiently high, the empirical literature points to the importance of vertical technological flows.

The results of both the theoretical and empirical studies show that the effect of product substitutability on firms' strategies of output and R&D has not been explored. This paper extends Atallah's (2002) and Ishi's (2006) analysis by considering differentiated products, whereas all previous studies deal with homogeneous goods in both industries. Although previous analyses studied the ranking of cooperation settings in terms of R&D, there is no literature about the ranking of settings in terms of profitability. This paper makes several contributions to the literature. First, it investigates the impact of product differentiation and R&D cooperation on innovation and welfare in vertically related industries with vertical and horizontal spillovers. Second, the paper studies the impact of cooperative settings, spillovers, and product differentiation on firms' behavior. Lastly, the paper studies the ranking of cooperation settings in terms of R&D and profitability, which is important for policy making. The results from this paper indicate the potential role of R&D policy in stimulating R&D investment.

The model incorporates two vertically related duopolistic industries with horizontal spillovers (within industries) and vertical spillovers (between industries) in a three–stage game–theoretic framework. The upstream industry provides a homogeneous intermediate good, whereas the downstream industry produces differentiated products. Firms invest in cost-reducing R&D under different cooperative structures and then compete in output. Three different types of cooperation are considered: no cooperation, horizontal cooperation, and vertical cooperation.

The main findings of the paper are summarized as follows. Vertical spillovers positively affect R&D directly due to their cost-reducing effect and indirectly due to their effect on horizontal spillovers and cooperative structures. Horizontal spillovers may increase or decrease R&D. Comparing cooperative structures in terms of R&D shows the superiority of vertical cooperation. Horizontal and vertical cooperation yield the same R&D level if and only if horizontal spillovers are perfect. Comparing cooperative

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structures in terms of profitability shows that no setting dominates the others. Retailers and suppliers may have different types of cooperation preferences. The ranking of cooperation settings depends on the sign and magnitudes of horizontal competitive externalities, vertical competitive externalities, and product differentiation. Product differentiation influences firms' behavior and affects the ranking of cooperative structures in terms of profitability.

Upstream industry requires developing and producing intermediate goods to meet the requirement of downstream firms. Bilateral exchange of information on new technology and materials helps R&D participating partners to adopt them quickly. Inter–industry (vertical) spillovers are usually desirable and voluntary, whereas intra–industry (horizontal) spillovers are often undesirable and involuntary (Atallah, 2002). According to d'Aspremont and Jacquemin (1988), Kamien et al. (1992), Suzumura (1992), and Yi (1996), if horizontal spillovers are sufficiently high, a horizontal R&D cartel yields higher technological improvement and welfare, whereas vertical R&D cartels yield higher welfare if horizontal spillovers between upstream firms are low.

Becker and Peters (1996) study the effect of R&D competition between two vertically related cooperation networks. They find that vertical spillovers not only stimulate the R&D process and competition between suppliers but also reduce the time of development and increase the probability for retailers to be the first to introduce the new product to the market.

Adams and Mircea (2004) show that research joint ventures increase innovation. Röller et al. (1997) analyze the determinants of research joint ventures formation and find that cost–sharing and technological similarities affect firms' R&D cooperation strategies. Atallah (2002) and Ishii (2004) study cooperative R&D between vertically related industries where both industries provide a homogeneous good. Atallah considers four possibilities for firms: to cooperate horizontally, vertically, both horizontally/vertically, or not to cooperate at all. He finds that no setting uniformly dominates other settings in terms of R&D, yet combined horizontal/vertical cooperation yields the highest R&D and welfare when spillovers are high. Ishii compares vertical R&D cartels, horizontal R&D cartels, vertical research joint ventures, and non–cooperative R&D. He shows that vertical research joint ventures yield the highest technological improvement. Although they considered a homogeneous product for both industries, in the real world a large variety of differentiated products are produced using a homogeneous intermediate good.

The importance of spillovers for research success is stressed by most of the analyses. Indeed, the effects of innovation complementarities, absorptive capacities, and technical similarities reinforce the efficiency of spillovers. Clark et al. (1987) study the impact of vertical spillovers on product development performance in the auto industry. They find that saving time and engineering hours are one of the most important effects of vertical cooperation on product development.

Harabi (2010) finds that the informal leakage of technological knowledge affects innovation through vertical R&D cooperation in German manufacturing. The study also highlights the importance of other key determinants of innovative activities, such as technological opportunities, appropriability conditions, and market demand. Cassiman and Veugelers (1999) and Veugelers and Cassiman (1999) study the Belgian manufacturing industry and find that firms develop R&D strategies to maximize their benefit from technological information flows.

The majority of authors who studied R&D cooperation find a positive impact of cooperative R&D on innovation (e.g., Brouwer & Kleinknecht 1999). Powell and Grodal (2005) provide an extensive analysis showing that cooperative R&D has a positive effect on innovation. Darby et al. (2003) find a positive effect of R&D cooperation on patenting by U.S. firms. Kremp and Mairesse (2004) show that cooperative R&D increases innovation by French firms. Lokshin *et al.* (2008) state that R&D cooperation of German firms, and cooperating with different types of partners have a positive effect on innovation.

Aschhoff and Schmidt (2008) find that in Germany, cooperation with competitors is profitable in terms of cost reduction. Lööf and Heshmati (2002) find that in Sweden, cooperation with competitors positively affects innovation output, while cooperation with suppliers restricts it. Winters and Stam (2007) show that R&D cooperation has a positive relationship with product and process innovation of high technology SMEs. The paper is organized as follows. Section 2 sets up and solves the model. The effects of spillovers and product differentiation on R&D and welfare are studied in Section 3. Section 4 compares cooperation settings in terms of R&D and profitability. Section 5 discusses some policy related issues and conclusions.

