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Co-Investment, Uncertainty, and Opportunism: *Ex-Ante* and *Ex-Post* Remedies

Abstract

In this paper, we study the impact of co-investment by incumbents and entrants on the roll-out of network infrastructures under demand uncertainty. We show that if entrants can wait to co-invest until demand is realized, the incumbents' investment incentives are reduced and total coverage can be lower than in a benchmark with earlier co-investment. We consider two remedies to correct these distortions: (i) co-investment options purchased *ex-ante* by entrants from incumbents, and (ii) risk premia paid *ex-post* by entrants. We show that co-investment options cannot fully reestablish total coverage, while premia can do so in most cases, though at the cost of less entry. Finally, we show that an appropriate combination of *ex-ante* and *ex-post* remedies can improve welfare.

JEL-Codes: L960, L510.

Keywords: co-investment, uncertainty, opportunism, options, risk premia.

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1 Introduction

In network industries, the roll-out of new infrastructures requires significant and sunk investments from market players. To ensure that investment takes place and in order to maintain a competitive environment, it may make sense to allow firms to share the burden of investment, that is, to "co-invest" in the deployment of new infrastructures. Co-investment is, for example, encouraged in the new regulatory framework introduced by the European Union for the deployment of next-generation access networks, which will deliver ultra-fast broadband connections to the Internet.[1]

When it deploys a new infrastructure in a local area, a firm will often face uncertainty about the level of demand for the services that this network can deliver. If co-investment takes place at the same time, potential co-investors will take their decision under the same level of uncertainty. However, as a way to maintain a competitive environment, European regulators have allowed entrants to ask for co-investment later (*ex post*), and therefore entrants can wait until enough information about demand has become available.[2] In this paper, we study the impact of such wait-and-see option on investment and co-investment incentives, and analyze regulatory provisions that may be useful to avoid the distortions that *ex-post* co-investment generates.[3]

We model a geographical market where an incumbent decides to deploy a new infrastructure in local areas with different sunk costs to be covered, and an entrant can decide to co-invest with the incumbent in some or all areas, taking on half of the investment cost. The level of demand only becomes known after the investment has taken place. As a benchmark, we first consider the situation where the entrant faces the same demand uncertainty as the incumbent (i.e., co-investment takes place simultaneously and *ex-ante*). We show that in

[1] See European Electronic Communications Code, Directive 2018/1972, Article 76.

[2] Article 76(a) states that a co-investment offer should be "open at any moment during the lifetime of the network to any provider of electronic communications networks or services."

[3] Annex IV of the Directive states that "the determination of the financial consideration to be provided by each co-investor needs to reflect the fact that early investors accept greater risks and engage capital sooner."

equilibrium, there is co-investment in the least costly areas of the market, and if monopoly profits are higher than the sum of duopoly profits, there are also monopoly areas where the incumbent invests by himself.

We then study the case where the entrant can wait for demand to be realized before deciding on co-investment (i.e., co-investment takes place *ex-post*). We show that this creates two distortions compared to the benchmark. First, it reduces the probability of entry in co-investment areas, while increasing the probability of entry in monopoly areas (market structure distortion). Second, it reduces the investment incentives of the incumbent, and as a consequence, it can lead to a lower coverage than in the benchmark (total coverage distortion). This happens in particular when the level of demand uncertainty is high. With a numerical example, we show that as a result, when demand uncertainty is sufficiently strong, *ex-post* co-investment decreases welfare, relative to the *ex-ante* benchmark.

Two possible remedies to curb the entrant's opportunism and correct these distortions are (i) a co-investment option purchased *ex ante* by the entrant from the incumbent, to be exercised *ex post*, and (ii) a risk premium paid *ex post* by the entrant.

We show that compared to the case of *ex-post* co-investment with no remedy, the co-investment option does not affect the entrant's co-investment decision in the areas covered by the incumbent, and therefore, it cannot correct the market structure distortion. However, the option reduces (but does not fully eliminate) the coverage distortion by making investment more attractive for the incumbent. By contrast, a positive risk premium increases coverage while reducing the entrant's willingness to co-invest and enter *ex post*. Only a negative premium (i.e., a subsidy paid by the incumbent to the entrant) could reduce the market structure distortion.

