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Optimal R&D disclosure in network industries

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Abstract

The R&D literature framed in a strategic context shows two unpleasant outcomes for the public goods nature of knowledge: 1) the private R&D activity results in under-investment (with no information leakage – no spillovers) or over-investment (with information leakage – positive spillovers) compared to the social optimum because of appropriability, and 2) the R&D outcome shared by each firm is lower than full disclosure, as innovators are not rewarded for disseminating information. This article departs from De Bondt et al. (1992), who consider the cost-reducing (process) innovation duopoly à la d'Aspremont and Jacquemin (1988, 1990) with non-network goods showing that the (second-best) social optimum requires partial disclosure if products are homogeneous. Unlike these studies, this work finds that, in a network industry, full disclosure becomes optimal depending on the extent of the network externality. Results offer clear policy implications.

JEL classification: D43, L13, O31

Keywords: Duopoly; Information-sharing; R&D investments

Declarations of interest: None

1. Introduction

Innovation is central to the political agenda and is broadly viewed as the engine behind economic growth. The European Union is a major sponsor of research and development activities in several socio-economic areas, as witnessed by its current objectives of "strengthening knowledge and innovation as drivers of our future growth… to re-focus R&D and innovation policy on the challenges facing our society… to prioritise knowledge expenditure… to promote greater private R&D investments" (European Commission 2020, pp. 11-13). A pearl of common wisdom is that policies should tend to incentivise, in various forms, private firms to spread their R&D knowledge to enhance social welfare (Buccella et al., 2023a).

Game-theoretic models, which consider strategic interactions amongst firms, are useful for describing the strategic interdependency of their R&D decisions. The pioneering textbook strategic investment model of d'Aspremont and Jacquemin (1988, 1990) (henceforth, AJ) typically analyses the innovative behaviour of firms in a two-stage game, in which, in the first stage, they choose process innovation R&D that reduces the constant unit production cost, and, in the second stage, by anticipating these strategic R&D choices, firms choose the control variables in the product market (according to the Cournot or Bertrand competition model with homogeneous or differentiated products). The crucial feature is that the newly developed R&D effort may exogenously – partially or totally – spill over to rivals, reflecting the public goods nature of knowledge.[1]

The issue of the circulation of knowledge with exogenous spillovers, despite its relevant policy implications, has received rather scant attention. An important exception is the article of De Bondt et al. (1992), which studies the implications of the spill-over rates for profitability, consumer surplus, and social welfare, showing that partial rather than full disclosure maximises firm output, consumer surplus, and profits in the case of homogeneous products. Indeed, Propositions 3 and 4 in these researchers' work show that profitability and welfare achieve a maximum for an extent of technological spill-over rate ranging between $1/2$ and 1 (specifically, the spill-over rate that maximises profits is greater than the leakage at which welfare is maximized). This holds in a non-network oligopoly with homogeneous or in a differentiated industry with many rivals. Alternatively, profits and welfare are maximised by perfect spillovers if and only if oligopolies are strongly concentrated (highly differentiated products and a few rivals).

[1] Over the course of the years, the literature has considered models in which the spill-over is exogenous (e.g., Henriques, 1990; Suzumura, 1992; De Bondt, 1996; Amir, 2000; Amir et al., 2003; Hinloopen, 2003; Poyago-Theotoky, 2007; Bacchiega et al., 2010; Burr, 2013; Buccella et al., 2023a, 2022b) or endogenous (e.g., Poyago-Theotoky, 1999; Lambertini et al., 2004; Gil-Moltó et al., 2005; Piga and Poyago-Theotoky, 2005; Milliou, 2009). There exists another relevant branch of the literature augmenting the AJ model with the analysis of R&D subsidies, i.e., Hinloopen (1997, 2000), Amir et al. (2019), and Buccella et al. (2023a). We also note that Amir (2000) and Hinloopen (2003) criticised the AJ setting essentially because of the existence of decreasing returns to R&D in combination with additive (output) spillovers and then proposed the use of input spillovers.

Then, in a duopoly industry with homogeneous products, which is the case considered in this article, the circulation of knowledge, measured by the extent of the spill-over rate, should be sufficiently lower than the full disclosure to maximise the selfish interests of firms and consumers and get the highest social welfare. The resulting policy message is interesting, showing that the full (or adequately high) circulation of R&D information ends up working against societal interest. However, this message involves industries producing standard non-network goods. Today, network industries – such as mobile devices and software – are becoming more and more relevant in modern economies and are chiefly characterised by oligopolistic market structures (Chirco and Scrimitore, 2013; Bhattacharjee and Pal, 2014; Naskar and Pal, 2020; Shrivastav, 2021; Buccella et al., 2022). For these products, the individual utility function is increasing in the number of users, so total sales increase the welfare of each consumer (e.g., Katz and Shapiro, 1985, Amir and Lazzati, 2011; Hoernig, 2012; Buccella et al., 2022; Choi and Lim, 2022).

This article addresses the following question: does the main result of De Bondt et al. (1992), i.e., welfare-maximising partial disclosure, hold in a network industry? The answer is no. When the strength of the network consumption externality is sufficiently high, full information sharing is optimal for society, but with standard goods, excessive R&D spread reduces the firm incentive to invest in cost-reducing R&D, and this lowers the possibility to reduce production costs by eventually decreasing production, consumer surplus, and social welfare. Furthermore, the incentive to invest in cost-reducing R&D in a network industry is increased by the positive R&D externality, i.e., the quantity affecting both the investing firm and the rival. Therefore, innovating firms are indirectly rewarded for disseminating their R&D-related outcomes through the increased consumption induced by the network effect, and full information sharing becomes socially optimal. The article explores the full spectrum of compatibility issues between the product on the demand side and gives theoretical results accordingly depending on the degree of the (positive or negative) network externality. In this regard, full disclosure is welfare maximising when the network externality is sufficiently high. This holds under full compatibility, partial compatibility, or no compatibility. A positive network externality favours the result of optimal full disclosure through high or full compatibility between products. A negative network externality favours the result of optimal full disclosure through low or no compatibility between products.

The policy recipe is clear and far-reaching: in network industries, the policymaker should intervene to favour full information sharing depending on the degree of the network effect and then apply the results in Buccella et al. (2023a) by adopting an ad hoc R&D subsidy to disclosure. In the standard case of a positive network externality (e.g., software, mobile phone), the policymaker should be able to intervene by incentivising the production of compatible products.

The rest of the article is organized as follows. Section 2 describes the model. It then derives the subgame-perfect Nash equilibrium when firms privately undertake the R&D activity and then presents the main results of the article. Section 3 provides some concluding remarks. The Appendix provides some mathematical details of the model and the proofs of the main results.

2. The model

On the supply side, the economy is bi-sectorial with a competitive sector producing the numeraire good m and a duopolistic sector in which firm i and firm j ($i = \{1,2\}$; $i \neq j$) produce goods of variety (network) i (q_i) and variety (network) j (q_j), respectively. These goods are perceived as homogeneous by customers. Firms also face the perspective of investing in cost-reducing R&D (process innovation) along the line of the model developed by AJ.

On the demand side, the mechanism of network effects (consumption externalities) described in the present article follows the seminal work of Katz and Shapiro (1985), which is adopted in several recent articles belonging to the IO literature framed in strategic competitive markets with (Naskar and Pal, 2020; Shrivastav, 2021; Buccella et al., 2022) and without process innovation (Hoernig, 2012; Chirco and Scrimitore, 2013; Bhattacharjee and Pal, 2014; Pal, 2014, 2015; Song and Wang, 2017; Fanti and Gori, 2019; Choi and Lim, 2022). By assuming a quasi-linear utility function following the recent contributions by Amir et al. (2017) and Choné and Linnemer (2020), the solution of the constrained utility maximisation gives the following linear inverse demand for product of network i for the representative consumer (see the appendix for details):

$$p_i = 1 - q_i - q_j + n(y_i + ky_j), \tag{1}$$

where p_i represents the price of (i.e., the marginal willingness to pay for) product of variety i, parameter $-1 \leq n < 1$ is the strength of the network effect ($n = 0$ represents the standard case of non-network goods) and $0 \leq k \leq 1$ measures the degree of compatibility of the network of product j towards the network of product i (and vice versa).

Positive (resp. negative) values of n reflect a positive (resp. negative) consumption externality. Several network industries exhibit positive externalities (mobile communications, software, internet-related activities, online social networks, fashion, etc.): a greater number of users contribute to increase the value of the product to each consumer (there exists a positive feedback loop if the network becomes more valuable). Several real-world industries exhibit both kinds of externalities; for example, the automobile industry, which might also show negative consumption externalities with more cars sold, greater traffic congestion, parking difficulties, and other related issues. Therefore, a negative network externality implies that an increasing number of users reduces the value of the goods for each consumer (for instance, traffic congestion or network congestion over limited bandwidth). The term $y_i + ky_j$ represents the expected effective network size of firm i's consumers. For example, $k = 1$ implies that the network of product j is perfectly compatible with the network of product i (full compatibility), whereas $k = 0$ implies that the network of product j is perfectly incompatible with the network of product i (no compatibility). The intermediate cases

$0 < k < 1$ represent different degrees of imperfect or asymmetric compatibility of the network of product j with the network of product i (and vice versa). To study the welfare effects of R&D disclosure, the article concentrates on the three symmetric cases of network product compatibility.

- First, $k = 1$ implies symmetric full compatibility between the two networks.
- Second, $k = 0$ implies symmetric incompatibility between the two networks.
- Third, $k < 1$ implies symmetric imperfect compatibility between the two networks.

The asymmetric case $k_i \neq k_j$ implies asymmetric compatibility of the network of product j towards the network of product i (including the cases of asymmetric extreme (in)compatibility, implying full compatibility of one of the two networks and no compatibility of the other one, i.e., $k_i = 1$ and $k_j = 0$ or $k_i = 0$ and $k_j = 1$). This case is not presented to save space, but the outcomes of the article do not change compared to the symmetric cases that will be studied later.

As is clear from the expression in (1), the network externality enters additively in the market demand of product i (Economides, 1996). If the network externality is positive (resp. negative), an increase in the feedback loop of the network causes an outward (resp. inward) shift in the demand curve that implies an increase (resp. reduction) in the quantity bought by consumers for any given value of the price. This externality therefore acts as a device that increases (resp. reduces) the market size. Though q_i and q_j are evaluated as homogeneous goods by customers, the marginal willingness to pay for product i and product j differs because of the different degree of compatibility between the two networks. Alternatively, this variation could arise because of the different effort exerted in the market of product i and the market of product j by the degree of compatibility in the cases of symmetric (imperfect) compatibility ($k < 1$) and symmetric no compatibility ($k = 0$).

Under symmetric full compatibility ($k = 1$), the externality generated by the expected effective network size is the highest in both cases of positive and negative network effects. Therefore, the external effect due to the consumers' expectations about firm j's equilibrium total sales affects the demand of product of network i at the highest degree, strengthening the external effect due to the consumers' expectations about firm i's equilibrium total sales at its maximum intensity. Under symmetric incompatibility, this strengthening effect does not exist, and the externality generated by the expected effective network size is the lowest in both cases of positive and negative network effects. In this case, the demand of network i is positively or negatively affected only by the external effect generated by the consumers' expectations about firm i's equilibrium total sales.

In the first stage of the game, firms non-cooperatively invest in cost-reducing (process) innovation along the line of AJ. In the second stage, firms compete in quantities in the product market. The game is solved by backward induction.

For the sake of generality, we pinpoint here that the timing of the game and the kind of consumers' expectation formation are relevant in a network economy following the contribution of Katz and Shapiro (1985) and its applications. We also use the quadratic utility and linear demand made first by Hoernig (2012), later followed by Chirco and Scrimitore (2013) and Song and Wang (2017), Fanti and Gori (2019), Buccella et al. (2022), and Choi and Lim (2022), among others. The model proposed in the present article strictly considers the narrative presented in the main text by Katz and Shapiro (1985), who considered the case in which firms do not commit themselves to an announced output level. Mixing Katz and Shapiro (1985) and d'Aspremont and Jacquemin (1988, 1990) in a model with linear demand, the non-commitment scenario implies that the timing of the game becomes the following: firms choose not to commit themselves to an announced output level before consumers make their purchase decisions. This holds in the pre-stage of the game. Then, in the first stage, firms non-cooperatively invest in cost-reducing (process) innovation along the line of AJ. In the second stage, firms compete in quantities in the product market following the main idea of Katz and Shapiro (1985), which has been used more recently by Hoernig (2012) and Choi and Lim (2022) in a duopoly with linear demand. Then, the market demand depends on consumers' expectations about the network size. As consumers are rational, expectations are realised in equilibrium so that $q_i = y_i$ ($i = \{1,2\}$; $i \neq j$). A possible alternative may resemble the commitment scenario studied by Katz and Shapiro (1985) in an ad hoc appendix of their contribution. If firms can commit themselves to an announced output level before consumers make their purchase decisions, the utility function and the market demand do not depend on expectations of the network size, but directly on the realised values of the output to which firms are committing. Therefore, firms choose to commit themselves to an announced output level before consumers make their purchase decisions. This holds in the pre-stage of the game. Then, in the first stage, firms non-cooperatively invest in cost-reducing (process) innovation along the line of AJ. In the second stage, firms compete in quantities in the product market. In this case, however, the market demand does not depend on consumers' expectations about the network size, but on the quantities produced by the firms, which are exactly those the two firms have committed to producing. Similar qualitative results (though with quantitative differences) about the optimal R&D disclosure under the commitment scenario can be obtained compared to the case of non-commitment analysed in the present article. We avoid replicating the analysis in detail but briefly sketch the microeconomic foundation (see the appendix) to compute the market demand when firms commit themselves to an announced output level and report the equilibrium R&D effort, output, and profit emerging in that case.