## 2. The model

There are two identical suppliers $(s_1, s_2)$ providing a homogeneous input, and two symmetric retailers $(r_1, r_2)$ transforming the input into the final product using a fixed coefficient technology and competing a la Cournot. The final good is differentiated. A representative consumer consumes both goods, $r_1$ and $r_2$. Undertaking no R&D, suppliers acquire a constant unit production cost of $s$ and sell the input to retailers at a unit price of $t$, the wholesale price. Retailers incur an additional internal production cost of $r$. Lastly, retailers sell the product to consumers at a price $p$. The consumer buys quantities $y_{r1}$ and $y_{r2}$ and maximizes its utility function subject to the budget constraint $(M = p_1 y_{r1} + p_2 y_{r2} + y_0)$ where $y_0$ is the numeraire and $M$ is income. The consumer's utility function is given by

$$U = a(y_{r1} + y_{r2}) - \frac{(y_{r1}^2 + y_{r2}^2)}{2} - b y_{r1} y_{r2} + y_0,$$

where $y_{ri}$ denotes retailer $i$'s output and $b \in [0,1]$ is a parameter of product substitutability (negatively related to product differentiation). Final goods are homogeneous if $b = 1$, imperfect substitutes if $0 < b < 1$ and independent when $b = 0$. Maximizing utility over $y_{r1}$ and $y_{r2}$ yields the retailers' demand functions:

$$p_i(y_{ri}, y_{rj}) = a - y_{ri} - b\, y_{rj} \qquad i=1,2$$

Firms can undertake cost-reducing R&D activities. The dollar cost of $x$ units of R&D for firm $i$ is $ux_i^2$, where $x_i$ represents the R&D output of firm $i$, and $u > 0$ is a cost parameter. Assume that $u$ is sufficiently high for the profit function to be strictly concave, and sufficiently low for firms to undertake strictly positive amounts of R&D. The total R&D is denoted by $X$:

$$X = x_{r1} + x_{r2} + x_{s1} + x_{s2}$$

Each unit of R&D conducted by a firm reduces its cost by one dollar, the cost of its competitor by $h$ dollars (horizontal spillovers), and the cost of each firm in the other industry by $v$ dollars (vertical spillovers), with $h, v \in [0,1]$. $h$ and $v$ can be different for many reasons such as different absorptive capacities, different technologies, different efficiency of communication channels, *etc*. The unit cost of downstream firm $i$ is:

$$c_{ri} = t + r - x_{ri} - h x_{rj} - v(x_{s1} + x_{s2}), \; i=1,2$$

The unit cost of upstream firm $i$ is:

$$c_{si} = s - x_{si} - h x_{sj} - v(x_{r1} + x_{r2}), \; i=1,2$$

The final cost of each firm depends on the R&D choices of all firms. Suppliers and retailers mutually benefit from R&D activities of one another through vertical spillovers, while competitors benefit from R&D investments of each other through horizontal spillovers. Higher R&D leads to lower cost and consequently higher output. Moreover, higher output increases the value of R&D to a firm since more units of output benefit from the cost reduction effects.

To ensure that unit costs are non-negative, parameters are assumed to be such that

$$r > x_{r1} + h x_{r2} + v(x_{s1} + x_{s2})$$

$$s > x_{s1} + h x_{s2} + v(x_{r1} + x_{r2})$$

The game has three stages. In the first stage, all firms choose their R&D simultaneously. In the second stage, upstream firms choose output competing a la Cournot, anticipating the derived demand curve of the downstream industry. In the third stage, downstream firms choose output competing a la Cournot, taking the wholesale price as given.

*2.1. Downstream output stage*

In the third stage retailers choose output to maximize profits non–cooperatively. Retailer $i$'s problem is:

$$max_{y_{ri}} \pi_{ri} = (p_i(y_{ri}, y_{rj}) - c_{ri}) y_{ri} - u x_{ri}^2, \quad i=1,2 \qquad (1)$$

Given that retailers are symmetric, they have symmetrical behavior. Maximizing and solving the first-order conditions (f.o.c.) simultaneously yields:

$$y_{ri} = \frac{(2-b)[(a-r-t)+v(x_{s1}+x_{s2})]+(2-bh)x_{ri}-(b-2h)x_{rj}}{(4-b^2)}, i = 1,2 \qquad (2)$$

$$p_i = \frac{(2-b)\left[a+(1+b)\left(r+t-v(x_{s1}+x_{s2})\right)\right]-\left[(2-b^2-bh)x_{ri}+(b+2h-b^2h)x_{rj}\right]}{(4-b^2)}, i = 1,2$$

The total output is the sum of downstream firms' output, $Y = y_{r1} + y_{r2}$. From (2), the inverse demand curve of suppliers is derived as:

*2.3. R&D stage*

In the first stage, all firms choose R&D investments simultaneously. To capture the variety of cooperative structures, three scenarios are considered.

The first scenario is non–cooperative R&D (*NC*), so that each firm chooses its R&D to maximize its own profit.

$$t(y_{si}, y_{sj}) = \frac{(1+h)(x_{r1}+x_{r2}) - (2+b)(y_{si}+y_{sj}) + 2[(a-r)+v(x_{si}+x_{sj})]}{2}, i = 1,2 \qquad (3)$$

*2.2. Upstream output stage*

In the second stage, each supplier $i$ non–cooperatively chooses its own output, $y_{si}$, to maximize its profit considering the derived inverse demand of retailers, Eq.(3).

Thus, supplier $i$ solves the following problem:

$$max_{y_{si}}\ \pi_{si} = (t(y_{si}, y_{sj}) - c_{si})y_{si} - ux_{si}^2,\ i=1,2 \qquad (4)$$

Since suppliers are identical and produce a homogeneous intermediate good, they will hold identical positions ex–post. Maximizing and solving the f.o.c. yields:

$$y_{si} = \frac{2(a-r-s)+(1+h+2v)(x_{r1}+x_{r2})+2(2-h+v)x_{si}+2(2h+v-1)x_{sj})}{3(2+b)}, i = 1,2$$

Considering that each unit purchased from suppliers is transformed into one unit provided by retailers, the total output is the same for upstream and downstream industries.

Thus, the total output is:

The second scenario is horizontal cooperative R&D (*HC*), where each firm cooperates with its competitor. The third scenario is vertical cooperative R&D (*VC*), in which each supplier cooperates with one retailer.