Finally, we discuss the possibility of combining remedies, by implementing co-investment options in some areas and risk premia in others. First, we show that a negative risk premium (i.e., subsidies) allows correcting partially – but not fully – the market structure distortion in the areas with less entry than in the benchmark. Second, we show that to correct the total coverage distortion, one should implement co-investment options in areas with intermediate cost to be covered and a risk premium in the most outlying and costlier areas. Using a numerical example, we show that introducing such a combination of *ex-ante* and *ex-post* remedies can increase total welfare, compared to the outcome under *ex-post* co-investment.

Our paper relates to the literature on co-investment and other risk-sharing agreements in network industries (for a survey, see, e.g., Briglauer et al., 2015, and Abrardi and Cambini, 2019).[4] Nitsche and Wiethaus (2011) model co-investment as a joint venture decision, where firms jointly decide on an investment in quality that maximizes their expected joint profits. In the presence of demand uncertainty, they show that co-investment can be beneficial in terms both of investment incentives and consumer welfare, when compared to standard access regulation (e.g., LRIC access pricing). Different from their paper, we model the investment choice as non-cooperative coverage decisions rather than as a joint quality choice. We also capture the fact that under the European legal framework, co-investment is a decision made by the entrant and investigate remedies to the resulting distortions.

Inderst and Peitz (2012) analyze cost-sharing agreements between an incumbent firm and an entrant, in the form of long-term contracts concluded before the investment is made, as opposed to contracting taking place after the network has been constructed. In their model, investment corresponds to a quality improvement, which is different from the coverage decision we consider in our paper. The authors show that long-term contracts reduce the duplication of investment and may lead to higher quality, but they assume that coordination at the investment level directly implies reduced competition in the areas covered. They do not consider an *ex-post* agreement and the distortions it would cause.

The structure of our model draws on Bourreau et al. (2018), in which the authors focus on co-investment as an alternative to standard access regulation. They show that, in the presence of demand uncertainty, *ex-ante* co-investment involves a pre-commitment, and thus, does not suffer from the opportunism that access regulation generates, leading to

[4] See also Sand-Zantman (2017) for a report on the economics of cooperative agreements for the deployment of network infrastructures.

more investment and also higher welfare. Different from that paper, here we consider the possibility that co-investment itself can take place *ex post*, as the European legal framework permits, and how to reduce the resulting distortions.

In the literature, several formal studies have investigated the impact of access regulation on investment incentives by incumbent and entrant firms in the presence of demand uncertainty, for example, Hori and Mizuno (2006), Klumpp and Su (2010), and Inderst and Peitz (2013). In a recent companion paper, Bourreau et al. (2019), we compare various regulated access schemes under demand uncertainty. None of these papers, though, considers co-investment, as we do here, since their focus is on standard access pricing regulation.

The rest of the paper is organized as follows. In Section 2 we set up the model. In Section 3, we solve for the coverage equilibrium when co-investment takes place *ex-ante*, which constitutes our benchmark, and when it takes place *ex-post*. In Section 4, we consider two remedies: co-investment options and risk premia. Section 5 concludes.

2 Model Setup

We consider a country consisting of a continuum of areas $z \in \mathbb{R}_+$, with identical distribution of uncertain demand, but different sunk costs of coverage by a new network infrastructure. The cost of covering area z is $c(z)$, where $c(0) = 0$, $c(.)$ is continuous and strictly increasing, and $\lim_{z\to+\infty} c(z) = +\infty$. We denote by $C(z) = \int_0^z c(x)\,dx$ the total cost of covering the areas $[0, z]$.

There is one incumbent, firm 1, and one potential entrant, firm e. We assume sequential investment decisions. The incumbent first decides on the areas where it will invest. Then, firm e can co-invest in any area covered by the incumbent, taking on half of the investment cost. Firm e can only enter through co-investment. Under co-investment, the entrant can access the infrastructure under the same conditions as the incumbent (and in particular, at the same marginal cost of access). Finally, firms compete in local areas, and profits are realized.

Firms can adjust their prices according to local competitive conditions. In each co-investment area, firms 1 and e make the expected symmetric retail duopoly profits $\pi^d > 0$, with corresponding social welfare w^d, where welfare is defined as the sum of consumer surplus and industry profits. In the areas covered by the incumbent and where the entrant does not co-invest, the incumbent makes a higher expected profit $\pi^m \geq \pi^d$; we denote by w^m the social welfare in these areas. The profit π^m can correspond to the monopoly profit, or a profit smaller than the monopoly profit in case there is competition from an old technology. For simplicity, in the following we refer to these as monopoly areas and profits, respectively.