Though the article concentrates on the case of symmetric disclosure, we briefly sketch the model by considering the more general case of asymmetric disclosure and then make the required simplified assumption of homogeneous disclosure. The total cost of production and the R&D cost incurred by (and representing the R&D investment of) firm i are respectively given by the following expressions:

$$C_i(q_i, x_i, x_j) = (w - x_i - \beta_j x_j)q_i, \tag{2}$$

and

$$X_i(x_i) = \frac{g}{2}x_i^2, \tag{3}$$

where: 1) x_i and x_j represent the monetary equivalent of the resulting R&D activity or effort that firm i and firm j exert, respectively; 2) $g > 0$ is a parameter that measures R&D efficiency and scales up/down R&D investment total costs. A reduction in g can be interpreted as a technological advance such that R&D activities are cheaper; 3) $\beta_j \in [0,1]$ is the exogenous degree of technological spillovers (alternatively, it represents the exogenous rate of knowledge disclosure) of the R&D activity exerted by firm j flowing towards firm i as a cost-reducing device. It is assumed that both firms share this characteristic: firm i discloses at the rate β_i towards firm j, and firm j discloses at the rate β_j towards firm i. In what follows, we will consider the symmetric case $\beta_i = \beta_j = \beta$ (homogeneous disclosure).

As the spill-over parameter is exogenous, each firm has no control over the extent of disclosure for, e.g., technological reasons (see Henriques, 1990; Suzumura, 1992; Kamien et al., 1992; De Bondt, 1996; Bacchiega et al., 2010; Buccella et al., 2023a, 2023b). When $\beta_j = 0$, there is no knowledge disclosure; when $\beta_j = 1$, firm j's R&D outcomes are fully shared with firm i.

The parameter $0 < w < 1$ measures the unitary production cost. The firm's technology in Eq. (2) implies that this unitary production cost should be positive; thus, the condition $w - x_i - \beta x_j > 0$ must hold for any β_j. Moreover, the cost of firm i's R&D investment in Eq. (3) reveals decreasing returns in R&D technology.

Knowing that 1) the R&D outcomes are shared at the same exogenous rate β between firm i and firm j and 2) the degree of compatibility between the networks of products i and j is symmetric so that $k_i = k_j = k$ holds, we use Eqs. (1)-(3) to write the profit function of firm i as follows:

$$\Pi_i = [1 - q_i - q_j + n(y_i + ky_j)]q_i - (w - x_i - \beta x_j)q_i - \frac{g}{2}x_i^2. \tag{4}$$

At the market stage of the game, each firm chooses the amount of output to maximise profits. Solving the maximisation problem in Eq. (4) for q_i, by taking y_i and y_j as given, we obtain firm i's downward-sloping reaction function in the (q_i, q_j) space as a function also of R&D efforts x_i and x_j. This is done by additionally assuming, as is usually considered since at least Katz and Shapiro (1985) and following some more recent work as Hoernig (2012) Naskar and Pal (2020), Shrivastav (2021), Buccella et al. (2022), and Choi and Lim (2022), that consumers are endowed with rational expectations. This means that $q_i = y_i$ and $q_j = y_j$ hold in equilibrium. Therefore, we get:

$$\frac{\partial \Pi_i}{\partial q_i} = 0 \Leftrightarrow q_i(q_j, x_i, x_j) = \frac{1 - w - q_j(1 - nk) + x_i + \beta x_j}{2 - n}. \tag{5}$$

The numerator of Eq. (5) clearly reveals the existence of positive standard effects on the output of firm i caused directly by the R&D effort exerted by firm i and indirectly (through the spreading of knowledge, which exogenously discloses at the rate β) by the R&D effort exerted by the rival (firm j). These effects contribute to shift outwards the reaction function of firm i ($i = \{1,2\}$, $i \neq j$) drawn in the geometric space (q_i, q_j) and then increase its production. However, an additional effect exerted by the network externalities can arise. This effect is twofold and passes through the extent of the network strength (n) and the degree of compatibility (k). The former exerts its effects both separately of and jointly with k. The latter, however, affects the reaction function only through the network strength. In the case of positive (resp. negative) externality, an increase in the extent of the network effect directly contributes to expand (resp. shrinks) the demand for firm i by further shifting outwards (resp. by shifting inwards) its reaction function. However, there also exists an indirect effect of the network passing through the production of the rival. This effect is weighted by the extent of the degree of compatibility of the products of the two networks. In the case of positive (resp. negative) externality, an increase in the strength of the network effect positively (resp. negatively) affects the production of firm i through the production of firm j. This effect gets stronger as the degree of compatibility gets larger. If products are fully compatible ($k = 1$), the strength of this effect is the highest, and both firms can jointly benefit from (resp. damaged by) product compatibility if $n > 0$ (resp. $n < 0$). If products are not compatible at all ($k = 0$), the strength of this effect is the lowest (null), and firm i can benefit (resp. is being negatively affected) by its network only if n[2] > 0 (resp. $n < 0$).

From Eq. (5) and the counterpart for firm j, we obtain the system of output reaction functions that depend on the R&D efforts. The solution functions $q_i(q_j, x_i, x_j)$ for $i = \{1,2\}$, $i \neq j$ leads to the following equilibrium output at the second stage of the game:

$$\bar{q}_i(x_i, x_j) = \frac{(1-w)[1-n(1-k)]+x_i[2-\beta-n(1-\beta k)]+[(2\beta-1)-n(\beta-k)]x_j}{[1-n(1-k)][3-n(1+k)]}. \tag{6}$$

Eq. (6) reveals that firm i's output depends both on its R&D activity and on the R&D activity performed by the rival (firm j) because of knowledge disclosure. These effects also depend on the main parameters weighting the network activity, i.e., n and k, which also directly affect the output of firm i (net of the unitary production cost w). This direct effect works out positively (resp. negatively) on $\bar{q}_i(x_i, x_j)$ in the case of positive (resp. negative) externality. The positive (resp. negative) effect is strengthened (resp. weakened) by the degree of compatibility. This strengthening (resp. weakening) effect is the highest (resp. lowest) in the case of full (resp. no) compatibility.

Regarding the R&D investment effects, on one hand, firm i's R&D activity leads to a direct expansion of its output because of the strategic interaction with the rival. On the other hand, x_i mitigates the expansion of q_i, reducing production via this channel, because of the size of the R&D-related information externalities flowing from firm i

[2] The direct effect is measured by computing the first-order derivative of the term $\frac{1-w}{3-n(1+k)}$ with respect to n. This derivative is monotonically positive (resp. negative) for any $n > 0$ (resp. $n < 0$). Then, by computing the second-order derivative with respect to k, we find that it is monotonically positive (resp. negative) for any $n > 0$ (resp. $n < 0$).

to firm j (β). Additionally, there exist the combined effects of the network strength and the degree of compatibility. A positive network externality reduces the beneficial effects of the R&D activity of firm i (the higher the positive network effect, the lower the need to invest in R&D). This negative effect is mitigated by the joint multiplicative effect exerted by the degree of compatibility and the degree of spill-over, but in the absence of disclosure, this effect is null. In contrast, a negative network externality increases the beneficial effects of the R&D activity of firm i (the higher the negative network effect, the higher the need to invest in R&D). This positive effect is mitigated by the joint multiplicative effect exerted by the degree of compatibility and the degree of spill-over, but in the absence of disclosure, this effect is null. Definitively, the strength of this network effect through x_i is decreasing (resp. increasing) with the size of the positive (resp. negative) externality, and it is mitigated by the degree of compatibility. Nonetheless, the strength of the disclosure effect and the strength of the network effect (along with the mitigation effect of the degree of compatibility) never offset the strength of the direct positive effect of x_i on $\bar{q}_i(x_i, x_j)$, even in the case of full disclosure ($\beta = 1$). Therefore, an increase in x_i always increases q_i.

Moreover, the firms' R&D information flow leads to a further increase in firm i's output via the R&D activity of firm j if and only if the degree of technological spillovers is satisfactorily large, that is $\beta > \frac{1-nk}{2-n}$, implying that x_i and x_j are strategic complements. Otherwise, if the technological spillovers are sufficiently small, that is $\beta < \frac{1-nk}{2-n}$, implying that x_i and x_j are strategic substitutes, output decreases through this channel. If $n = 0$, the threshold $\frac{1-nk}{2-n}$ boils down to that obtained by Bacchiega et al. (2010). If $n \neq 0$, an increase in k shifts leftward this threshold and then monotonically favours strategic complementarity. This tends to increase the positive feedback look of x_j on q_i. An increase in n shifts rightward (resp. leftward) by favouring strategic substitutability (resp. complementarity) if and only if $k < \frac{1}{2}$ (resp. $k > \frac{1}{2}$). Therefore, if the degree of compatibility is sufficiently low, an increase in the positive network effect tends to favour strategic substitutability and then strengthen the positive feedback look of x_j on q_i. In contrast, if the degree of compatibility is sufficiently high, an increase in the positive network effect tends to favour strategic complementarity, and then the feedback look of x_j on q_i becomes negative. The effects are reversed in the case of negative network externality.

Substituting out Eq. (6) and its counterpart for firm j in Eq. (4), we get firm i's profits as a function of x_i and x_j. Therefore, maximisation of firm i's profits in the first stage of the game for x_i yields:

$$\frac{\partial \Pi_i(x_i, x_j)}{\partial x_i} = 0 \Leftrightarrow x_i(x_j) = \frac{2[2-\beta-n(1-\beta k)]\{(1-w)[1-n(1-k)]+[\beta(2-n)-1+nk]x_j\}}{g[1-n(1-k)]^2[3-n(1+k)]^2-2[2-\beta-n(1-\beta k)]^2}. \quad (7)$$

Eq. (7) and the corresponding counterpart for firm j provides the system of R&D reaction functions in the space (x_i, x_j). The effects of the network externality come from the combined effects of direct and indirect effects passing also through the degree of compatibility and the spill-over rate.

The solution of this system yields firm i's (and consequently the symmetrical firm j's response) R&D effort in equilibrium, x^*, which is summarised in Table 1 together with the other main equilibrium outcomes of the model (production and profits) when the R&D activity is disclosed at the exogenous rate β. From q^* and Π^* we obtain the equilibrium values of the consumer surplus, the producer surplus, and the social welfare, which are respectively given by $CS^* = [2 - n(1+k)](q^*)^2$, $PS^* = 2\Pi^*$, and $W^* = CS^* + PS^*$. The feasibility conditions, allowing us to bound the values of the main parameters of the problem to have meaningful Nash equilibria, are summarised in the appendix (see also Hinloopen, 2015; Buccella et al., 2022, 2023b). These conditions are $g > g_{SC}^{\beta_{low}}(\beta, n, k)$, $g > g_{SC}^{\beta_{high}}(\beta, n, k)$, $g > g_{SOC}(\beta, n, k)$, and $g > g_T(\beta, n, k)$. The first and the second conditions represent the stability condition (SC), prevailing respectively when $\beta < \frac{1-kn}{2-n}$ (x_i and x_j are strategic substitutes) and when $\beta > \frac{1-kn}{2-n}$ (x_i and x_j are strategic complements). The third is the second-order condition (SOC) for a maximum (concavity). The fourth is the R&D cost condition (T) that guarantees that $w - x_i - \beta x_j > 0$ is positive in equilibrium. When the stability conditions are satisfied, the second-order condition holds accordingly. By assuming that the feasibility conditions are fulfilled, the equilibrium values reported in Table 1 and the consumer surplus are positive for any $0 \le k \le 1$ if $-1 \le n < 1$, which is then assumed to hold.

Table 1. Equilibrium outcomes in the AJ model with spillovers, network externalities, and product compatibility, in which firms do not commit to an announced output level and consumers have rational expectations.

x^*	$\frac{2(1-w)[2-\beta-n(1-\beta k)]}{g[1-n(1-k)][3-n(1+k)]^2-2(1+\beta)[2-\beta-n(1-\beta k)]}$
q^*	$\frac{g(1-w)[1-n(1-k)][3-n(1+k)]}{g[1-n(1-k)][3-n(1+k)]^2-2(1+\beta)[2-\beta-n(1-\beta k)]}$
Π^*	$\frac{g(1-w)^2\{g[1-n(1-k)]^2[3-n(1+k)]^2-2[2-\beta-n(1-k\beta)]^2\}}{\{g[1-n(1-k)][3-n(1+k)]^2-2(1+\beta)[2-\beta-n(1-\beta k)]\}^2}$

An analytical inspection of the expressions in Table 1 allows to derive the following results.

Lemma 1. Irrespective of the extent of the network externality, the direct effect of the extent of technological spillovers on production is positive and proportional to the R&D effort. An increase in the extent of the positive (resp. negative) network externality strengthens (resp. weakens) this direct effect. An increase in the rate of compatibility goes in the same direction as the network externality effect depending on whether the network effect is positive or negative.

Proof. See the Appendix.

Lemma 2. Irrespective of the extent of the network externality, the indirect effect of the R&D activity, at the equilibrium, on production is positive and increases with the extent of technological spillovers. An increase in the extent of the positive (resp. negative) network externality strengthens (resp. weakens) this indirect effect. An increase in the rate of compatibility goes in the same direction as the network externality effect depending on whether the network effect is positive or negative.

Proof. See the Appendix.

Lemma 3. Irrespective of the extent of the network externality, the effect of knowledge spill-over on the R&D activity is negative for any $0 \leq \beta \leq 1$.

Proof. See the Appendix.

The following expression shows the effect of the extent of technological spill-over on output at the equilibrium:

$$\frac{dq^*}{d\beta} = \overbrace{\frac{\partial q^*}{\partial \beta}}^{+} + \overbrace{\frac{\partial q^*}{\partial x^*}}^{+} \cdot \overbrace{\frac{\partial x^*}{\partial \beta}}^{-}, \quad (8)$$

Eq. (8) is the total derivative of q^* for the spill-over rate. It shows that the total effect of a change in the extent of technological spill-over is composed of three partial effects passing through 1) a direct channel, the direct positive effect on the quantity (Lemma 1), and 2) a twofold indirect channel caused by the positive effect exerted by the R&D activity on production at the equilibrium (Lemma 2) and the negative effect exerted by the spill-over rate on the R&D activity (Lemma 3), i.e., the larger the extent of disclosure (positive externality) passing from one firm to another, the lower the need by each firm to invest in R&D.

Given these counterbalancing forces, the following results generally hold:

Proposition 1. [Consumer surplus]. [1] An increase in the extent of technological spill-over in a network industry monotonically increases (resp. decreases) q^* and CS^* if $\beta < \beta°$ (resp. $\beta > \beta°$), where $\beta° = \frac{1-n(1-k)}{2(1-nk)}$ is the rate of technological spill-over that maximises the output and consumer surplus. [2] If $n = 0$, then $\beta° = \frac{1}{2}$ (De Bondt et al., 1992). If $n > 0$ and $k < \frac{1}{2}$ (or $n < 0$ and $k > \frac{1}{2}$), then $\beta° < \frac{1}{2}$; if $n > 0$ and $k > \frac{1}{2}$ (or $n < 0$ and $k < \frac{1}{2}$), then $\beta° > \frac{1}{2}$. [3] If $n = \frac{1}{3k-1} = n°$, then $\beta° = 1$, where $n° \leq 1$ for any $k \geq \frac{2}{3}$, $n° < -1$ for any $0 < k < \frac{2}{3}$, $n° = -1$ if $k = 0$, and $n° = \frac{1}{2}$ if $k = 1$. [4] $n°$ is a monotonic decreasing function of k.