Denote the R&D set of all firms as $\beta \equiv \{x_{r1}, x_{r2}, x_{s1}, x_{s2}\}$. The profit of a downstream firm can be rewritten as

$$\pi_{ri}(\beta) = [p_i(\beta) - c_{ri}(\beta)]y_{ri}(\beta) - ux_{ri}^2, \qquad i=1,2$$

and the profit of an upstream firm is

$$\pi_{si}(\beta) = [t(\beta) - c_{si}(\beta)]y_{si}(\beta) - ux_{si}^2, \qquad i=1,2$$

Therefore, welfare is also a function of R&D since

$$W(\beta) = \left(\pi_{r1}(\beta) + \pi_{r2}(\beta) + \pi_{s1}(\beta) + \pi_{s2}(\beta)\right) + CS.$$ [1]

In the first stage, under *NC* each firm chooses its R&D to maximize its own profit. Each retailer solves the following problem:

$$max_{x_{ri}}\ \pi_{ri}(\beta) \qquad i=1,2 \qquad (5)$$

Each supplier faces the following problem:

$$max_{x_{si}}\ \pi_{si}(\beta) \qquad i=1,2 \qquad (6)$$

$$Y = \frac{2[2a - 2r - 2s + (1+h+2v)(x_{r1}+x_{r2}) + (1+h+2v)(x_{s1}+x_{s2})]}{3(2+b)}$$

and the final price is:

$$p = \frac{a(4+b) + 2(1+b)(r+s) - (1+b)(1+h+2v)(x_{r1}+x_{r2}) - (1+b)(1+h+2v)(x_{s1}+x_{s2})}{3(2+b)}$$

The wholesale price charged by suppliers is:

$$t = \frac{2(a-r+2s)+(1+h-4v)(x_{r1}+x_{r2})-2(1+h-v)(x_{s1}+x_{s2})}{6}$$

Maximizing and simultaneously solving these four f.o.c., we obtain R&D under *NC*:

$$x_{ri}^{NC} = \frac{(a-r-s)[2(5-h+4v)-b(5h+4v-1)]}{(72u-26-2h(8-5h)-9b^3u-68v+4hv-32v^2+b[(h(4+5h)-1)+36u+2v+14hv+8v^2]-2b^2[h^2+9u+h(v-1)-(2+5v+2v^2)]}, i = 1,2$$

$$x_{si}^{NC} = \frac{2(4-b^2)(a-r-s)(2-h+v)}{(72u-26-2h(8-5h)-9b^3u-68v+4hv-32v^2+b[(h(4+5h)-1)+36u+2v+14hv+8v^2]-2b^2[h^2+9u+h(v-1)-(2+5v+2v^2)]}, i = 1,2$$

Under *HC*, competitors choose R&D to maximize joint profits. Thus, in the downstream industry retailers solve

$$max_{x_{r1},x_{r2}} \ (\pi_{r1}(\beta) + \pi_{r2}(\beta)) \qquad (7)$$

and in the upstream industry suppliers solve

$$max_{x_{s1},x_{s2}} \ (\pi_{s1}(\beta) + \pi_{s2}(\beta)) \qquad (8)$$

Maximizing and simultaneously solving these four f.o.c., we obtain R&D under *HC*:

$$x_{ri}^{HC} = \frac{4(a-r-s)(1+h+2v)}{(9b^2u-8(h+2v)^2-4(2+4h-9u+8v)-2b\left(h^2-18u+(1+2v)^2+2h(1+2v)\right))}, i = 1,2$$

$$x_{si}^{HC} = \frac{2(a-r-s)(1+h+2v)(2+b)}{(9b^2u-8(h+2v)^2-4(2+4h-9u+8v)-2b\left(h^2-18u+(1+2v)^2+2h(1+2v)\right))}, i = 1,2$$

Under *VC*, each retailer cooperates with one supplier. Given that suppliers are identical and produce a homogeneous intermediate good, it is immaterial which retailer cooperates with which supplier. Without loss of generality, let $r_i$ cooperate with $s_i$ ($i$=1,2).

$$max_{x_{ri},x_{si}} \ (\pi_{ri}(\beta) + \pi_{si}(\beta)), i=1,2 \qquad (9)$$

Following the maximization of Eq. (9), we obtain R&D under *VC*:

$$x_{ri}^{VC} = \frac{(a-r-s)[14+b-b^2+h(2-5b-b^2)+2v(8-2b-b^2)]}{72u-34-32h-9b^3u-100v+2(h-16v)(h+2v)+b^2[5+4h-h^2-18u+2v(7+h)+8v^2]+b[1+h(8+7h)+36u+10v+22hv+16v^2]} \ i = 1,2$$

$$x_{si}^{VC} = \frac{(a-r-s)(4-2b)[5+2b-h(1+b)+v(b+4)]}{72u-34-32h-9b^3u-100v+2(h-16v)(h+2v)+b^2[5+4h-h^2-18u+2v(7+h)+8v^2]+b[1+h(8+7h)+36u+10v+22hv+16v^2]} \ i = 1,2$$

Retailers benefit from higher $v$ due to its cost reduction effect and through access to a greater quantity of inputs.

$\partial c_{ri}(h,v,\beta(h,v))/\partial v < 0$, while $\partial \pi_{ri}/\partial c_{ri} < 0$ and $\partial \pi_{ri}/\partial y_{ri} > 0$ $i$=1,2
$\partial c_{si}(h,v,\beta(h,v))/\partial v < 0$, while $\partial \pi_{si}/\partial c_{si} < 0$ and $\partial \pi_{si}/\partial y_{si} > 0$ $i$=1,2

This encourages retailers to increase output and their demand for the intermediate good, which benefits suppliers as well.

Higher output increases the net benefit of R&D, inducing a further increase in R&D. Higher output is also associated with higher consumer surplus and welfare. Thus, an increase in vertical spillovers increases innovation, output, and welfare. These findings are consistent with those of Atallah (2002); however, he considered only homogeneous goods.

## 3. The impacts of spillovers and product differentiation on R&D and welfare

This section addresses the effects of vertical and horizontal spillovers on innovation, output, and welfare where cooperative structures are varied.[2]

**Proposition 1.**

*Vertical spillovers increase R&D by all firms, output, and welfare, independently of product substitutability.*

An increase in vertical spillovers reduces the production costs of all firms under any type of cooperation.

**Proposition 2.**

*The impact of vertical spillovers on firms' behavior depends on product substitutability and horizontal spillovers. An increase in vertical spillovers increases retailers' innovation less than suppliers' regardless of substitutability. Suppliers and retailers increase their innovation efforts equally under different cooperation settings in response to changes in horizontal spillovers and substitutability.*

Although higher $v$ increases R&D by all firms, when final goods are substitutes ($b > 0$), retailers increase R&D less than suppliers. However, firms in both industries tend to increase R&D equally when goods are independent.