We assume that the level of demand in each local area is uncertain *ex-ante* when the incumbent makes its investment decision. Information about the level of demand is revealed after the infrastructure is deployed and then observed by all market players. As a benchmark, we will first consider the case where the entrant also makes its co-investment decision under demand uncertainty, prior to the deployment of the infrastructure (*ex-ante* co-investment). Then, we will allow the entrant to wait for demand to be realized (*ex-post* co-investment).

The demand levels in the different areas of the country are identically distributed, but may not be independent. In any given area, we assume that the demand level, δ, is uniformly distributed over $[1-\sigma, 1+\sigma]$, with $\sigma \in (0,1)$. The expected level of demand is $\mathbb{E}[\delta] = 1$, and $\sigma^2/3$ is its variance. We interpret σ as the degree of demand uncertainty. The expected profit for an area of type $\tau = d, m$ is then $\mathbb{E}[\delta\pi^\tau] = \pi^\tau$.

3 Co-Investment

In this section, we solve for the equilibrium of the (co-)investment game when co-investment takes place *ex ante*, before demand is realized, and then when it takes place *ex post*.

3.1 Benchmark: *ex-ante* co-investment

As a benchmark, we first assume that the incumbent and the entrant both make their investment decisions *ex ante* under demand uncertainty. We solve the game backwards, starting from the entrant's decision.[5]

Entrant's decision. If the entrant co-invests in a given area z covered by the incumbent, it makes the expected profit $\pi_e(z) = \pi^d - c(z)/2$. The entrant decides to co-invest in the area if and only if $\pi_e(z) \geq 0$, that is, if $z \leq \bar{z}^c \equiv c^{-1}\left(2\pi^d\right)$.

Incumbent's decision. The incumbent decides whether to invest in a given area, taking into account whether it will later be matched by the entrant's co-investment.

In any area $z \leq \bar{z}^c$, the entrant will co-invest. The incumbent's expected profit in such an area is $\pi_1(z) = \pi^d - c(z)/2$, which is positive for all $z \leq \bar{z}^c$. Thus, the incumbent will invest in all the areas $z \leq \bar{z}^c$.

In areas $z > \bar{z}^c$ the entrant will not co-invest. The incumbent will enjoy a monopoly position and obtain the expected profit $\pi_1(z) = \pi^m - c(z)$. This is positive if and only if $z \leq \bar{z}^m \equiv c^{-1}(\pi^m)$. There is a set of monopoly areas in equilibrium if $\bar{z}^m > \bar{z}^c$, which happens if $\pi^m > 2\pi^d$ (i.e., when duopoly profits are low because services are close substitutes). Summing up:

Proposition 1 *Under ex-ante co-investment, the incumbent and the entrant cover the areas* $[0, \bar{z}^c]$. *Furthermore,*

1. *If* $\pi^m \leq 2\pi^d$, *there are no monopoly areas.*

2. *If* $\pi^m > 2\pi^d$, *the incumbent also covers the monopoly areas* $(\bar{z}^c, \bar{z}^m]$.

In this benchmark with *ex-ante* co-investment, total coverage in equilibrium is given by $\max\{\bar{z}^c, \bar{z}^m\}$. The market structure is characterized by a duopoly in the co-investment

[5] The analysis is similar to Bourreau, Cambini and Hoernig (2018), but slightly more general here since we do not make the assumption that firms (co-)invest in intervals of areas.

areas $[0, \bar{z}^c]$ and a monopoly in the monopoly areas $(\bar{z}^c, z^m]$ (when they exist). In the next subsection, we study how the equilibrium is affected when co-investment takes place *ex post*.

3.2 *Ex-post* co-investment

We now consider the case where the entrant can wait and ask for co-investment in any given area *ex post*, after demand is realized.