Proof. See the Appendix.

A priori, there exist two counterbalancing forces that knowledge disclosure triggers on production and consumer surplus at the equilibrium (see Eq. (8)). This holds irrespective of the existence of network goods, as already pinpointed by De Bondt et al. (1992). On the one hand, an increase in the spill-over rate increases production in proportion to the R&D activity chosen by both firms (positive direct effect). On the other hand, it reduces the level of R&D activity due to the knowledge appropriability problem (negative indirect effect). As the more intense the extent of disclosure, the lower the R&D activity, the more likely the sign of (8) turns to be negative. This is because, when β increases, the under-investment (indirect) effect of high spillovers becomes increasingly important. When $\beta < \beta°$, the positive direct cost-reducing effect of the spill-over rate on production is greater than the under-investment (indirect) effect. This implies that production and consumer surplus increase with β. When $\beta > \beta°$, the positive direct cost-reducing effect of the spill-over on production becomes lesser than the under-investment (indirect) effect so that production and consumer surplus reduce with β. Under non-network goods (De Bondt et al., 1992), this threshold is $1/2$. Under network goods, this threshold can be larger or smaller than $1/2$, depending on the relative extent of the (positive or negative) network strength and the degree of compatibility.

In what follows, we concentrate on the polar symmetric cases $k = 0$ (no compatibility) and $k = 1$ (full compatibility) as well as on the case of symmetric imperfect compatibility $k < 1$ to show the differences between an economy à la De Bondt et al. (1992) with non-network goods and a network industry.

The polar cases of symmetric full ($k = 1$) and no ($k = 0$) compatibility are studied and presented in Section 2.1. The corresponding results are reported in Proposition 1, Result 1, Result 2, and Figures 1-9. The other parameter values used to draw all the figures are $g = 4$ and $w = 0.8$. The value of g has been chosen to guarantee that the feasibility conditions of the model are satisfied for the values of n and k used to plot the figures and for any $0 \leq \beta \leq 1$.

The case of symmetric imperfect compatibility ($k < 1$) is shown numerically in Tables 2-5 and presented in Section 2.2 (see also the appendix for a complete set of optimal values of β when n and k vary in their relevant range of feasibility). The other parameter values used to compute the optimal values of β in all the tables are $g = 100$ and $w = 0.8$. The value of g is increased compared to those used in Section 2.1 to guarantee that the feasibility conditions of the model are satisfied for all values of $-1 \leq n < 1$ and $0 \leq k \leq 1$ used to build on the tables and for any $0 \leq \beta \leq 1$. The values of g and w used in the simulations have been chosen only for illustrative purposes, as the results that follow hold for any w for all values of g belonging to the relevant range of feasibility.

To avoid lengthening the article too much, we do not present other simulations here, but they can easily be reported to confirm the results of the work.

2.1. The polar cases of symmetric full ($k = 1$) and no ($k = 0$) compatibility

If the network externality is positive (resp. negative), an increase in the network strength shifts the demand curve outward (resp. inward), and this implies that production will increase (resp. reduce) for any given level of the price by eventually causing an increase (resp. a reduction) in the consumer surplus and the firm profit. The consumption externality (through the network strength) therefore strengthens or weakens the effects of knowledge disclosure on production depending on the relative weight of the degree of compatibility, as was reported in Proposition 1.

If the consumption externality is positive ($n > 0$) and the degree of compatibility between products is the highest ($k = 1$), the network strength can work positively with the highest effectiveness so that the positive direct cost-reducing effect of the spill-over rate becomes increasingly important with n and greater than in a non-network industry. The positive direct cost-reducing effect dominates the negative indirect under-investment effect for any $\beta < \beta°$. If $n > 0$ and $k = 1$, then $\beta° = \frac{1}{2(1-n)} > \frac{1}{2}$ for any $n > 0$. If $n \geq \frac{1}{2}$, then $\beta° \geq 1$. This implies that the positive cost-reducing effect of knowledge disclosure always dominates the negative indirect under-investment effect when the positive network strength is sufficiently high. Then, production and consumer surplus are monotonically increasing with β for any $0 \leq \beta \leq 1$.

If the consumption externality is positive ($n > 0$) and the degree of compatibility between products is the lowest ($k = 0$), the network strength can work positively with the lowest effectiveness so that the positive direct cost-reducing effect of the spill-over rate becomes less important with n and smaller than in a non-network industry. If $n > 0$ and $k = 0$, then $\beta° = \frac{1-n}{2} < \frac{1}{2}$ for any $n > 0$. The external benefits of the consumption externality are substantially reduced by a perfect degree of incompatibility. In this case, it is not possible to find a positive value of the network strength to let the positive cost-reducing effect of knowledge disclosure always dominate the negative indirect under-investment effect. Therefore, production and consumer surplus increase with β only in the range $0 \leq \beta \leq \beta°$, whose extent is smaller than in a non-network industry.

If the consumption externality is negative ($n < 0$) and the degree of compatibility between products is the highest ($k = 1$), the network strength can work negatively with the highest effectiveness so that the positive direct cost-reducing effect of the spill-over rate becomes less important with n and smaller than in a non-network industry. In this case, the negative network effect is augmented by the highest degree of compatibility, so that the negative network effect of one firm's product on its demand is added, through the degree of compatibility, to the negative network effect generated by the product of the rival. If $n < 0$ and $k = 1$, then $\beta° = \frac{1}{2(1-n)} < \frac{1}{2}$ for any $n < 0$. The external damages of the consumption externality are substantially augmented by a perfect degree of compatibility. In this case, it is not possible to find a negative value of the network strength to let the positive cost-reducing effect of knowledge disclosure always dominate the negative indirect under-investment effect. Therefore, production and consumer surplus increase with β only in the range $0 \leq \beta \leq \beta°$, whose extent is smaller than in a non-network industry.

If the consumption externality is negative ($n < 0$) and the degree of compatibility between products is the lowest ($k = 0$), the network strength can work negatively with the lowest effectiveness so that the positive direct cost-reducing effect of the spill-over rate becomes increasingly important with n and larger than in a non-network industry. In this case, the negative network effect is reduced by the lowest degree of compatibility, so that the negative network effect of one firm's product on its demand cannot be added to the negative network effect generated by the product of the rival. The positive direct cost-reducing effect dominates the negative indirect under-investment effect for any $\beta < \beta°$. If $n < 0$ and $k = 0$, then $\beta° = \frac{1-n}{2} > \frac{1}{2}$ for any $n < 0$. If $n = -1$, then $\beta° = 1$. This implies that the positive cost-reducing effect of knowledge disclosure always dominates the negative indirect under-investment effect when the negative network strength is at its highest rate so that production and consumer surplus are monotonically increasing with β for any $0 \leq \beta \leq 1$.

Figure 1 ($n = 0$), Figure 2 ($n > 0$), and Figure 3 ($n < 0$) clarify this issue showing the existence of a value of β (independent of g), corresponding to which the consumer surplus is maximised. If $n = 0$, this value is $1/2$. If $n \neq 0$, this value can be larger or smaller than 1 depending on the extent of the (positive or negative) network strength and the extent of the rate of compatibility. In the case of positive externalities ($n > 0$), e.g., software, mobile phone, and internet device, which is the case most observed in the market, a perfect degree of compatibility favours the birth of a positive monotonic relationship between consumer surplus and the spill-over rate. This positive relationship, which is due to the relative increasing of the positive direct cost-reducing effect of knowledge disclosure, holds for any $0 \leq \beta \leq 1$ if $n \geq 1/2$.

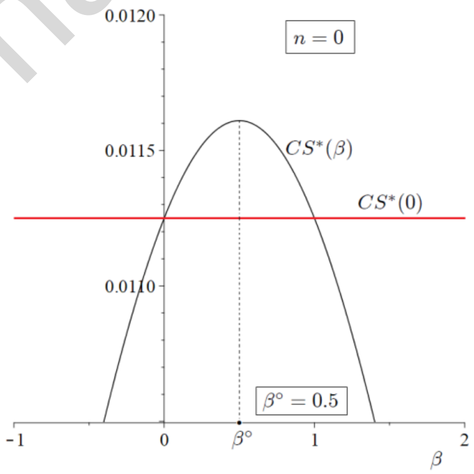
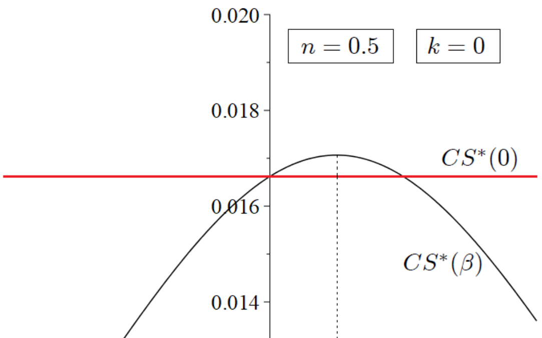
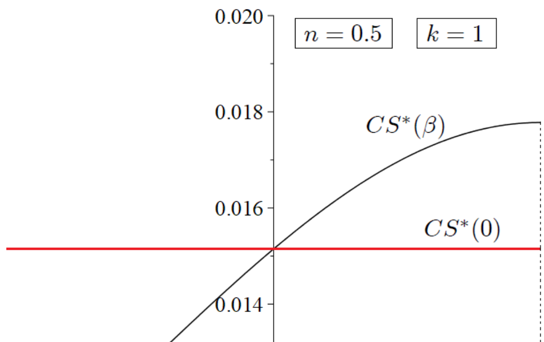


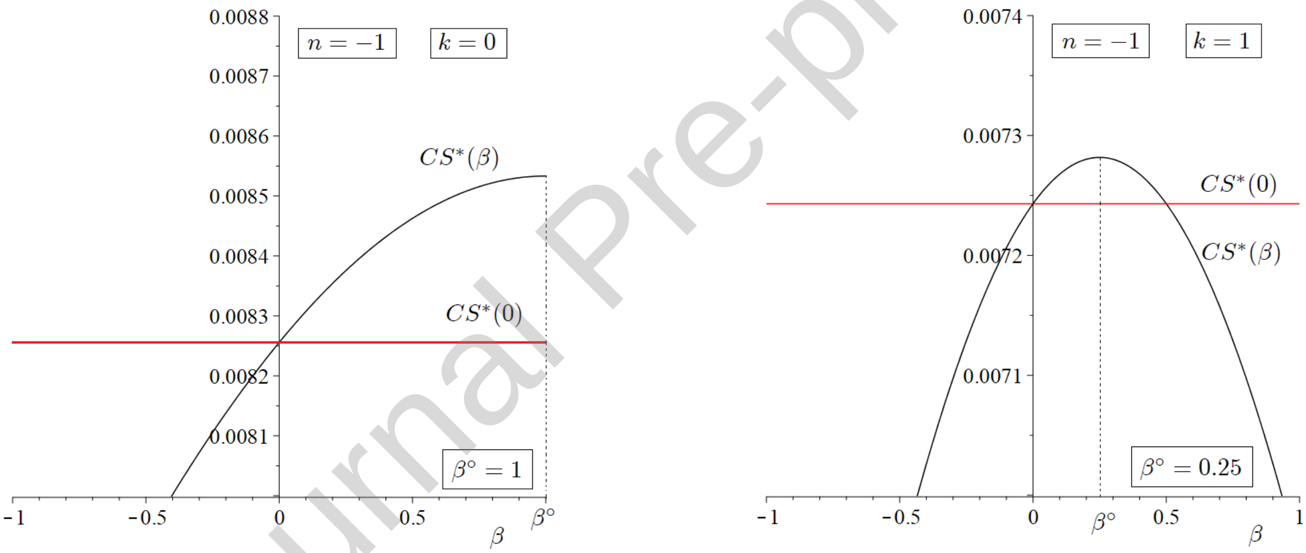
Figure 1. Consumer surplus as a function of β in a non-network industry ($n = 0$, De Bondt et al., 1992). The value of β that maximises $CS^*(\beta)$ is $\beta° = 0.5$. Parameters: $g = 4$ and $w = 0.8$.





(A) (B)

Figure 2. Consumer surplus as a function of β in a network industry with positive externality ($n = 0.5$). Panel A: no compatibility ($k = 0$); the value of β that maximises $CS^*(\beta)$ is $\beta^\circ = 0.25$. Panel B: full compatibility ($k = 1$); the value of β that maximises $CS^*(\beta)$ is $\beta^\circ = 1$. Parameters: $g = 4$ and $w = 0.8$.



(C) (D)

Figure 3. Consumer surplus as a function of β in a network industry with negative externality ($n = -1$). Panel A: no compatibility ($k = 0$); the value of β that maximises $CS^*(\beta)$ is $\beta^\circ = 1$. Panel B: full compatibility ($k = 1$); the value of β that maximises $CS^*(\beta)$ is $\beta^\circ = 0.25$. Parameters: $g = 4$ and $w = 0.8$.

Once we have disentangled the ambiguous effect of the R&D disclosure on the side of consumers, our focus moves to profits and social welfare. As the profit function and the welfare function cannot be treated in a neat analytical form, we cannot proceed to write down and rigorously show a proposition with arguments like those used for the consumer surplus but will simply state the related results (nonetheless supported by geometrical representations) to clarify the role of the extent of knowledge disclosure on profits (Result 1) and social welfare (Result 2). This is done by considering the polar cases of no compatibility ($k = 0$) and full compatibility ($k = 1$). We recall here that, when $n = 0$, the model boils down to an AJ duopoly à la De Bondt et al. (1992). In this sense, Result 1 and Result 2 include threshold values of β, i.e., $\beta^{\circ\circ}$ and $\beta^{\circ\circ\circ}$ resembling the result obtained by De Bondt et al. (1992). For an analysis of the shape of $\beta^{\circ\circ}$ and $\beta^{\circ\circ\circ}$ when g varies, we refer to the appendix that reports a thoughtful analysis of the AJ non-network duopoly developed by De Bondt et al. (1992).