As soon as products become imperfect substitutes $(b > 0)$, competition between retailers increases, which reduces $p$. Higher $b$ changes the position (the intercept and the slope through $x_{ri}$ and $x_{si}$) of retailers' demand curve. Thus, retailers reduce output, R&D, and their demand for the intermediate good.

Although higher product substitutability reduces the demand for the intermediate good, it increases the wholesale price $(\partial t(\beta(b))/\partial b > 0)$ which mitigates the negative effect of $b$ on suppliers' profit. This reflects the power of suppliers. Indeed, retailers suffer from an increase in $b$ more than suppliers. Finally, the sum of the positive effects of higher $v$ and the negative effects of $b$ on profits induces retailers to increase R&D less than suppliers.

Under *NC* and *VC*, firms are worried about the information leakage to their competitor. When products are independent, retailers may neglect $h$, whereas suppliers providing a homogeneous intermediate good are concerned about the flow of technological information to their competitor. In consequence, when $h$ is sufficiently high and goods are independent, an increase in $v$ induces retailers and suppliers to increase R&D equally.

Although under *HC* firms internalize $h$, an increase in $v$ induces suppliers and retailers to increase R&D equally when goods are independent. Suppliers increase R&D more than retailers when goods are substitutes since $b$ has a negative effect on retailers' net benefit of R&D.

(1) Under any type of cooperation, $\frac{\partial x_{ri}}{\partial v} < \frac{\partial x_{si}}{\partial v}$ if $0 < b \leq 1$.

(2) Under *NC* and *VC*, $\frac{\partial x_{ri}}{\partial v} = \frac{\partial x_{si}}{\partial v}$ if $b = 0$ and $h = 1$.

(3) Under *HC*, $\frac{\partial x_{ri}}{\partial v} = \frac{\partial x_{si}}{\partial v}$ if $b = 0$.

(4) Under *VC*, $\frac{\partial x_{ri}}{\partial v} = \frac{\partial x_{si}}{\partial v}$ if $b = 1$.

Moreover, under *VC* partners internalize $v$ which boosts the benefit of its cost reduction effects, inducing suppliers to increase R&D more than retailers when goods are independent or imperfect substitutes.

When both industries produce a homogeneous product, their marginal gain from R&D is equal, thus they increase R&D equally.

**Proposition 3.**

*(i) An increase in horizontal spillovers reduces R&D by all firms under NC, and increases R&D by all firms under HC, independent of substitutability. This increases retailers' R&D under VC if products are independent; however, it reduces retailers' R&D when products are substitutes and vertical spillovers are sufficiently low. Suppliers increase R&D if vertical spillovers are high and vice versa if vertical spillovers are sufficiently low, independent of substitutability.*

*(ii) An increase in horizontal spillovers increases welfare and output under HC and VC, independent of substitutability. This increases welfare and output under NC if products are independent, whereas it reduces them if products are substitutes.*

Under *NC*, an increase in $h$ lessens the R&D of all firms. Higher $h$ reduces the net benefit of R&D since it reduces the rival's cost. Thus, firms in both industries reduce R&D. The reduction in R&D increases firms' production costs and consequently affects their output and prices.

Additionally, higher $b$ boosts competition among retailers, reduces price and induces retailers to reduce output. Ultimately, the sum of these two effects determines output. Higher output is associated with higher consumer surplus and welfare.

Thus, consumer surplus and welfare are reduced when the sum of the effects of $h$ and $b$ on output is negative; otherwise, they are increased.

Table 1 summarizes the results of Proposition 3.

Table 1. *Summary of comparative statics (h)*

| | *No Cooperation* | *Horizontal Cooperation* | *Vertical Cooperation* |
|---|---|---|---|
| $\partial x_{ri}/\partial h$ | $-$ | $+$ | $+$ if $b = 0$<br>$\pm$ if $b > 0$ |
| $\partial x_{si}/\partial h$ | $-$ | $+$ | $\pm$ |
| $\partial X/\partial h$ | $-$ | $+$ | $\pm$ |
| $\partial Y/\partial h$ | $\pm$ | $+$ | $+$ |
| $\partial W/\partial h$ | $\pm$ | $+$ | $+$ |

Source: Authors' research

Under *HC*, competitors choose R&D to maximize joint profits. Thus, intra–industry firms, internalizing *h*, may not worry about the information leakage to the rival, as they benefit from higher *h* and increase R&D. Higher R&D is associated with lower production cost which induces firms to increase output, boosting consumer surplus and welfare.

Under *VC*, higher *h* reduces the rival's production cost, reducing the net benefit of R&D to the firm. From the perspective of retailers, when goods are independent, the information leakage is negligible. Thus, retailers increase R&D since the private gains from R&D offset the negative effects of higher *h*. As *b* increases, competition among retailers becomes intense and the negative effect of outgoing information to the rival dominates the positive effect of incoming spillovers, which induces retailers to reduce R&D when *h* is high and *v* is low.

However, retailers increase R&D when *v* is high enough to mitigate the negative impact of *h*. An increase in *h* affects suppliers significantly since they produce a homogeneous input and are concerned about the information leakage to their competitor.

Thus, suppliers increase R&D when *v* is high enough to mitigate the negative effects of *h;* otherwise, they reduce R&D. *VC* internalizes *v* which boosts its cost reduction effects, offsets the sum of the effects of higher *h* and *b* on output, and thereby induces firms to increase output, boosting consumer surplus and welfare.

**Proposition 4.**

*The impact of horizontal spillovers on firms' behavior depends on horizontal spillovers and product substitutability.*

Although higher *h* decreases R&D in both industries under *NC*, when final goods are independent, retailers decrease R&D less than suppliers. This result shows that suppliers producing a homogeneous good are worried about the information leakage to their competitor, while retailers providing independent products are not concerned about higher *h*.