Entrant's decision. In a given area z covered by the incumbent, with realized demand δ, firm e asks for co-investment if and only if $\delta\pi^d \geq c(z)/2$, that is, if demand is high enough, $\delta \geq c(z)/(2\pi^d)$. We define $\underline{\delta}(z) \equiv \min\{1+\sigma, \max\{1-\sigma, c(z)/(2\pi^d)\}\}$ as the minimum level of demand for entry to occur.[6] We also define $\underline{z}$ as the solution of $c(z)/(2\pi^d) = 1-\sigma$ and $\overline{z}$ as the solution of $c(z)/(2\pi^d) = 1+\sigma$. Since $c(\cdot)$ is strictly increasing, $\underline{\delta}(\cdot)$ is strictly increasing for $z \in [\underline{z}, \overline{z}]$, with $\underline{\delta}(\underline{z}) = 1-\sigma$ and $\underline{\delta}(\overline{z}) = 1+\sigma$. We have $0 \leq \underline{z} \leq \bar{z}^c \leq \overline{z}$, and we have $\overline{z} < \bar{z}^m$ if and only if $\pi^m > 2\,(1+\sigma)\,\pi^d$.

The (*ex-ante*) probability that the entrant enters via co-investment in an area z covered by the incumbent is then given by

$$p^e(z) = \int_{\underline{\delta}(z)}^{1+\sigma} \frac{d\delta}{2\sigma} = \frac{1+\sigma-\underline{\delta}(z)}{2\sigma}, \tag{1}$$

with $p^e(z) = 1$ for all $z \leq \underline{z}$ and $p^e(z) = 0$ for all $z \geq \overline{z}$. From (1), entry via co-investment is less likely in more costly areas (with a larger z). Higher uncertainty makes entry less likely in cheaper areas ($\underline{\delta}(z) < 1$) but more likely in costlier areas ($\underline{\delta}(z) > 1$), because in the latter it raises the upside value.

For further reference, let $\delta^e(z) \equiv \left(1+\sigma+\underline{\delta}(z)\right)/2$ and $\delta^n(z) \equiv (1-\sigma+\underline{\delta}(z))/2$ represent the expected levels of demand conditional on entry and no entry, respectively. Note that we have $p^e(z)\delta^e(z) + (1-p^e(z))\,\delta^n(z) = \mathbb{E}[\delta] = 1$. The entrant's expected profit can then be

[6] The minimum level of demand $\underline{\delta}$ is bounded from below and from above because of our assumptions on the support of the distribution.

written as $\hat{\pi}_e(z) = p^e(z)\left(\delta^e(z)\pi^d - c(z)/2\right)$.

We can now compare the probability of entry with *ex-post* co-investment with the probability of entry in the benchmark.

Lemma 1 *Compared to the benchmark with ex-ante co-investment, if the entrant can wait for demand to be realized, it is:*

1. *as likely to co-invest in the least costly areas* $z \leq \underline{z}$*;*
2. *less likely to co-invest in areas with intermediate costs* $z \in (\underline{z}, \bar{z}^c)$*;*
3. *more likely to co-invest in the more costly areas* $z \in (\bar{z}^c, \overline{z}]$*.*

Proof. In the benchmark, the entrant co-invests (with probability one) in the areas $z \leq \bar{z}^c$, and does not co-invest (hence, co-invests with probability zero) in the areas $z > \bar{z}^c$. When it can wait for demand to be realized, the entrant co-invests with probability one in the areas $z \leq \underline{z}$, as in the benchmark. If $z \in (\underline{z}, \bar{z}^c)$, the entrant co-invests with probability $p^e(z) < 1$, that is, with a lower probability than in the benchmark. Finally, if $z \geq \bar{z}^c$, the entrant co-invests with probability $p^e(z) > 0$, that is, with a higher probability than in the benchmark. ■

This result shows that the possibility of *ex-post* co-investment introduces a *market structure distortion*: compared to the *ex-ante* benchmark, there is less entry in low-cost areas, and more entry in high-cost areas.

Incumbent's decision. We now solve for the incumbent's coverage decision. In a given area z, the entrant will co-invest if $\delta \geq \underline{\delta}(z)$. Thus, the incumbent's expected profit in the area is given by

$$\hat{\pi}_1(z) = \int_{1-\sigma}^{\underline{\delta}(z)} \left(\delta\pi^m - c(z)\right)\frac{d\delta}{2\sigma} + \int_{\underline{\delta}(z)}^{1+\sigma} \left(\delta\pi^d - c(z)/2\right)\frac{d\delta}{2\sigma}.$$

In the low states of demand ($\delta < \underline{\delta}(z)$), the entrant does not co-invest and the incumbent enjoys a monopoly position, whereas in the high states of demand ($\delta \geq \underline{\delta}(z)$), the entrant co-invests and the firms compete in the retail market.