Result 1. [Profits]. [1] An increase in the extent of technological spill-over in a network industry monotonically increases (resp. decreases) Π^* if $\beta < \beta^{\circ\circ}$ (resp. $\beta > \beta^{\circ\circ}$), where $\beta^{\circ\circ}$ is the profit-maximising value of the rate of knowledge disclosure. [2] If $n = 0$ (non-network industry), then $\beta^{\circ\circ} \in (0.9324,1)$, depending on g (De Bondt et al., 1992). Under positive network effects and full disclosure ($n > 0$ and $k = 1$) [or under negative network effects and no disclosure ($n < 0$ and $k = 0$)] then, for any g, we can have $\beta^{\circ\circ} = 1$ if the absolute value of the network strength is sufficiently high. Under positive network effects and no disclosure ($n > 0$ and $k = 0$) [or under negative network effects and full disclosure ($n < 0$ and $k = 1$)], then, for any g, we have $\beta^{\circ\circ} < 0.9324$ if the absolute value of the network strength is sufficiently high.

Result 1 follows from the analysis of Π^* in Table 1, that is $\frac{\partial \Pi^*}{\partial \beta} \gtrless 0 \Leftrightarrow \beta \lessgtr \beta^{\circ\circ}$. Unfortunately, this derivative cannot be treated in a neat analytical form. However, it is possible to resort to a geometrical representation depicting 1) the shape of Π^* when β varies for $n = 0$, clearly showing the existence of a maximum of Π^* corresponding to $\beta^{\circ\circ} = 0.9893$ (Figure 4), 2) the shape of Π^* when β varies for $n > 0$ in the cases of no compatibility, $k = 0$, and full compatibility, $k = 1$ (Figures 5A and 5B), and 3) the shape of Π^* when β varies for $n < 0$ in the cases of no compatibility, $k = 0$, and full compatibility, $k = 1$ (Figures 6A and 6B).

In greater detail, Figure 5B clearly shows a positive monotonic relationship between profits and the extent of knowledge disclosure in the case of positive network strength and full compatibility. Indeed, the positive network externality works out in the direction of expanding the market demand, causing a reduction in the negative effects of knowledge disclosure due to the appropriability by enabling the private incentive of each firm going in the direction of fully sharing the R&D-related outcomes to benefit from those produced by the rival (indeed, quantity and price both increase). Though R&D disclosure negatively affects the individual incentive to invest in R&D, the (positive) consumption externality reduces the relative weight of this negative effects by increasing the positive effect that the R&D spill-over play on production. Definitively, even when spillovers are very high, the indirect cost effect cannot counterbalance the increasing revenues effect, and then profits increase. Results go in the oppositive direction when the consumption externality is positive, but products are perfectly incompatible. In this case, in fact, the weight of the negative R&D cost effect becomes larger, and the profit-maximising value of the rate of knowledge disclosure falls short. Those cases can be observed in the absence of a network, thus reducing the incentive to spread the R&D-related outcomes. The case of negative network externality mirrors those of the positive externality, but the role of the extent of product compatibility is reversed. This is because an increase in the extent of the network externality shifts inward the market demand and then contributes to reduce both quantity and price. This increases the relative weight of the negative R&D cost effect. However, the more products are incompatible, the lower the negative R&D cost effect becomes.

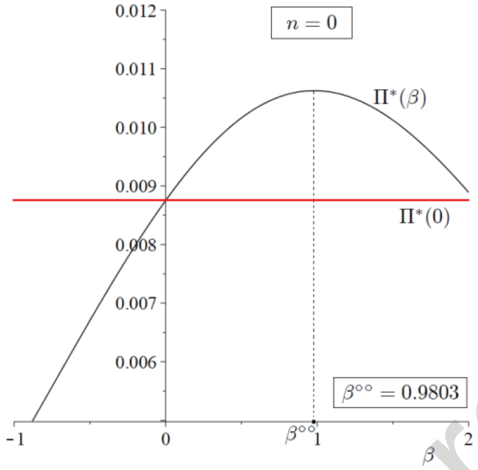
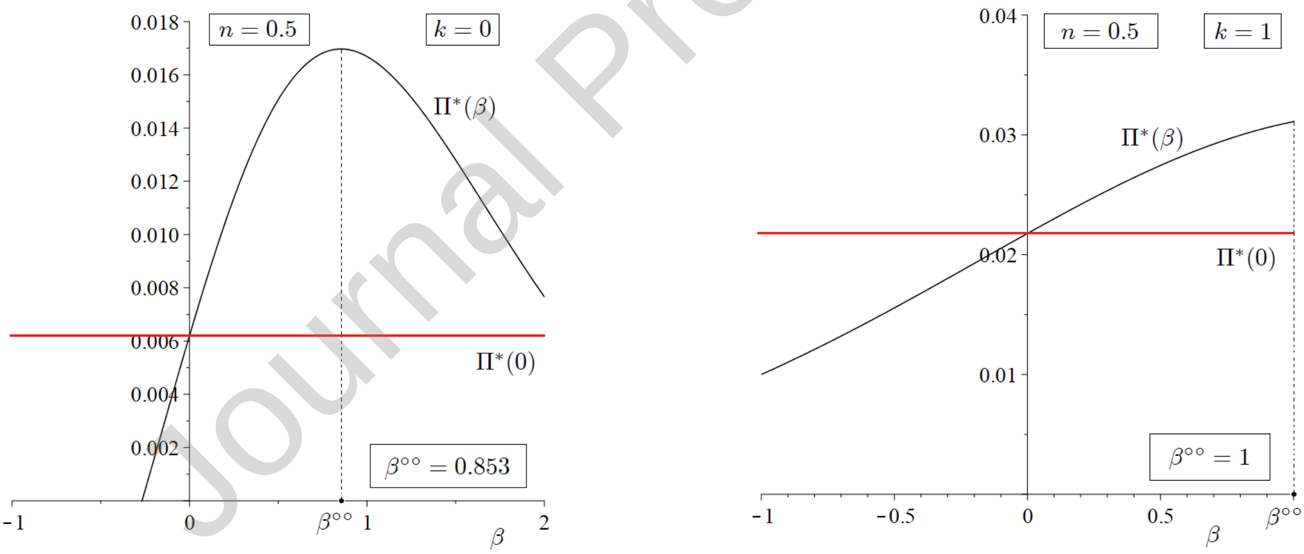
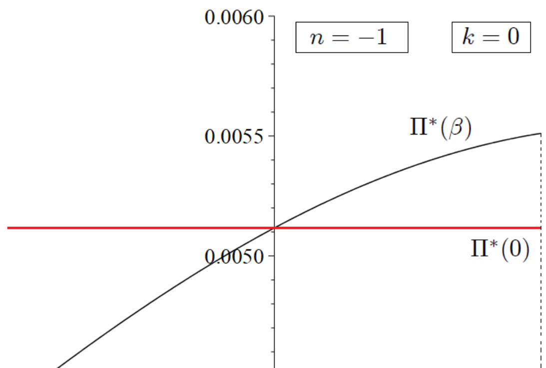


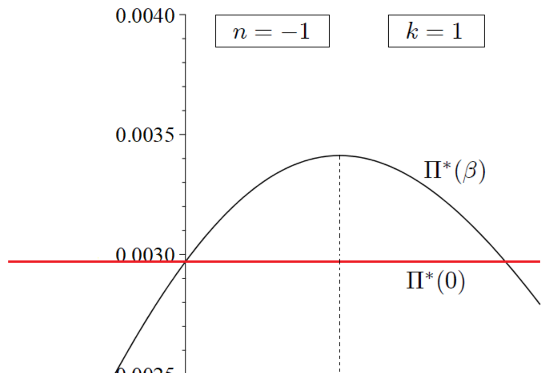
Figure 4. Profits as a function of β in a non-network industry ($n = 0$, De Bondt et al., 1992). The value of β that maximises $\Pi^*(\beta)$ is $\beta^{\circ\circ} = 0.9803$. Parameters: $g = 4$ and $w = 0.8$.



(A) (B)

Figure 5. Profits as a function of β in a network industry with positive externality ($n = 0.5$). Panel A: no compatibility ($k = 0$); the value of β that maximises $\Pi^*(\beta)$ is $\beta^{\circ\circ} = 0.853$. Panel B: full compatibility ($k = 1$); the value of β that maximises $\Pi^*(\beta)$ is $\beta^{\circ\circ} = 1$. Parameters: $g = 4$ and $w = 0.8$.





(A) (B)

Figure 6. Profits as a function of β in a network industry with negative externality ($n = -1$). Panel A: no compatibility ($k = 0$); the value of β that maximises $\Pi^*(\beta)$ is $\beta^{\circ\circ} = 1$. Panel B: full compatibility ($k = 1$); the value of β that maximises $\Pi^*(\beta)$ is $\beta^{\circ\circ} = 0.869$. Parameters: $g = 4$ and $w = 0.8$.

Result 2. [Social welfare]. [1] An increase in the extent of technological spill-over in a network industry monotonically increases (resp. decreases) W^* if $\beta < \beta^{\circ\circ\circ}$ (resp. $\beta > \beta^{\circ\circ\circ}$), where $\beta^{\circ\circ\circ}$ is the welfare-maximising value of the rate of knowledge disclosure. [2] If $n = 0$ (non-network industry), then $\beta^{\circ\circ\circ} \in (0.732, 0.8)$ depending on g (De Bondt et al., 1992). Under positive network effects and full disclosure ($n > 0$ and $k = 1$) [or under negative network effects and no disclosure ($n < 0$ and $k = 0$)], for any g, we can have $\beta^{\circ\circ\circ} = 1$ if the absolute value of the network strength is sufficiently high. Under positive network effects and no disclosure ($n > 0$ and $k = 0$) [or under negative network effects and full disclosure ($n < 0$ and $k = 1$)], for any g, we can have $\beta^{\circ\circ\circ} < 0.732$ if the absolute value of the network strength is sufficiently high.

Result 2 follows from the analysis of W^* in Table 1, that is $\frac{\partial W^*}{\partial \beta} \gtrless 0 \Leftrightarrow \beta \lesseqgtr \beta^{\circ\circ\circ}$. Unfortunately, this derivative cannot be treated in a neat, analytical form. However, it is possible to resort to a geometrical representation depicting 1) the shape of W^* when β varies for $n = 0$, clearly showing the existence of a maximum of W^* corresponding to $\beta^{\circ\circ\circ} = 0.779$ (Figure 7); 2) the shape of W^* when β varies for $n > 0$ in the cases of no compatibility, $k = 0$, and full compatibility, $k = 1$ (Figures 8A and 8B); and 3) the shape of W^* when β varies for $n < 0$ in the cases of no compatibility, $k = 0$, and full compatibility, $k = 1$ (Figures 9A and 9B).

The implication of Result 2 is striking. Unlike De Bondt et al. (1992), who argue that the target of maximal welfare would not require full disclosure in a non-network duopoly with homogeneous products, the network externality may solve the trade-off occurring between the consumers' interest and the producers' interest by reducing the weight of the negative impact of the R&D cost effect. The result then establishes that spreading R&D-related outcomes at the highest rate (public good, i.e., full disclosure) represents a win-win result going toward a Pareto-superior scenario than any value of the rate of knowledge disclosure smaller than one.

Importantly, full disclosure is optimal when the (absolute value of) the network externality – acting on the demand side – is sufficiently high. However, this result depends on the relative size of the degree of compatibility of products of network i and network j. Specifically, full disclosure can be optimal under full compatibility, partial compatibility or no compatibility. A positive network externality favours optimal full disclosure through high or full compatibility between products of the two networks. A negative network externality favours optimal full disclosure through low or no compatibility between products of the two networks. Therefore, going through full disclosure in network industries strictly depends on the values of n and k: (1) positive network externalities (bandwagon effect) should be associated with high/full degree of compatibility, and (2) negative network externalities (snob effect) should be associated with low/no compatibility. These two results and the subsequent policy recipes will be confirmed in Section 2.2, studying the case of symmetric imperfect compatibility (see Tables 2-5).

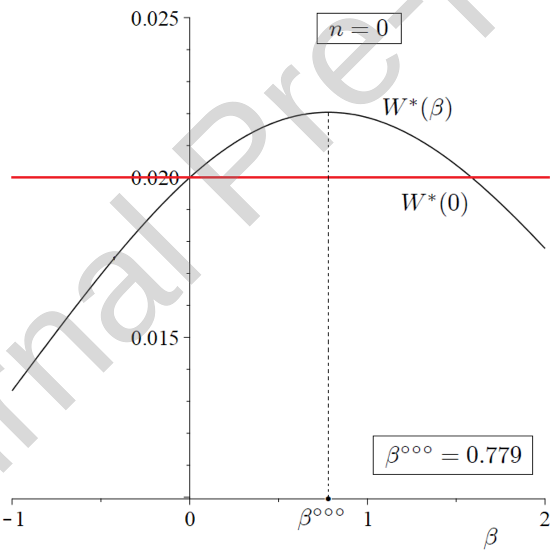
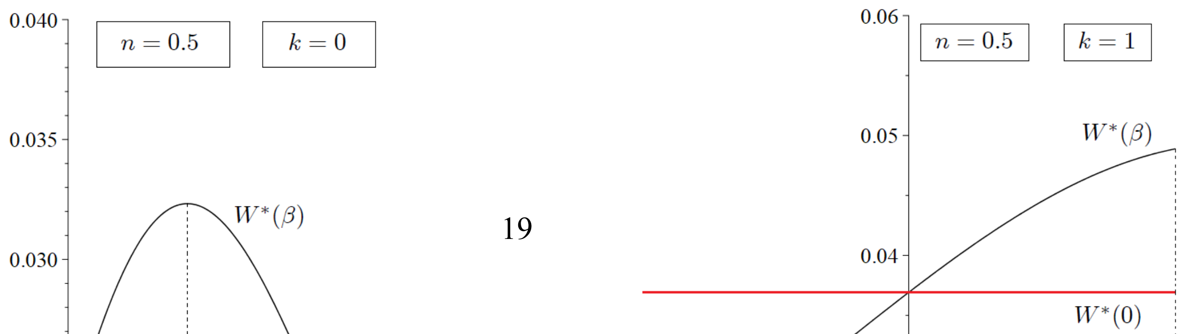
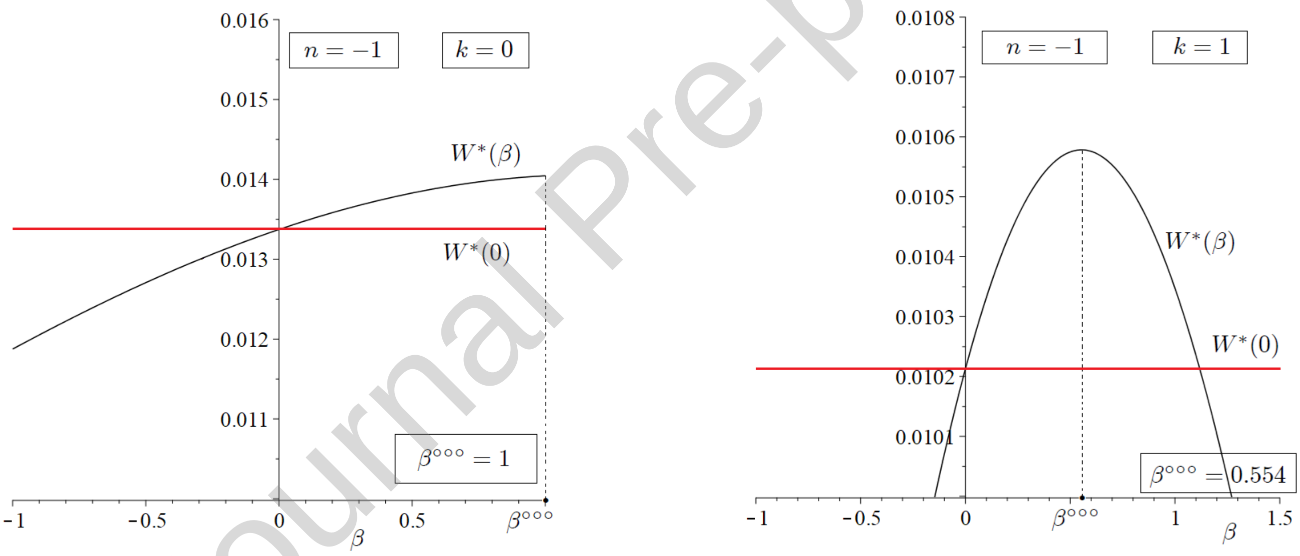