Although profits are negatively affected by *b*, the effects on retailers' profits (through lower output and higher *t*) are higher than the effects on suppliers' profits (through lower demand, but higher *t*). Thus, higher *h* reduces retailers' profit more than suppliers' and induces retailers to reduce R&D more than suppliers when goods are substitutes. Under *NC*:

(1) $\left|\frac{\partial x_{ri}}{\partial h}\right| < \left|\frac{\partial x_{si}}{\partial h}\right|$ if $b = 0$

(2) $\left|\frac{\partial x_{ri}}{\partial h}\right| > \left|\frac{\partial x_{si}}{\partial h}\right|$ if $b > 0$.

Under *HC*, higher *h* increases R&D by all firms. Competitors internalize *h* and benefit from it. When final goods are independent, suppliers and retailers increase R&D equally since their marginal benefit from R&D is equal. However, as *b* increases, suppliers increase R&D more than retailers. This result reflects the sum of the effects of *b* and *h* along with the effects of cooperative structures on firms' behavior.

Although higher *h* increases firms' benefit through its cost reduction effect (under *HC*), higher *b* reduces firms' net benefit of R&D. Although the sum of the effects of *h* and *b* on firms' profits is positive, the effects on suppliers' profits are higher than on retailers' profits. Thus, when goods are substitutes, suppliers increase R&D more than retailers. Under *HC*:

(1) $\frac{\partial x_{ri}}{\partial h} = \frac{\partial x_{si}}{\partial h}$ if $b = 0$

(2) $\frac{\partial x_{ri}}{\partial h} < \frac{\partial x_{si}}{\partial h}$ if $b > 0$.

Under $VC$, retailers and suppliers internalize $v$. Internalizing $v$ mitigates the negative effects of $h$ on firms' marginal profit of R&D. When goods are independent, retailers are not concerned about $h$. Thus, an increase in $h$ induces retailers to increase R&D.

Suppliers providing a homogeneous input are worried about the information leakage to their competitor. Therefore, suppliers increase R&D only if $h$ is sufficiently low and $v$ is high enough; otherwise, they reduce it.

When goods are imperfect substitutes, competition among retailers is severe which affects retailers' output, and thereby affects suppliers. Suppliers providing a homogeneous input are worried about the flow of spillovers to their competitor. Indeed, an increase in $h$ reinforces these effects, such that suppliers reduce R&D when $v$ is not high enough to mitigate the negative effect of $h$. As a result, an increase in $h$ induces retailers to increase R&D more than suppliers when goods are imperfect substitutes.

When goods are homogeneous, inter–industry firms' net benefits of R&D are equal, and thereby higher $h$ induces them to increase (decrease) R&D equally when $h$ is low (high) and $v$ is high (low) enough. Under $VC$:

(1) $\frac{\partial x_{ri}}{\partial h} > \frac{\partial x_{si}}{\partial h}$ if $b = 0, h$ is sufficiently low and $v$ is high enough; otherwise, $\frac{\partial x_{si}}{\partial h} < 0$.

(2) $\frac{\partial x_{ri}}{\partial h} > \frac{\partial x_{si}}{\partial h}$ if $b > 0$.

(3) $\frac{\partial x_{ri}}{\partial h} = \frac{\partial x_{si}}{\partial h}$ if $b = 1$.

## 4. Comparison of cooperative structures

In this section, cooperation settings are compared in terms of R&D and profitability. This comparison is essential to determine the appropriate choices of R&D cooperation with respect to associated technological improvement, profit, and welfare.

This comparison helps firms to decide to cooperate with whom if they choose to cooperate. This also helps the regulator to introduce policies to encourage firms to participate in a cooperative setting associated with higher innovation and welfare.

**Proposition 5.**

*The ranking of cooperation settings in terms of R&D depends on product substitutability and spillovers.*

*(i)* $(X_{VC} = X_{HC}) > X_{NC}$ *iff* $h = 1$, *independent of substitutability.*

*(ii)* $X_{VC} > X_{NC} > X_{HC}$ *if $h$ is sufficiently low; otherwise* $X_{VC} > X_{HC} > X_{NC}$*. The results are independent of substitutability.*

Although ranking cooperation settings in terms of R&D requires numerical parameter values, the same results are attainable by an analytical study of the signs and magnitudes of competitive externalities internalized by each cooperative structure. Internalizing the effect of a firm's R&D on the profit of other firms is the key to this analysis.

Horizontal competitive externalities ($HCEs$)[3] represent the marginal effect of a firm's R&D on its competitor's profit ($HCE_{ri} = \partial\pi_{ri}(\beta)/\partial x_{rj}$, $HCE_{si} = \partial\pi_{si}(\beta)/\partial x_{sj}, i = 1,2$). $HCEs$ are positive (negative) when an increase in R&D by a firm increases (decreases) the competitor's profit. Moreover, an increase in R&D by a firm increases (decreases) its competitor's profit when $h$ is high (low). $HCE_{ri}$ is negative if $(10 + b)h + (8 - 4b)v - (2 + 5b) < 0$ and $HCE_{si}$ is negative if $(2h + v - 1) < 0$.

Although $h$ and $v$ have positive effects on $HCEs$, product substitutability negatively affects them. The effect of $b$ on $HCE_{ri}$ is stronger than its effect on $HCE_{si}$. Comparing industries' $HCEs$ shows that $HCE_{si} > HCE_{ri}$, and the difference decreases with $b$. $HC$ internalizes $HCEs$.

Vertical competitive externalities ($VCEs$)[4] represent the marginal effect of a firm's R&D on the profits of firms in the other industry ($VCE_{ri} = \partial\pi_{ri}(\beta)/\partial x_{si}$, $VCE_{si} = \partial\pi_{si}(\beta)/\partial x_{ri}, i = 1,2$).

This externality is positive, given that the higher R&D of a firm increases the benefits of its supplier (customer). Product substitutability has a negative effect on $VCEs$.

The effect on $VCE_{ri}$ is stronger than on $VCE_{si}$. Comparing industries' $VCEs$ shows that $VCE_{si} = VCE_{ri}$ when goods are independent; otherwise $VCE_{si} > VCE_{ri}$. Comparing $HCEs$ and $VCEs$ shows that $VCEs \geq HCEs$, such that they are equal when $h = 1$.

In consequence, internalizing a positive externality boosts R&D, whereas internalizing a negative externality reduces R&D. Thus, the cooperation setting which internalizes greater positive competitive externalities yields higher R&D.

The first part of Proposition 5 states that $(X_{VC} = X_{HC}) > X_{NC}$ if and only if $h = 1$. *VC* internalizes *VCEs* which are positive and increase R&D. No externality is internalized by *NC*. Thus, *VC* yields higher R&D than *NC*. *HC* internalizes *HCEs* which may be positive or negative. If and only if $h = 1$, then *VCEs* = *HCEs,* and thereby, *VC* and *HC* yield the same R&D level. However, *VC* yields higher R&D than *HC* if $h < 1$. Ultimately, comparing these settings shows that $(X_{VC} = X_{HC}) > X_{NC}$ if $h = 1$.

Part *ii* of Proposition 5 states that $X_{VC} > X_{NC} > X_{HC}$ when spillovers are low. Obviously, *VC* yields the highest R&D by internalizing the positive *VCEs* for any values of $h$ and $v$. Comparing *NC* and *HC,* we note that *NC* internalizes no externalities and *HC* internalizes *HCEs* which can be positive or negative. When $h$ is sufficiently low, *HCEs* are negative. Internalizing these negative externalities reduces joint profits and induces firms to decrease R&D.

Therefore, when $h$ is sufficiently low *NC* yields higher R&D and $X_{VC} > X_{NC} > X_{HC}$. When $h$ is high, its externalities are positive. These positive *HCEs* are still less than the positive *VCEs* for any value of the parameters. Internalizing the positive *HCEs* induces the competitor to increase its R&D and yields $X_{VC} > X_{HC} > X_{NC}$. Higher R&D is associated with higher output, which reflects a higher value of cost reduction. Thus, we conclude that the same ranking is observed for welfare.

Moreover, higher $b$ reduces competitive externalities and increases the required threshold of spillovers[5] to turn *HCEs* positive. Note that *VCEs* are positive and larger than *HCEs*. Thus, higher $b$ has no significant effect on the ranking of cooperation settings in terms of R&D and just influences the required threshold of $h$ and $v$ to keep the ranking unchanged.

Now, the question arises whether firms tend to cooperate vertically voluntarily. Is *VC* associated with the highest profit for all firms? To answer these questions, we study the ranking of cooperation settings in terms of profitability.

**Proposition 6.**

(i) *If products are independent:* $\pi_{ri}^{VC} > \pi_{ri}^{NC} > \pi_{ri}^{HC}$ *when* $h = 0$ *and* $v = 0$; $\pi_{ri}^{VC} > \pi_{ri}^{HC} > \pi_{ri}^{NC}$ *when* $0 \leq h < 1$ *and* $v > 0$; $(\pi_{ri}^{VC} = \pi_{ri}^{HC}) > \pi_{ri}^{NC}$ *when* $h = 1$.

(ii) *If products are imperfect substitutes:* $\pi_{ri}^{NC} > \pi_{ri}^{VC} > \pi_{ri}^{HC}$ *when* $h = 0$ *and* $v = 0$; $\pi_{ri}^{VC} > \pi_{ri}^{HC} > \pi_{ri}^{NC}$ *when* $h = 0$ *and* $v = 1$; $\pi_{ri}^{HC} > \pi_{ri}^{VC} > \pi_{ri}^{NC}$ *when* $h = 1$ *and* $v = 0$.

(iii) *If products are homogeneous:* $\pi_{ri}^{HC} > \pi_{ri}^{NC} > \pi_{ri}^{VC}$ *when* $h = 0$ *and* $v = 0$; $\pi_{ri}^{VC} > \pi_{ri}^{HC} > \pi_{ri}^{NC}$ *when* $h = 0$ *and* $v = 1$; $\pi_{ri}^{HC} > \pi_{ri}^{VC} > \pi_{ri}^{NC}$ *when* $h = 1$ *and* $v = 0$.

The analytical results to rank the cooperation settings in terms of profitability are attained by focusing on the impact of $h$, $v$, and $b$ on R&D along with the effects of internalized competitive externalities on profit.

The comparison rests on the signs and magnitudes of $h$, $v$, and $b$ as well as *HCEs* and *VCEs*. Although firms benefit from spillovers through their cost reduction effects, this benefit is substantial when they are large, such that the incoming spillovers dominate the outgoing technological information.

Additionally, higher $b$ boosts competition among retailers, negatively affects market demand and reduces retailers' profits.

Part *i* of Proposition 6 states that retailers' profit producing independent goods is ranked as $\pi_{ri}^{VC} > \pi_{ri}^{NC} > \pi_{ri}^{HC}$ if $h = v = 0$.

When products are independent, retailers are not concerned about the information leakage to their competitor and increase R&D to benefit from its cost reduction effect. Note that $VCE_{ri}$ is positive, whereas $HCE_{ri}$ is negative when $h = v = 0$.

Indeed, suppliers providing a homogeneous input are highly sensitive to their rivals' spillovers. When $h = 0$, suppliers increase R&D, which benefits retailers through the positive $VCE_{ri}$. Thus, retailers benefit from $VC$, whereas they suffer from $HC$, internalizing the negative $HCE_{ri}$. $NC$ internalizes no externality. Thus, $\pi_{ri}^{VC} > \pi_{ri}^{NC} > \pi_{ri}^{HC}$. As spillovers increase, $HCE_{ri}$ turns positive, yet $VCE_{ri} > HCE_{ri}$. Thus, $\pi_{ri}^{VC} > \pi_{ri}^{HC} > \pi_{ri}^{NC}$. Moreover, $HCE_{ri} = VCE_{ri}$ when $h = 1$ which results in $\pi_{ri}^{VC} = \pi_{ri}^{HC} > \pi_{ri}^{NC}$.

Part *ii* of Proposition 6 states that $\pi_{ri}^{NC} > \pi_{ri}^{VC} > \pi_{ri}^{HC}$ when products are imperfect substitutes and $h = v = 0$. When products are substitutes, competition among retailers is strong. Thus, retailers reduce output and demand of the intermediate good which reduces suppliers' profit and R&D. Thus, $VC$ may lead to over–investment. Indeed, $HCE_{ri}$ is negative when spillovers are low, and thereby leads firms to under–invest. Although $VC$ yields higher profit than $HC$, the highest profit is attained by $NC$ internalizing no externality since $NC$ prevents retailers from over–investing, which may occur under $VC$. Thus, $\pi_{ri}^{NC} > \pi_{ri}^{VC} > \pi_{ri}^{HC}$. Higher $v$ benefits firms and mitigates the negative effects of $b$ on profit.