Figure 7. Social welfare as a function of β in a non-network industry ($n = 0$, De Bondt et al., 1992). The value of β that maximises $W^*(\beta)$ is $\beta^{\circ\circ\circ} = 0.779$. Parameters: $g = 4$ and $w = 0.8$.



(A) (B)

Figure 8. Social welfare as a function of β in a network industry with positive externality ($n = 0.5$). Panel A: no compatibility ($k = 0$); the value of β that maximises $W^*(\beta)$ is $\beta^{\circ\circ\circ} = 0.671$. Panel B: full compatibility ($k = 1$); the value of β that maximises $W^*(\beta)$ is $\beta^{\circ\circ\circ} = 1$. Parameters: $g = 4$ and $w = 0.8$.



(A) (B)

Figure 9. Social welfare as a function of β in a network industry with negative externality ($n = -1$). Panel A: no compatibility ($k = 0$); the value of β that maximises $W^*(\beta)$ is $\beta^{\circ\circ\circ} = 1$. Panel B: full compatibility ($k = 1$); the value of β that maximises $W^*(\beta)$ is $\beta^{\circ\circ\circ} = 0.554$. Parameters: $g = 4$ and $w = 0.8$.

2.2. The case of symmetric imperfect compatibility ($k < 1$)

The analysis so far is augmented to incorporate the case-symmetric-imperfect compatibility $k < 1$. As the producer surplus and the social welfare function are not easily tractable analytically, we resort to numerical analysis to calculate the values of the extent of disclosure that maximise the consumer surplus (β°), the producer surplus ($\beta^{\circ\circ}$), and the social welfare ($\beta^{\circ\circ\circ}$) in equilibrium for a wide spectrum of the strength of the network externality and let them vary with the degree of compatibility. In the interest of space, we present here the analysis for two positive values of n ($n = 0.3$ and $n = 0.7$) and two negative values of n ($n = -0.3$ and $n = -0.7$) and leave the study of the optimal values of β for a complete set of values of n in the appendix. The cases of positive (resp. negative) consumption externality are summarised in Tables 2 and 3 (resp. Tables 4 and 5). The parameter values used to compute β°, $\beta^{\circ\circ}$, and $\beta^{\circ\circ\circ}$ are $g = 100$ and $w = 0.8$. The value of g is high enough to guarantee that the feasibility conditions are satisfied for all values of n and k used in the simulations and for any $0 \leq \beta \leq 1$. These values, however, are used only for illustrative purposes, as the results below hold for all values of the main parameters of the problem that satisfy the feasibility conditions.

The tables confirm the results obtained in the previous section: from a societal perspective, if the network externality is positive, it is optimal (second-best outcome) to increase the extent to which R&D-related information is shared between firms when the degree of compatibility increases. Unlike this, if the network externality is negative, it is optimal (second-best outcome) to increase the extent to which R&D-related information is shared between firms when the degree of compatibility is reduced. Therefore, full disclosure (open source) is favoured by high (resp. low) values of the degree of compatibility when the network externality is positive (resp. negative), contributing to improve (resp. reduce) the bandwagon (resp. snob) effect of the positive (resp. negative) consumption externality.

Table 2. Optimal values of β when $n = 0.3$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.35	0.376	0.404	0.434	0.465	0.5	0.536	0.575	0.618	0.664	0.714
$\beta^{\circ\circ}$	0.911	0.924	0.939	0.957	0.976	0.998	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.725	0.741	0.759	0.779	0.802	0.828	0.857	0.888	0.923	0.962	1

Table 3. Optimal values of β when $n = 0.7$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.15	0.198	0.255	0.322	0.402	0.5	0.62	0.774	0.977	1	1
$\beta^{\circ\circ}$	0.868	0.865	0.875	0.898	0.938	0.998	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.726	0.722	0.734	0.762	0.809	0.877	0.972	1	1	1	1

Table 4. Optimal values of β when $n = -0.3$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.65	0.616	0.584	0.555	0.526	0.5	0.474	0.45	0.427	0.405	0.384
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.982	0.967	0.953	0.941	0.929
$\beta^{\circ\circ\circ}$	0.899	0.87	0.844	0.819	0.796	0.774	0.754	0.736	0.719	0.703	0.689

Table 5. Optimal values of β when $n = -0.7$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.85	0.761	0.684	0.615	0.554	0.5	0.45	0.406	0.365	0.328	0.295
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.967	0.941	0.919	0.902	0.888
$\beta^{\circ\circ\circ}$	1	0.974	0.904	0.844	0.752	0.747	0.708	0.675	0.646	0.623	0.603

3. Conclusions

This work has investigated the impact of the exogenous R&D disclosure on social welfare in network industries, challenging the established result that R&D private information should never be fully spread in a Cournot duopoly with homogeneous products and exogenous technological spillovers (as established by De Bondt et al., 1992). Knowledge has the nature of public goods (Poyago-Theotoky, 2007); consequently, two disagreeable aspects emerge: 1) due to appropriability, firms under-invest (resp. over-invest) in R&D when there are no spillovers (resp. there are spillovers) compared to the social optimum, and 2) as innovators are not rewarded for disclose knowledge, the value of R&D-related information shared by firms is lower than the social optimum. In contrast to the locus communis, this work has shown that, in the presence of positive network effects – as is the case of most innovative and growing industries – the achievement of the social optimum tends to require the full disclosure of the private R&D outcomes of firms. If the government could control the extent of the technological spillovers, it would choose an open-source policy, in sharp contrast with the policy of granting a certain extent of knowledge protection in the traditional non-network case, following the policy recipes detailed in Buccella et al. (2023a) about the disclosure of R&D-related information.

The results of the present work rely on a set of simplifying assumptions such as quantity competition with homogeneous goods. A first extension is to introduce product differentiation and check the robustness of these results in both Cournot and Bertrand competition duopolies.

We can also continue the analysis of optimal disclosure, considering the basic quantity competition setting and studying the relationship between different degrees of market competition through a model including conjectural variation. Our finding could be checked by using a model à la Kamien et al. (1992), in which spillovers are in the R&D input.

Finally, the issue of the optimal spill-over can be investigated not only for process innovations but also for product innovation (which, for instance, increases the choke price of a linear demand).

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Compliance with ethical standards

Disclosure of potential conflict of interest The authors declare that they have no conflict of interest.

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Declarations of interest None.

Appendix

The microeconomic foundations of the market demand if firms do not commit themselves to an announced output level

This section briefly presents the microeconomic foundations of the market demand if firms do not commit themselves to an announced output level before consumers make their purchase decision. This follows the mechanism detailed by Katz and Shapiro (1985) in the model presented in the main body of the text of their contribution with consumers having rational expectations.

On the supply side, the economy is bi-sectorial with a competitive sector producing the numeraire good m and a duopolistic industry in which firm i and firm j ($i = \{1,2\}$; $i \neq j$) produce network goods of variety (network) i and variety (network) j, respectively. These goods are perceived as homogeneous by customers. Firms also face the perspective of investing in cost-reducing R&D (process innovation) along the line of the model developed by d'Aspremont and Jacquemin (1988, 1990).

On the demand side, there are identical consumers with preferences described by the utility function $V(q_i, q_j, y_i, y_j, m) = U(q_i, q_j, y_i, y_j) + m$, which is linear in the numeraire good m. Utility V is maximised subject to the budget constraint $p_i q_i + p_j q_j + m = R$, where U is a twice-continuously differentiable function, q_i and q_j are the control variables of the problem, p_i and p_j represent the price of (i.e., the marginal willingness to pay of the representative consumer for) the product of variety i and variety j, respectively, and R is the consumer's exogenous nominal income. This income is high enough to avoid the emergence of income effects on the demand of q_i and q_j (i.e., the goods enter non-linearly in V). In this regard, in fact, the utility function V is quasi-linear in m so that all the related properties about the demand of m and that of q_i and q_j hold (Amir et al., 2017; Choné and Linnemer, 2020).

In contrast to the traditional IO literature, we assume the existence of network externalities in consumption, i.e., one person's demand also depends on the demand of other customers. In this regard, y_i represents an external effect denoting the consumers' expectations about firm i's equilibrium total sales.

The simple mechanism of network effects described so far follows the seminal work of Katz and Shapiro (1985), used in several recent articles belonging to the IO literature framed in strategic competitive markets with (Naskar and Pal, 2020; Shrivastav, 2021; Buccella et al., 2022) and without process innovation (Hoernig, 2012; Chirco and Scrimitore, 2013; Bhattacharjee and Pal, 2014; Pal, 2014, 2015; Song and Wang, 2017; Fanti and Gori, 2019; Choi and Lim, 2022).

The function U follows the specification of a quadratic utility:

$$U = q_i + q_j - \frac{1}{2}(q_i^2 + q_j^2 + 2q_iq_j) + n[q_i(y_i + ky_j) + q_j(y_j + ky_i)] - \frac{n}{2}(y_i^2 + y_j^2 + 2ky_iy_j), \quad \text{(A.1)}$$

where $-1 \leq n \leq 1$ is the strength of the network effect ($n = 0$ represents the standard case of non-network goods). Positive (resp. negative) values of n reflect a positive (resp. negative) consumption externality. A positive (negative) network externality implies that an increasing number of users increases (reduces) the value of the goods for each consumer. The terms $y_i + ky_j$ and $y_j + ky_i$ represent the expected effective network size of firm i's consumers and of firm j's consumers, respectively. The parameter $0 \leq k \leq 1$ measures the degree of compatibility of the network of product j toward the network of product i (and vice versa). For example, $k = 1$ implies that the network of product j is perfectly compatible with the network of product i (full compatibility), whereas $k = 0$ implies that the network of product j is perfectly incompatible with the network of product i (no compatibility). The intermediate cases $0 < k < 1$ represent different degrees of imperfect or asymmetric compatibility of the network of product j with the network of product i. We note that, if $k < 1$, then $-1 \leq n \leq 1$; if $k = 1$, then $-1 \leq n < 1$.

The solution of the constrained utility maximisation problem by the representative consumer following Amir et al. (2017) and Choné and Linnemer (2020) gives the following linear inverse demand for product of network i:

$$p_i = 1 - q_i - q_j + n(y_i + ky_j),\ i,j = \{1,2\},\ i \neq j. \quad \text{(A.2)}$$

The market demand in (A.2) resembles that of the model developed by Hoernig (2012), who was the first to consider network externalities à la Katz and Shapiro (1985) in a model with linear demand.

Feasibility conditions

This section summarises the feasibility conditions following the equilibrium values of the main variables of the model, which are summarised in Table 1 in the main text (see also Hinloopen, 2015; Buccella et al., 2022, 2023b). These conditions define the parametric range in which the Nash equilibrium of the model is meaningful, given by the following inequalities:

$$g > \frac{2(1-\beta)[2-\beta-n(1-\beta k)]}{[1-n(1-k)]^2[3-n(1+k)]} \coloneqq g_{SC}^{\beta_{low}}(\beta, n, k), \quad \text{(A.3)}$$

which represents the stability condition (SC) prevailing when x_i and x_j are strategic substitutes, i.e., $\beta < \frac{1-kn}{2-n}$,

$$g > \frac{2(1+\beta)[2-\beta-n(1-\beta k)]}{[1-n(1-k)][3-n(1+k)]^2} := g_{SC}^{\beta_{high}}(\beta, n, k), \quad \text{(A.4)}$$

which represents the stability condition (SC) prevailing when x_i and x_j are strategic complements, i.e., $\beta > \frac{1-kn}{2-n}$,

$$g > \frac{2[2-\beta-n(1-\beta k)]^2}{[1-n(1-k)]^2[3-n(1+k)]^2} := g_{SOC}(\beta, n, k), \quad \text{(A.5)}$$

which represents the second-order condition (SOC) for a maximum (concavity), and

$$g > \frac{2(1+\beta)[2-\beta-n(1-\beta k)]}{w[1-n(1-k)][3-n(1+k)]^2} := g_T(\beta, n, k, w), \quad \text{(A.6)}$$

which represents the R&D cost condition (T) that must hold to guarantee that the inequality $w - x_i - \beta x_j > 0$ is fulfilled at the equilibrium.