When $v = 1$, firms benefit from R&D activities of one another and increase R&D which turns $HCE_{ri}$ positive, such that $VCE_{ri} > HCE_{ri}$. Moreover, $HCE_{ri}$ is positive up to the point where $b \leq 2/3$ if $h = 0$ and thereby, $\pi_{ri}^{VC} > \pi_{ri}^{HC} > \pi_{ri}^{NC}$. When $h = 1$ and $v$ is sufficiently low, retailers gain higher profit by internalizing $HCE_{ri}$ than by internalizing $VCE_{ri}$, since $HCE_{ri} > VCE_{ri}$ up to the point where $b \leq 2/3$, and thereby $\pi_{ri}^{HC} > \pi_{ri}^{VC} > \pi_{ri}^{NC}$.

Part *iii* of Proposition 6 states that $\pi_{ri}^{HC} > \pi_{ri}^{NC} > \pi_{ri}^{VC}$ when goods are homogeneous and $h = v = 0$. When goods are homogeneous, competition among retailers is intense, which induces retailers to reduce output and demand of the intermediate good, which reduces suppliers' profit and R&D. In this context, $VC$ may lead to over–investment. $NC$ may also lead them to over–invest due to strong competition; however, $VC$ is associated with a greater over–investment which reduces retailers' profits. $HC$ internalizes the negative $HCE_{ri}$ which is mitigated by $b$ when products are homogeneous. Thus, retailers benefit from $HC$ since it prevents them from over–investing. Comparing the settings shows that $\pi_{ri}^{HC} > \pi_{ri}^{NC} > \pi_{ri}^{VC}$. When $v = 1$, internalizing $v$ reinforces its positive effects, increasing the net benefit of R&D to all firms. Thus, $VC$ is more profitable to both industries since $VCE_{ri} > HCE_{ri}$ and thus $\pi_{ri}^{VC} > \pi_{ri}^{HC} > \pi_{ri}^{NC}$.

Proposition 6 shows that retailers attain the highest profit under $VC$ when goods are independent and spillovers are sufficiently low. Higher $b$ affects firms' R&D due to its effects on output. Higher $b$ mitigates the effects of horizontal competitive externalities. $NC$ is associated with higher profits by preventing retailers from over–investing when goods are imperfect substitutes and spillovers are sufficiently low. Furthermore, $NC$ and $VC$ may induce retailers to over–invest when products are homogeneous and spillovers are sufficiently low. In this case, retailers gain higher profit under $HC$. The negative effects of over–investing on retailers' profit more than offset the gains associated with the cost reduction effects of R&D. $VC$ leads retailers to the highest profit when $v$ is high enough.

Now, consider the profit of suppliers providing a homogeneous intermediate good. Although higher $b$ reduces the demand of the intermediate good, it increases the wholesale price which reflects the power of suppliers.

**Proposition 7.**

(i) *If goods are independent:* $\pi_{si}^{HC} > \pi_{si}^{NC} > \pi_{si}^{VC}$ *when* $h = 0$ *and* $v = 0$; $\pi_{si}^{VC} > \pi_{si}^{HC} > \pi_{si}^{NC}$ *when* $h = 0$ *and* $v = 1$; $(\pi_{si}^{VC} = \pi_{si}^{HC}) > \pi_{si}^{NC}$ *when* $h = 1$.

(ii) *If goods are imperfect substitutes:* $\pi_{si}^{NC} > \pi_{si}^{VC} > \pi_{si}^{HC}$ *when* $h = 0$ *and* $v = 0$; *otherwise,* $\pi_{si}^{VC} > \pi_{si}^{HC} > \pi_{si}^{NC}$.

(iii) *If goods are homogeneous:* $\pi_{si}^{VC} > \pi_{si}^{NC} > \pi_{si}^{HC}$ *when* $h = 0$ *and* $v = 0$; *otherwise,* $\pi_{si}^{VC} > \pi_{si}^{HC} > \pi_{si}^{NC}$.

Part *i* of Proposition 7 states that $\pi_{si}^{HC} > \pi_{si}^{NC} > \pi_{si}^{VC}$ when final products are independent and spillovers are sufficiently low. In this case, suppliers benefit from higher demand and have enough incentive to increase R&D when $h$ is sufficiently low. Retailers also increase R&D.

Although $HCE_{si}$ is negative when $h = 0$, suppliers benefit from internalizing these negative $HCE_{si}$ since it mitigates suppliers' concerns about the flow of spillovers to the competitor, and prevents them from over–investing. This result shows that $VC$ may induce suppliers to over–invest, which reduces profits. Although $NC$ internalizes no externality, suppliers benefit from $NC$ since it also prevents them from over–investing.

The over–investment under $VC$ is stronger than under $NC$. Thus, $\pi_{si}^{HC} > \pi_{si}^{NC} > \pi_{si}^{VC}$. As $v$ increases, yet $h$ is sufficiently low, firms increase R&D further. Additionally, when $v = 1$, firms benefit from internalizing $VCE_{si}$ which reinforces the cost reduction effects of $v$. Vertical spillovers also mitigate the negative $HCE_{si}$, such that $\pi_{si}^{VC} > \pi_{si}^{HC} > \pi_{si}^{NC}$. Ultimately, $HCE_{si} = VCE_{si}$ when $h = 1$ which results in $\pi_{si}^{VC} = \pi_{si}^{HC} > \pi_{si}^{NC}$.

Part *ii* of Proposition 7 states that $\pi_{si}^{NC} > \pi_{si}^{VC} > \pi_{si}^{HC}$ when products are imperfect substitutes and $h = v = 0$. When products are substitutes, competition among retailers is strong. Thus, retailers reduce output which reduces suppliers' output as well. These effects reduce firms' incentive to increase R&D and thereby, $VC$ leads firms to over–invest. Furthermore, $HCE_{si}$ is negative due to the low spillovers.

Internalizing these negative competitive externalities leads suppliers to under–invest, which reduces their profit. In this case, $VC$ yields higher profit than $HC$, while $NC$ internalizing no externality yields the highest profit to suppliers since $NC$ prevents them from over–investing and (or) under–investing. Thus, $\pi_{si}^{NC} > \pi_{si}^{VC} > \pi_{si}^{HC}$.