The stability conditions require that $\left|\frac{dx_i}{dx_j}\right| < 1$ in both cases of strategic substitutability and strategic complementarity. The second-order condition for a maximum (concavity) requires that $\frac{\partial^2 \Pi_i(x_i,x_j)}{\partial x_i^2}\bigg|_{x_i=x^*} < 0$.

From (A.3)-(A.6), the R&D cost condition tends toward the stability condition prevailing when x_i and x_j are strategic complements if $w \to 1$. The stability conditions that prevail when x_i and x_j are strategic substitutes ($\beta < \frac{1-kn}{2-n}$) or strategic complements ($\beta > \frac{1-kn}{2-n}$) are always larger than the second-order condition in the (β, g) space. Therefore, the second-order condition is never binding for any $0 \leq \beta \leq 1$. Definitively, if $w \leq \frac{1-n(1-k)}{3-n(1+k)}$, then the R&D cost condition is binding for any $0 \leq \beta \leq 1$ in the (β, g) space. If $w > \frac{1-n(1-k)}{3-n(1+k)}$, then the stability condition prevailing when x_i and x_j are strategic substitutes is binding for any $0 \leq \beta < \frac{3w-1-n[k-1+w(1+k)]}{3w+1-n[1-k+w(1+k)]}$, and the R&D cost condition is binding for any $\frac{3w-1-n[k-1+w(1+k)]}{3w+1-n[1-k+w(1+k)]} < \beta \leq 1$ in the (β, g) space. In what follows, we assume that g is always larger than the prevailing constraint to guarantee economic feasibility in the (β, g) space.

Proofs of the main results

Proof of Lemma 1. By considering the sign of the first derivative of Eq. (6) in the main text with respect to β, evaluated at equilibrium, we obtain $\frac{\partial \bar{q}_i(x_i,x_j)}{\partial \beta}\bigg|_{\substack{x_i=x^* \\ x_j=x^*}} = \frac{x^*}{3-n(1+k)} > 0$. The second and third points follow from $\frac{\partial^2 \bar{q}_i(x_i,x_j)}{\partial \beta \partial n}\bigg|_{\substack{x_i=x^* \\ x_j=x^*}} > 0$ (resp. < 0) for any $n > 0$ (resp. $n < 0$) and $\frac{\partial^2 \bar{q}_i(x_i,x_j)}{\partial \beta \partial k}\bigg|_{\substack{x_i=x^* \\ x_j=x^*}} > 0$ (resp. < 0) for any $n > 0$ (resp. $n < 0$), respectively. **Q.E.D.**

Proof of Lemma 2. The proof straightforwardly follows from the sign of the first derivative of Eq. (6) in the main text with respect to x^*; that is, $\frac{\partial \bar{q}_i(x^*)}{\partial x^*} = \frac{1+\beta}{3-n(1+k)} > 0$. The second and third points follow from $\frac{\partial^2 \bar{q}_i(x^*)}{\partial x^* \partial n} > 0$ (resp. < 0) for any $n > 0$ (resp. $n < 0$) and $\frac{\partial^2 \bar{q}_i(x^*)}{\partial x^* \partial k} > 0$ (resp. < 0) for any $n > 0$ (resp. $n < 0$), respectively. **Q.E.D.**

Proof of Lemma 3. The proof straightforwardly follows from the sign of the first derivative of x^* with respect to β. If $n = 0$, then $\frac{\partial x^*}{\partial \beta} = \frac{-2(1-w)[9g-2(2-\beta)^2]}{[9g-2(1+\beta)(2-\beta)]^2} < 0$ for any $0 \leq \beta \leq 1$. This is because the term in brackets at the numerator should always be positive as it represents the second-order condition. If $n \neq 0$, then $\frac{\partial x^*}{\partial \beta} = \frac{2(1-w)\{g(1-nk)[1-n(1-k)][3-n(1+k)]^2-2[2-\beta-n(1-\beta k)]^2\}}{\{g[1-n(1-k)][3-n(1+k)]^2-2(1+\beta)[2-\beta-n(1-\beta k)]\}^2} < 0$ for any $0 \leq \beta \leq 1$. This is because the numerator is a quadratic function of β, whose solutions are given by $\beta_1^x < 0$ and $1 > \beta_2^x > 0$, which are given by

$$\beta_1^x = \frac{4-2n-[3-n(1+k)]\sqrt{2g(1-nk)[1-n(1-k)]}}{[1-n(1-k)][3-n(1+k)]^2},$$

and

$$\beta_2^x = \frac{4-2n+[3-n(1+k)]\sqrt{2g(1-nk)[1-n(1-k)]}}{[1-n(1-k)][3-n(1+k)]^2}.$$

Q.E.D.

Proof of Proposition 1. The proof of Point [1] follows from:

$$sgn\left\{\frac{dq^*}{d\beta}\right\} = sgn\left\{\frac{dCS^*}{d\beta}\right\} = sgn\{1-n(1-k)-2\beta(1-nk)\}.$$

Then, $\frac{dq^*}{d\beta} > 0$ and $\frac{dCS^*}{d\beta} > 0$ (resp. < 0) for any $\beta < \beta^\circ$ (resp. $\beta > \beta^\circ$), where β° is the spill-over rate that maximises q^* and CS^*. The proof of Points [2] and [3] immediately follows from the study of β°. The proof of Point [4] is given by $\frac{dn^\circ}{dk} = \frac{-3}{(3k-1)^2} < 0$. **Q.E.D.**

Analysis of the main results emerging in a non-network industry (De Bondt et al., 1992)

This section briefly surveys a non-network duopoly à la De Bondt et al. (1992) with homogeneous goods and presents some results resembling those pinpointed in the main text of the article for the case $n = 0$, showing – amongst other things – the shape of the optimal values of the extent of the rate of disclosure that maximise the consumer surplus (β°), the producer surplus ($\beta^{\circ\circ}$), and the social welfare ($\beta^{\circ\circ\circ}$) in equilibrium when g varies.

By assuming $n = 0$, the linear (normalised inverse) demand for the product of firm i is:

$$p = 1 - Q,\ i,j = \{1,2\},\ i \neq j, \tag{A.7}$$

where $Q = q_i + q_j$ is the total supply, whereas the total cost of production and the R&D cost of firm i become:

$$C_i(q_i, x_i, x_j) = (w - x_i - \beta_j x_j)q_i, \tag{A.8}$$

and

$$X_i(x_i) = \frac{g}{2}x_i^2, \tag{A.9}$$

Using Eqs. (A.7)-(A.9) and assuming $\beta_i = \beta_j = \beta$, the profit function of firm i can be written as follows:

$$\Pi_i = (1 - Q)q_i - (w - x_i - \beta x_j)q_i - \frac{g}{2}x_i^2. \tag{A.10}$$

At the market stage of the game, each firm chooses output to maximise profits. Solving the maximisation problem in Eq. (A.10) with respect to q_i, we obtain firm i's downward-sloping reaction function in the (q_i, q_j) space as a function also of R&D efforts x_i and x_j:

$$\frac{\partial \Pi_i}{\partial q_i} = 0 \Leftrightarrow q_i(q_j, x_i, x_j) = \frac{1-w-q_j+x_i+\beta x_j}{2}. \tag{A.11}$$

From Eq. (A.11) and the counterpart for firm j, we obtain the system of output reaction functions that depend on the R&D efforts. The solution of the system of the reaction functions $q_i(q_j, x_i, x_j)$ for $i = \{1,2\}$, $i \neq j$ leads to the following equilibrium output at the second stage of the game:

$$\bar{q}_i(x_i, x_j) = \frac{1-w+(2-\beta)x_i+(2\beta-1)x_j}{3}. \tag{A.12}$$

Eq. (A.12) reveals that firm i's output depends both on its R&D investment and on the R&D investment of the rival (firm j) because of the R&D externality. On the one hand, firm i's R&D investment leads to a direct expansion of its output because of the strategic interaction with the rival. On the other hand, because of the size of R&D-related information externalities flowing from firm i to firm j, x_i mitigates the expansion of q_i, reducing production via this channel. Nonetheless, the latter effect never offset the strength of the former, even in the case of full disclosure ($\beta = 1$): an increase in x_i always increases q_i. Moreover, the firms' R&D information flow leads to a further increase in firm i's output via the R&D investment of firm j if and only if the degree of technological spill-overs is satisfactorily large ($\beta > 1/2$, i.e., x_i and x_j are strategic complements); otherwise, if the technological spill-overs are adequately small ($\beta < 1/2$, i.e., x_i and x_j are strategic substitutes), output decreases. Thus, increasing market share in the product market needs a high disclosure rate.

Substituting out Eq. (A.12) and its counterpart for firm j in Eq. (A.12), we get firm i's profits as a function of x_i and x_j. At the first stage of the game, maximisation of firm i's profits with respect to x_i yields:

$$\frac{\partial \Pi_i(x_i, x_j)}{\partial x_i} = 0 \Leftrightarrow x_i(x_j) = \frac{2(2-\beta)[1-w+(2\beta-1)x_j]}{9g+2\beta(4-\beta)-8}. \tag{A.13}$$

Eq. (A.13) and the corresponding counterpart for firm j provides the system of R&D reaction functions in the space (x_i, x_j). The solution of this system yields firm i's (and consequently the symmetrical firm j's response) investment size in equilibrium, $x^*(\beta)$.

Table A.1 summarizes these results together with the other main equilibrium outcomes of the model when the R&D activity is disclosed at the exogenous rate β, where $CS = 2q^2$, $PS = 2\Pi$ and $W = CS + PS$ represent consumers' surplus, producers' surplus and social welfare, respectively.

The feasibility conditions in a non-network economy à la DE Bondt et al. (1992) are the following: 1) $g > \frac{2(1-\beta)(2-\beta)}{3} \coloneqq g_{SC}^{\beta_{low}}(\beta)$ (the stability condition that prevails when x_i and x_j are strategic substitutes, i.e., $\beta < 1/2$), 2) $g > \frac{2(1+\beta)(2-\beta)}{9} \coloneqq g_{SC}^{\beta_{high}}(\beta)$ (the stability condition that prevails when x_i and x_j are strategic complements, i.e., $\beta > 1/2$), 3) $g > \frac{2(2-\beta)^2}{9} \coloneqq g_{SOC}(\beta)$ (the second-order condition), and 4) $g > \frac{2(1+\beta)(2-\beta)}{9w} \coloneqq g_T(\beta, w)$ (the R&D cost condition that must hold to guarantee that the inequality $w - x_i - \beta x_j > 0$ is fulfilled at the equilibrium), which tends to the stability condition prevailing when x_i and x_j are strategic complements if $w \to 1$. The stability conditions prevailing when x_i and x_j are strategic substitutes ($\beta < 1/2$) or strategic complements ($\beta > 1/2$) are always larger than the second-order condition in the (β, g) space. Therefore, the second-order condition is never binding for any $0 \leq \beta \leq 1$. Definitively, if $w \leq 1/3$, then the R&D cost condition is binding for any $0 \leq \beta \leq 1$ in the (β, g) space. If $w > 1/3$, then the stability condition prevailing when x_i and x_j are strategic substitutes is binding for any $0 \leq \beta < \frac{3w-1}{3w+1}$, and the R&D cost condition is binding for any $\frac{3w-1}{3w+1} < \beta \leq 1$ in the (β, g) space. In what follows, we assume that g is always larger than the constraint prevailing to guarantee economic feasibility in the (β, g) space.

Table A.1. Equilibrium outcomes in the AJ duopoly model with spillovers and non-network goods (De Bondt et al., 1992).

$x^*(\beta)$	$\frac{2(1-w)(2-\beta)}{9g-2(1+\beta)(2-\beta)}$
$q^*(\beta)$	$\frac{3g(1-w)}{9g-2(1+\beta)(2-\beta)}$
$p^*(\beta)$	$\frac{3g(1+2w)-2(1+\beta)(2-\beta)}{9g-2(1+\beta)(2-\beta)}$
$\Pi^*(\beta)$	$\frac{g(1-w)^2[9g-2(2-\beta)^2]}{[9g-2(1+\beta)(2-\beta)]^2}$

$CS^*(\beta)$	$\frac{18g^2(1-w)^2}{[9g-2(1+\beta)(2-\beta)]^2}$
$W^*(\beta)$	$\frac{4g(1-w)^2[9g-(2-\beta)^2]}{[9g-2(1+\beta)(2-\beta)]^2}$

Having derived the equilibrium values of all the relevant variables, an analytical inspection allows us to derive the following Lemmas.

Lemma A.1. The direct effect of the spillovers rate on the quantity produced by both firms is always positive and proportional to the R&D effort.

Proof. This straightforwardly follows from the sign of the first derivative of Eq. (A.12) with respect to β, evaluated at equilibrium, that is $\frac{\partial \bar{q}_i(x_i,x_j)}{\partial \beta} = \frac{x^*}{3} > 0$.

Lemma A.2. The direct effect of the R&D investment on the quantity produced by firms is always positive and increasing with the levels of the spillover rate.

Proof. This straightforwardly follows from the sign of the first derivative of Eq. (A.12) with respect to x_i, evaluated at equilibrium, that is $\frac{\partial \bar{q}_i(x_i,x_j)}{\partial x_i} = \frac{1+\beta}{3} > 0$.

Lemma A.3. The effect of the knowledge circulation on R&D investment is always negative for every level of the spillover rate.

Proof. This straightforwardly follows from the sign of the first derivative of x^* with respect to β, that is $\frac{\partial x^*}{\partial \beta} = \frac{-2(1-w)[9g-2(2-\beta)^2]}{[9g-2(1+\beta)(2-\beta)]^2} < 0$ for any $0 \leq \beta \leq 1$. This is because the term in brackets should be always positive representing the second-order condition detailed so far.

Additionally, the following expression shows the total effect of the spillover rate on production:

$$\frac{dq^*}{d\beta} = \overbrace{\frac{\partial q^*}{\partial \beta}}^{+} + \overbrace{\frac{\partial q^*}{\partial x^*}}^{+} \cdot \overbrace{\frac{\partial x^*}{\partial \beta}}^{-}. \tag{A.14}$$

Eq. (A.14) is the total derivative of the quantity produced at equilibrium by the investing firms with respect to the spillover rate. The equation shows that the total effect of the spillover rate is composed of three partial effects working through both a direct channel, which is the partial direct positive effect on the quantity, and an indirect channel, composed of the partial effects exerted by the spillover rate on the R&D investment and the partial effect exerted by the R&D investment on the quantity produced at the equilibrium, which are positive and negative, respectively. Despite these counteracting effects, the following result generally holds:

Result A.1. An increase in the spillover rate monotonically increases (resp. decreases) the equilibrium production if $\beta \leq \beta^{\circ}$ (resp. $\beta > \beta^{\circ}$).