Higher $h$ and $v$ increase the net benefit of R&D, more than offset the effects of $b$ on profit, and positively affect firms' incentive to increase R&D. Thus, $\pi_{si}^{VC} > \pi_{si}^{HC} > \pi_{si}^{NC}$ when spillovers are high enough.

Part *iii* of Proposition 7 states that $\pi_{si}^{VC} > \pi_{si}^{NC} > \pi_{si}^{HC}$ when products are homogeneous and $h = v = 0$. When products are homogeneous, competition among firms is intense. This reduces firms' incentive to increase R&D. $NC$ internalizes no externality, yet boosts competition and induces suppliers to over–invest. $HC$ internalizes the negative $HCE_{si}$, inducing suppliers to under–invest. $HC$ reduces suppliers' profit (by under–investing) more than $NC$ does (by over–investing). In this case, $VC$ prevents suppliers from the overinvestment associated with $NC$ and thereby, suppliers attain the highest profit under $VC$. Thus, $\pi_{si}^{VC} > \pi_{si}^{NC} > \pi_{si}^{HC}$. As spillovers increase, firms have enough incentive to increase R&D, $HCE_{si}$ turns positive and $\pi_{si}^{VC} > \pi_{si}^{HC} > \pi_{si}^{NC}$.

Proposition 7 shows that when goods are independent and spillovers are sufficiently low, $VC$ leads suppliers to over–invest. To avoid over–investing, suppliers tend to $HC$. However, $HC$ leads suppliers to under–invest when products are imperfect substitutes, yet spillovers are sufficiently low. These results reflect the effects of $b$ on firms' R&D. $VC$ yields the highest profit for suppliers when products are homogeneous.

Choosing an appropriate cooperative setting under different levels of spillovers and product substitutability is critical to profit maximizing firms to choose the adequate innovation efforts.

## 5. Conclusion

This paper aims to study the impact of cooperative R&D on innovation, welfare, and profitability in vertically related industries where products are differentiated, with horizontal and vertical spillovers. A two-industry framework is considered, where upstream firms produce a homogeneous intermediate good and sell it to downstream firms, which produce differentiated products.

Although vertical spillovers increase R&D, horizontal spillovers may increase or decrease it. Inter–industry firms benefit from higher innovation efforts of one another. The impact of horizontal spillovers on R&D depends on the cooperative structure, horizontal and vertical spillovers, and product substitutability.

Retailers and suppliers respond differently to a change in spillovers and product substitutability. Although higher product differentiation mitigates retailers' concerns about horizontal spillovers, it has no significant effect on suppliers.

Higher product substitutability increases competition among retailers, affects the position of the demand curve, inducing retailers to reduce output and the demand of the intermediate good. Although the reduction in demand affects suppliers' net benefit of R&D, the power of suppliers mitigates this effect by increasing the wholesale price.

Comparing cooperative settings in terms of R&D shows that *VC* dominates. When horizontal spillovers are perfect, *HC* and *VC* yield the same R&D level. The second-best cooperation setting in terms of R&D and welfare is non–cooperative R&D if spillovers are sufficiently low; otherwise, *HC* is the second best. *HC* decreases R&D and welfare when spillovers are sufficiently low. This result does not necessarily hold when one of the spillovers is high.

The ranking of cooperation settings rests on the sign and magnitudes of competitive externalities, spillovers, and product substitutability. Product substitutability affects the required threshold of spillovers. Higher product differentiation yields higher output and R&D by all firms under any type of cooperation.

An important question that arises in the study of cooperation settings is their relative importance to firms' decisions. Cooperation settings were compared in terms of profitability. It was shown that profitability is affected by the sign and magnitudes of competitive externalities, product substitutability, as well as horizontal and vertical spillovers.

The result indicates that retailers and suppliers have no common interest to voluntarily form *VC*. Although suppliers gain the highest profit under *VC* when final goods are homogeneous, retailers attain the highest profit under *VC* only if vertical spillovers are sufficiently high. Moreover, *VC* may induce firms to over–invest, which reduces profits.

The study of cooperative R&D and of protecting innovation is certainly important for technology policy issues. Drawing policy recommendations requires prudence since it deals with many practical issues like asymmetric information between firms and regulators. However, the model suggests some considerations on R&D policy with respect to the incentives of cooperation settings' perspective.

The model suggests that the selection of cooperation settings and incentives to cooperate is imperative to the analysis of R&D. The regulator should favor policies to encourage *VC*, since it is associated with the highest levels of innovation and welfare. The optimal policy varies based on spillovers and product substitutability.

The model has many possible extensions. The importance of differentiating between outgoing technical knowledge and incoming technological information has not been addressed. It was assumed that the flow of horizontal (vertical) spillovers between firms in both industries is the same. In the real world, absorptive capacity, the pace and scope of technological change, and communication channels are different among firms (industries), which leads to different levels of spillovers.

Moreover, downstream firms dealing with the final consumer may bear more vertical spillovers, whereas upstream firms providing a homogeneous intermediate good may develop more horizontal spillovers. This, in turn, may affect the symmetry of horizontal and vertical spillovers.

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[1] Consumer surplus is defined as $CS = U(y_0, y_{r1}, y_{r2}) - (p_1 y_{r1} + p_2 y_{r2} + y_0)$.

[2] For proofs and technical derivations see Pourkarimi (2019).

[3] $HCE_{ri}$ ($HCE_{si}$) refers to horizontal competitive externalities of retailers (suppliers).

[4] $VCE_{ri}$ ($VCE_{si}$) refers to vertical competitive externalities of retailers (suppliers).

[5] For example: If $b = 0$, $(13h + 8v < 5)$ then $X_{VC} > X_{NC} > X_{HC}$, otherwise $X_{VC} > X_{HC} > X_{NC}$; if $b = 0.5$, $(h + 0.53v < 0.47)$ then $X_{VC} > X_{NC} > X_{HC}$, otherwise $X_{VC} > X_{HC} > X_{NC}$; and if $b = 1$, $(23h + 10v < 13)$ then $X_{VC} > X_{NC} > X_{HC}$, otherwise $X_{VC} > X_{HC} > X_{NC}$.