Proof. Result A.1 directly follows from the analysis of $q^*(\beta)$ from Table A.1. In fact,

$$\frac{\partial q^*}{\partial \beta} = \frac{6g(1-w)(2\beta-1)}{[9g-2(1+\beta)(2-\beta)]^2} \gtreqless 0 \Leftrightarrow \beta \lesseqgtr \beta^{\circ} = 1/2. \quad \text{(A.15)}$$

Corollary. As $CS^* = 2(q^*)^2$, then Result A.1 also holds for consumers' surplus.

A priori, there exist two counterbalancing forces that knowledge disclosure triggers on production and consumers' surplus at the equilibrium. On the one hand, it increases production in proportion to the R&D investment chosen by both firms. On the other hand, it reduces the level of R&D investment due to the knowledge appropriability problem. The more intense the extent of disclosure, the lower the R&D investment. The reason for the sign in (A.15) is that the under-investment effect of larger spillovers more than offsets the positive direct cost-reducing effect of the R&D investment on production. Figure A.1 clarifies this issue, clearly showing the existence of a value β (independent of g) corresponding to which the consumer surplus is maximised.

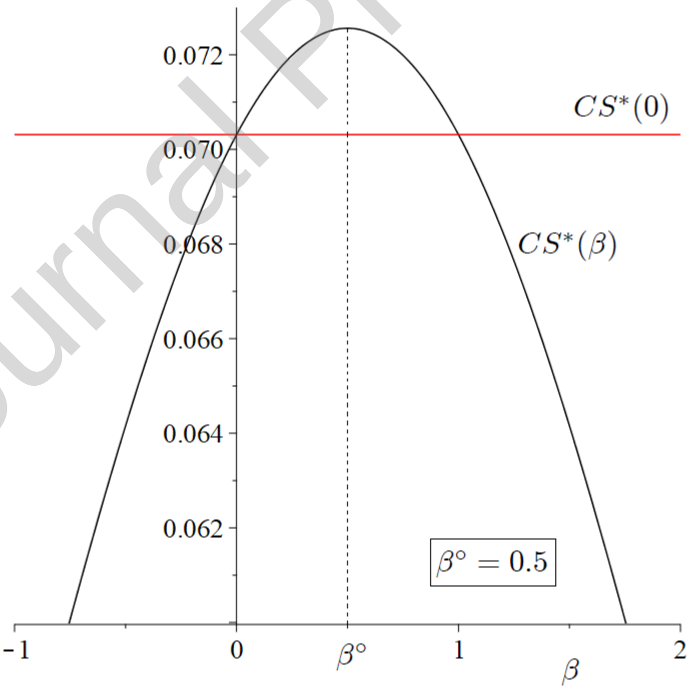


Figure A.1. Consumer surplus as a function of β in an AJ duopoly à la De Bondt et al. (1992). The value of β that maximises $CS^*(\beta)$ is $\beta^{\circ} = 0.5$.

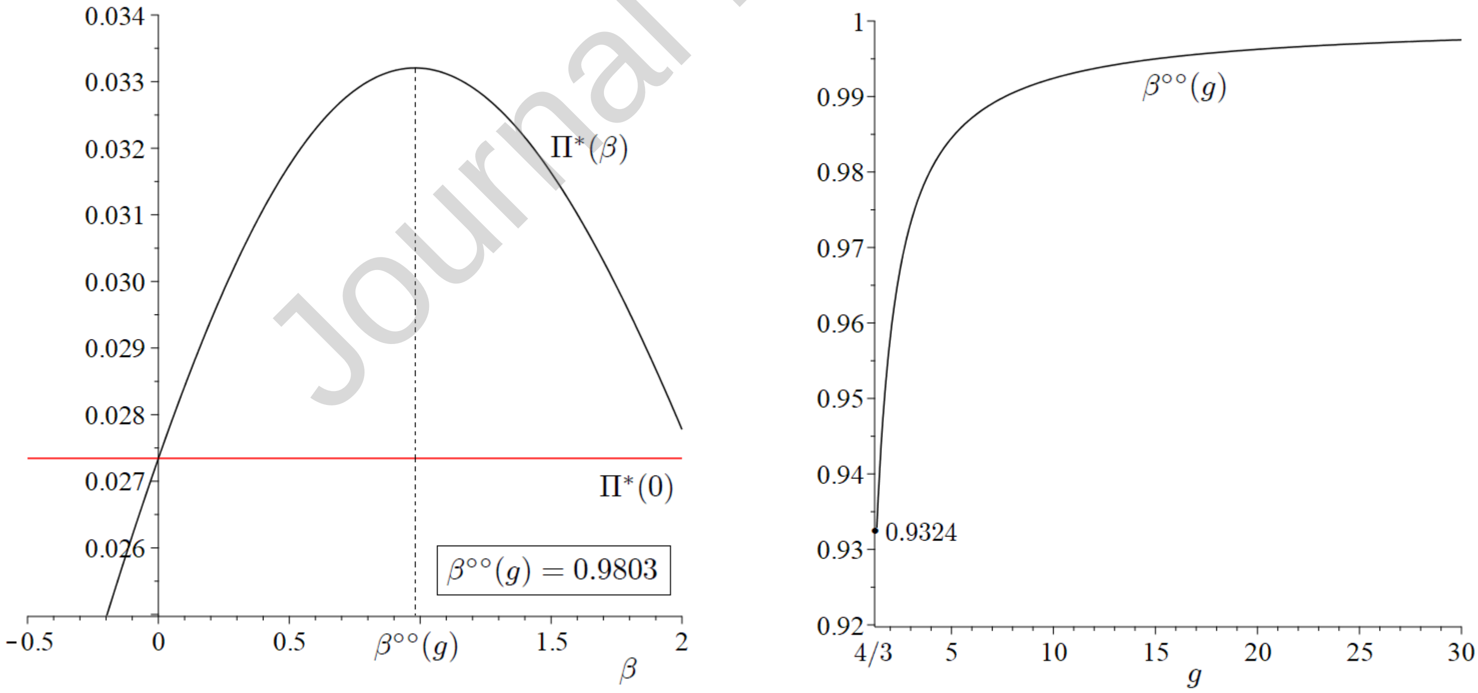
Once the ambiguous effect of the R&D disclosure on the side of consumers are established, the focus moves to profits (Result A.2) and social welfare (Result A.3).

Result A.2. An increase in the spillovers rate increases (resp. reduces) profits depending on whether $\beta \lesseqgtr \beta^{\circ\circ}(g)$.

Proof. The result follows from the analysis of $\Pi^*(\beta)$ in Table A.1, that is:

$$\frac{\partial \Pi^*}{\partial \beta} = \frac{4g(1-w)^2[2\beta^3-12\beta^2-3\beta(9g-8)+27g-16]}{[9g-2(1+\beta)(2-\beta)]^3} \gtreqless 0 \Leftrightarrow \beta \lesseqgtr \beta^{\circ\circ}(g), \qquad \text{(A.16)}$$

where the analytical solution of $\beta^{\circ\circ}(g)$, which depends only on g, is complex and cannot be presented in a neat analytical form. However, it is possible to resort to a geometrical projection depicting 1) the shape of $\Pi^*(\beta)$ when β varies for a given value of g ($g = 4$), clearly showing the existence of a maximum of Π^* corresponding to $\beta^{\circ\circ}$ (Figure A.2, Panel A), and 2) the shape of $\beta^{\circ\circ}(g)$ revealing that $\beta^{\circ\circ}(g) \in (0.9324,1)$ as g increases (Figure A.2, Panel B) starting from the lowest possible value that this parameter can take. That is, $g = 4/3$, emerging when the stability condition prevailing when x_i and x_j are strategic substitutes, that is $g > \frac{2(1-\beta)(2-\beta)}{3}$, is binding for $\beta = 0$.



(A) (B)

Figure A.2. Panel A. Profits as a function of β in an AJ duopoly à la De Bondt et al. (1992). The value of β that maximises $\Pi^*(\beta)$ is $\beta^{\circ\circ}(g) = 0.9803$ ($g = 4$). Panel B. Shape of $\beta^{\circ\circ}(g)$ when g varies in an AJ duopoly à la De Bondt et al. (1992).

In this regard, we assume that $w = 0.5$ (used also to plot Figure A.2, Panel A and Figure A.3, Panel A) so that $g > \frac{2(1-\beta)(2-\beta)}{3}$ is binding for any $0 \leq \beta < \frac{3w-1}{3w+1} = 0.2$ and $g > \frac{2(1+\beta)(2-\beta)}{9w}$ for any $0.2 = \frac{3w-1}{3w+1} < \beta \leq 1$.
In greater detail, Figure A.2, Panel A clearly shows the existence of a value β (dependent on g) corresponding to which profit is maximised, which is given by $\beta^{\circ\circ}(g)$. Relatedly, the figure shows that a sufficiently high value of the spillover rate reduces profits. This happens when the spillover rate is larger than $\beta^{\circ\circ}(g)$, which varies between the lowest possible value, i.e., 0.9324 obtained when $g = 4/3$, and the highest value, which tends to 1 as g becomes larger. Indeed, on one hand, higher reciprocal spillovers always increase total revenues; however, on the other hand, R&D disclosure always reduces cost-reducing R&D investments. Therefore, when spillovers are very high, the increasing costs effect more than counterbalances the increasing revenue effect.

Result A.3. An increase in the spillover rate increases (resp. reduces) social welfare profits depending on whether $\beta \lesseqgtr \beta^{\circ\circ\circ}(g)$.

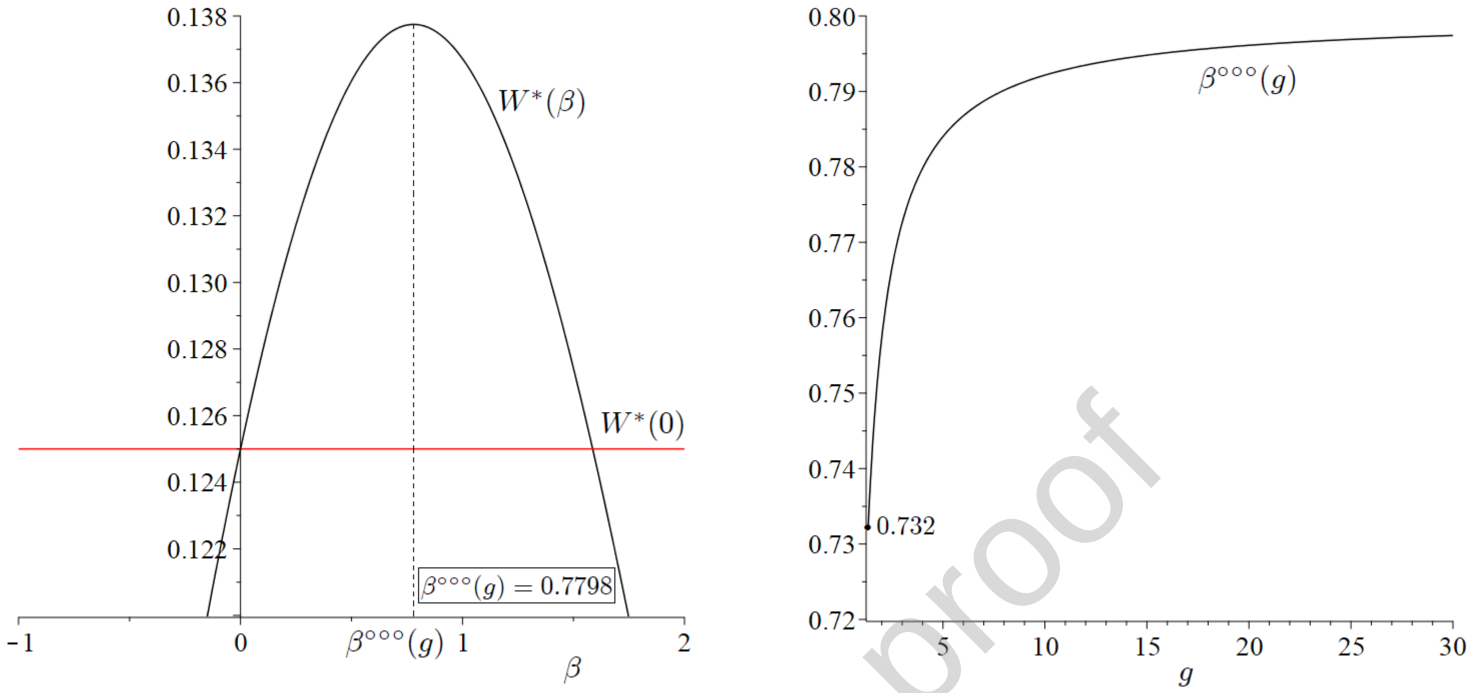
Proof. The result follows from the analysis of $W^*(\beta)$ in Table A.1, that is:

$$\frac{\partial W^*}{\partial \beta} = \frac{8g(1-w)^2[2\beta^3-12\beta^2-3\beta(15g-8)+4(9g-4)]}{[9g-2(1+\beta)(2-\beta)]^3} \gtreqless 0 \Leftrightarrow \beta \lesseqgtr \beta^{\circ\circ\circ}(g), \qquad \text{(A.17)}$$

where the analytical solution of $\beta^{\circ\circ\circ}(g)$, which depends only on g, is complex and cannot be presented in a neat analytical form. However, as discussed so far, it is possible to resort to a geometrical projection depicting 1) the shape of $W^*(\beta)$ when β varies for a given value of g ($g = 4$), clearly showing the existence of a maximum of W^* corresponding to $\beta^{\circ\circ\circ}$ (Figure A.3, Panel A), and 2) the shape of $\beta^{\circ\circ\circ}(g)$ revealing that $\beta^{\circ\circ\circ}(g) \in (0.732, 0.8)$ as g increases (Figure A.3, Panel B) starting from the lowest possible value that this parameter can take. That is, $g = 4/3$, emerging when the stability condition prevailing when x_i and x_j are strategic substitutes, that is $g > \frac{2(1-\beta)(2-\beta)}{3}$, is binding for $\beta = 0$.

The implication of Result A.3 is striking, arguing that the target of maximal welfare would require full disclosure is not correct. When the R&D-related knowledge spreads at high rates (tending to become a public good), it causes a loss-loss outcome. In other words, it is Pareto inferior as it reduces both consumer and producer surpluses. These results are robust as they hold for every value of the extent of the cost-reducing R&D technology (g). In particular, the counterintuitive result that the circulation of knowledge is harmful for society occurs more likely when the cost-reducing technology is very effective.[3]

[3] From Lemma A.3 we get $\frac{\partial (x^*)^2}{\partial \beta \partial g} > 0$, implying that an improvement in technological progress – as measured by a reduction in g – amplifies the negative effect of spillovers on the R&D effort. In other words, the more available an efficient technology is, the more investments in R&D are discouraged.



(A) (B)

Figure A.3. Panel A. Social welfare as a function of β in an AJ duopoly à la De Bondt et al. (1992). The value of β that maximises $W^*(\beta)$ is $\beta^{\circ\circ\circ}(g) = 0.7798$ ($g = 4$). Panel B. Shape of $\beta^{\circ\circ\circ}(g)$ when g varies in an AJ duopoly à la De Bondt et al. (1992).

Optimal values of β under symmetric imperfect compatibility ($k < 1$)

This section presents a wide spectrum of optimal values of the extent of disclosure that maximise the consumer surplus (β°), the producer surplus ($\beta^{\circ\circ}$), and the social welfare ($\beta^{\circ\circ\circ}$) in equilibrium for several values of the strength of the network externality when the degree of compatibility varies. The values presented in Tables A.2-A-20 are those that maximise $CS^*(\beta)$, $PS^*(\beta)$ and $W^*(\beta)$ for any $0 \leq k \leq 1$ for several values of n ranging from -1 to 0.9. The parameter values used to compute β°, $\beta^{\circ\circ}$, and $\beta^{\circ\circ\circ}$ are $g = 100$ and $w = 0.8$. The value of g is high enough to guarantee that the feasibility conditions are satisfied for all values of n and k used in the simulations and for any $0 \leq \beta \leq 1$. These values, however, are used only for illustrative purposes, as the results below hold for all values of the main parameters of the problem that satisfy the feasibility conditions.

Table A.2. Optimal values of β when $n = 0.1$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.45	0.459	0.469	0.479	0.489	0.5	0.51	0.521	0.532	0.543	0.555
$\beta^{\circ\circ}$	0.967	0.975	0.979	0.985	0.992	0.999	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.77	0.777	0.785	0.792	0.8	0.808	0.81	0.825	0.834	0.843	0.852

Table A.3. Optimal values of β when $n = 0.2$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

β°	0.4	0.418	0.437	0.457	0.478	0.5	0.522	0.546	0.571	0.597	0.625
$\beta^{\circ\circ}$	0.937	0.948	0.959	0.971	0.984	0.999	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.745	0.758	0.771	0.786	0.801	0.818	0.835	0.854	0.874	0.896	0.919

Table A.4. Optimal values of β when $n = 0.3$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.35	0.376	0.404	0.434	0.465	0.5	0.536	0.575	0.618	0.664	0.714
$\beta^{\circ\circ}$	0.911	0.924	0.939	0.957	0.976	0.998	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.725	0.741	0.759	0.779	0.802	0.828	0.857	0.888	0.923	0.962	1

Table A.5. Optimal values of β when $n = 0.4$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.3	0.333	0.369	0.409	0.452	0.5	0.552	0.611	0.676	0.75	0.833
$\beta^{\circ\circ}$	0.89	0.903	0.921	0.942	0.968	0.998	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.71	0.727	0.748	0.774	0.804	0.839	0.88	0.928	0.983	1	1

Table A.6. Optimal values of β when $n = 0.5$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.25	0.289	0.333	0.382	0.437	0.5	0.57	0.653	0.75	0.86	1
$\beta^{\circ\circ}$	0.874	0.886	0.903	0.927	0.959	0.99	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.703	0.718	0.74	0.769	0.805	0.851	0.907	0.975	1	1	1

Table A.7. Optimal values of β when $n = 0.6$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.2	0.244	0.295	0.353	0.421	0.5	0.593	0.706	0.846	1	1
$\beta^{\circ\circ}$	0.865	0.872	0.888	0.913	0.949	0.998	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.707	0.715	0.734	0.765	0.807	0.864	0.937	1	1	1	1

Table A.8. Optimal values of β when $n = 0.7$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.15	0.198	0.255	0.322	0.402	0.5	0.62	0.774	0.977	1	1
$\beta^{\circ\circ}$	0.868	0.865	0.875	0.898	0.938	0.998	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.726	0.722	0.734	0.762	0.809	0.877	0.972	1	1	1	1

Table A.9. Optimal values of β when $n = 0.8$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.1	0.15	0.214	0.289	0.382	0.5	0.653	0.863	1	1	1
$\beta^{\circ\circ}$	0.885	0.867	0.867	0.885	0.927	0.997	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.769	0.741	0.739	0.762	0.812	0.892	1	1	1	1	1

Table A.10. Optimal values of β when $n = 0.9$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.05	0.104	0.17	0.253	0.359	0.5	0.695	0.986	1	1	1
$\beta^{\circ\circ}$	0.924	0.882	0.865	0.874	0.915	0.997	1	1	1	1	1
$\beta^{\circ\circ\circ}$	0.85	0.781	0.755	0.766	0.814	0.908	1	1	1	1	1

Table A.11. Optimal values of β when $n = -0.1$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

β°	0.55	0.539	0.529	0.519	0.509	0.5	0.49	0.481	0.472	0.463	0.454
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.993	0.987	0.981	0.975	0.97
$\beta^{\circ\circ\circ}$	0.83	0.822	0.813	0.805	0.798	0.79	0.783	0.776	0.769	0.762	0.755

Table A.12. Optimal values of β when $n = -0.2$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.6	0.578	0.557	0.537	0.518	0.5	0.482	0.464	0.448	0.432	0.416
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.987	0.976	0.966	0.956	0.947
$\beta^{\circ\circ\circ}$	0.864	0.846	0.828	0.812	0.797	0.782	0.768	0.755	0.742	0.73	0.719

Table A.13. Optimal values of β when $n = -0.3$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.65	0.616	0.584	0.555	0.526	0.5	0.474	0.45	0.427	0.405	0.384
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.982	0.967	0.953	0.941	0.929
$\beta^{\circ\circ\circ}$	0.899	0.87	0.844	0.819	0.796	0.774	0.754	0.736	0.719	0.703	0.689

Table A.14. Optimal values of β when $n = -0.4$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.7	0.653	0.611	0.571	0.534	0.5	0.467	0.437	0.409	0.382	0.357
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.978	0.959	0.943	0.928	0.915
$\beta^{\circ\circ\circ}$	0.93	0.896	0.859	0.825	0.795	0.767	0.742	0.719	0.698	0.679	0.663

Table A.15. Optimal values of β when $n = -0.5$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.75	0.69	0.636	0.586	0.541	0.5	0.461	0.425	0.392	0.362	0.333
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.974	0.952	0.934	0.918	0.904
$\beta^{\circ\circ\circ}$	0.975	0.922	0.874	0.832	0.794	0.76	0.73	0.703	0.679	0.658	0.64

Table A.16. Optimal values of β when $n = -0.6$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.8	0.726	0.66	0.601	0.548	0.5	0.455	0.415	0.378	0.344	0.312
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.971	0.946	0.926	0.909	0.895
$\beta^{\circ\circ\circ}$	1	0.948	0.889	0.838	0.793	0.753	0.719	0.688	0.662	0.639	0.62

Table A.17. Optimal values of β when $n = -0.7$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.85	0.761	0.684	0.615	0.554	0.5	0.45	0.406	0.365	0.328	0.295
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.967	0.941	0.919	0.902	0.888
$\beta^{\circ\circ\circ}$	1	0.974	0.904	0.844	0.752	0.747	0.708	0.675	0.646	0.623	0.603

Table A.18. Optimal values of β when $n = -0.8$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	0.9	0.796	0.706	0.629	0.56	0.5	0.445	0.357	0.353	0.313	0.277
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.965	0.936	0.913	0.896	0.882
$\beta^{\circ\circ\circ}$	1	1	0.919	0.85	0.791	0.741	0.698	0.662	0.632	0.607	0.588

Table A.19. Optimal values of β when $n = -0.9$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

β°	0.95	0.83	0.728	0.641	0.566	0.5	0.441	0.389	0.343	0.301	0.263
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.962	0.932	0.908	0.891	0.878
$\beta^{\circ\circ\circ}$	1	1	0.934	0.856	0.79	0.735	0.689	0.65	0.619	0.593	0.574

Table A.20. Optimal values of β when $n = -1$.

k	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
β°	1	0.863	0.75	0.653	0.571	0.5	0.437	0.382	0.333	0.289	0.25
$\beta^{\circ\circ}$	1	1	1	1	1	0.999	0.959	0.928	0.904	0.886	0.874
$\beta^{\circ\circ\circ}$	1	1	0.948	0.862	0.79	0.73	0.68	0.635	0.606	0.581	0.562

The microeconomic foundations of the market demand if firms can commit themselves to an announced output level

This section briefly presents the microeconomic foundations of the market demand if firms do not commit themselves to an announced output level before consumers make their purchase decision. This follows the mechanism detailed by Katz and Shapiro (1985) in an ad hoc appendix of their contribution.

On the supply side, the economy is bi-sectorial with a competitive sector producing the numeraire good m and a duopolistic industry in which firm i and firm j ($i = \{1,2\}$; $i \neq j$) produce network goods of variety (network) i and variety (network) j, respectively. These goods are perceived as homogeneous by customers. Firms also face the perspective of investing in cost-reducing R&D (process innovation) along the line of the model developed by d'Aspremont and Jacquemin (1988, 1990).

On the demand side, there are identical consumers with preferences described by the utility function $V(q_i, q_j, m) = U(q_i, q_j) + m$, which is linear in the numeraire good m. The utility V is a maximised subject to the budget constraint $p_i q_i + p_j q_j + m = R$, where U is a twice continuously differentiable function; q_i and q_j are the control variables of the problem; p_i and p_j represent the price of (i.e., the marginal willingness to pay of the representative consumer for) the product of variety i and variety j, respectively; and R is the consumer's exogenous nominal income. This income is high enough to avoid the existence of income effects on the demand of q_i and q_j (i.e., the goods enter non-linearly in V). In this regard, in fact, the utility function V is quasi-linear in m so that all the related properties about the demand of m and that of q_i and q_j hold (Amir et al., 2017; Choné and Linnemer, 2020).

Departing from the traditional IO literature, we assume the existence of network externalities in consumption, i.e., one person's demand also depends on the demand of other customers. However, as firms now commit themselves to an announced output level, the utility function of the representative consumer does not depend on an external effect denoting the consumers' expectations about firm i's equilibrium total sales related to the network size. However, the utility function directly depends on the quantity q_i and q_j that firm i and firm j are respectively committed before consumers make their purchase decisions.

The function U modifies from (A.1) to become the following:

$$U = q_i + q_j - \frac{1}{2}(q_i^2 + q_j^2 + 2q_iq_j) + n[q_i(q_i + kq_j) + q_j(q_j + kq_i)] - \frac{n}{2}(q_i^2 + q_j^2 + 2kq_iq_j), \quad \text{(A.18)}$$

The solution of the constrained utility maximisation problem by the representative consumer from (A.18) gives the linear inverse demand for product of network i:

$$p_i = 1 - q_i - q_j + n(q_i + kq_j),\ i,j = \{1,2\},\ i \neq j. \quad \text{(A.19)}$$

The equilibrium values of the model in which firms commit to an announced output level, resembling the equilibrium values reported in Table 1 in the main text (referred to the model in which do not commit to an announced output level), are as follows:

Table A.21. Equilibrium outcomes in the AJ model with spillovers, network externalities, and product compatibility, in which firms commit to an announced output level.

x^*	$\frac{2(1-w)(1-n)[2-\beta-n(2-\beta k)]}{g[1-n(2-k)][3-n(2+k)]^2 - 2(1-n)(1+\beta)[2-\beta-n(2-\beta k)]}$
q^*	$\frac{g(1-w)[1-n(2-k)][3-n(2+k)]}{g[1-n(2-k)][3-n(2+k)]^2 - 2(1-n)(1+\beta)[2-\beta-n(2-\beta k)]}$
Π^*	$\frac{g(1-w)^2(1-n)\{g[1-n(2-k)]^2[3-n(2+k)]^2 - 2(1-n)[2-\beta-n(2-k\beta)]^2\}}{\{g[1-n(2-k)][3-n(2+k)]^2 - 2(1-n)(1+\beta)[2-\beta-n(2-\beta k)]\}^2}$

The technical condition that guarantees that x^* and q^* are positive is $n < \frac{1}{2-k}$. The feasibility conditions of the model with committing firms – contributing to define the bounds for feasibility of the Nash equilibrium – are the following:

$$g > \frac{2(1-n)(1-\beta)[2-\beta-n(2-\beta k)]}{[1-n(2-k)]^2[3-n(2+k)]} := g_{SC}^{\beta_{low}}(\beta,n,k), \quad \text{(A.20)}$$

which represents the stability condition (SC) prevailing when x_i and x_j are strategic substitutes, i.e., $\beta < \frac{1-kn}{2(1-n)}$,

$$g > \frac{2(1-n)(1+\beta)[2-\beta-n(2-\beta k)]}{[1-n(2-k)][3-n(2+k)]^2} := g_{SC}^{\beta_{high}}(\beta,n,k), \quad \text{(A.21)}$$

which represents the stability condition (SC) prevailing when x_i and x_j are strategic complements, i.e., $\beta > \frac{1-kn}{2(1-n)}$,

$$g > \frac{2(1-n)[2-\beta-n(2-\beta k)]^2}{[1-n(2-k)]^2[3-n(2+k)]^2} := g_{SOC}(\beta,n,k), \quad \text{(A.22)}$$

which represents the second-order condition (SOC) for a maximum (concavity), and

$$g > \frac{2(1-n)(1+\beta)[2-\beta-n(2-\beta k)]}{w[1-n(2-k)][3-n(2+k)]^2} := g_T(\beta,n,k,w), \quad \text{(A.23)}$$

which represents the R&D cost condition (T) that must hold to guarantee that the inequality $w - x_i - \beta x_j > 0$ is fulfilled at the equilibrium.

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