The incumbent's expected profit can be rewritten as

$$\hat{\pi}_1(z) = \pi^m - c(z) - p^e(z) \left[\delta^e(z) \left(\pi^m - \pi^d \right) - \frac{c(z)}{2} \right]. \tag{2}$$

If $z \leq \underline{z}$, we have $\underline{\delta}(z) = 1 - \sigma$ and hence, $\hat{\pi}_1(z) = \pi^d - c(z)/2 \geq 0$, where the inequality comes from the fact that $z \leq \underline{z} \leq \bar{z}^c$. If $z \geq \bar{z}$, we have $\underline{\delta}(z) = 1 + \sigma$ and $\hat{\pi}_1(z) = \pi^m - c(z)$, which is positive if and only if $z \leq \bar{z}^m$.

For $z \in (\underline{z}, \bar{z})$, the last term in (2) represents the externality from firm e's possible entry on firm 1's profit. Entry occurs with probability $p^e(z)$. If there is entry, the externality on firm 1's profit is equal to the lost profits in the high-demand states $\delta^e(z)(\pi^m - \pi^d)$ less the cost savings from co-investment $c(z)/2$. Thus, while entry has a negative effect on the incumbent's profit in low-cost areas, it may have a positive effect in high-cost areas due to large cost savings. This implies that in these areas, firm 1's profit may not always be decreasing with z.

The following proposition characterizes the equilibrium.

Proposition 2 *The equilibrium with ex-post co-investment is given by:*

1. *If* $\pi^m < \left(2 + \frac{\sigma}{2-\sigma}\right) \pi^d$, *the incumbent invests in the areas* $[0, \bar{z}^o]$, *with* $\bar{z}^o \in (\underline{z}, \bar{z}^c)$.

2. *If* $\left(2 + \frac{\sigma}{2-\sigma}\right) \pi^d \leq \pi^m < 2\left(1 + \sigma\right) \pi^d$, *the incumbent invests in the areas* $[0, \bar{z}^o]$, *with* $\bar{z}^o \in [\bar{z}^c, \bar{z}^m)$.

3. *If* $\pi^m \geq 2\left(1 + \sigma\right) \pi^d$, *the incumbent invests in the areas* $[0, \bar{z}^o]$, *with* $\bar{z}^o = \bar{z}^m$.

The entrant's probability of entry via co-investment in an area z *covered by the incumbent is given by* (1).

Proof. See the Appendix. ■

We can now compare the equilibrium outcome described in Proposition 2 to the equilibrium in the benchmark given in Proposition 1.

Proposition 3 *When the entrant can wait for demand to be realized, the incumbent covers fewer areas than in the ex-ante benchmark if* $\pi^m < 2\,(1+\sigma)\,\pi^d$. *The entrant co-invests less often in the areas with intermediate costs and more often in the more costly areas.*

Proof. Immediate. ■

When it co-invests *ex post*, the entrant can observe the realized demand in each local area and cherry-pick which areas to enter. This creates two distortions as compared to the *ex-ante* benchmark. First, there is the *market structure distortion.* As shown in Lemma 1, allowing for *ex-post* co-investment decreases the probability of entry in benchmark co-investment areas and increases the probability of entry in benchmark monopoly areas. Second, there is a *total coverage distortion.* Since there is more entry in monopoly areas, the incumbent's investment incentives are reduced, and total coverage is lower than in the benchmark unless monopoly profits are sufficiently high.

The incumbent fares worse compared to the benchmark, as co-investment is less likely to occur in the bad states of demand and there is more entry in the good states. Conversely, the entrant obtains a higher profit if it can wait for demand to realize. In the benchmark with *ex-ante* co-investment, the incumbent makes (at least weakly) more profit than the entrant; this is because the two firms make the same profits in the co-investment areas and the incumbent can earn additional profits in the monopoly areas.

Can *ex-post* co-investment hurt the incumbent and benefit the entrant to such an extent that the entrant obtains a higher expected profit than the incumbent? With an example, we show that this can be the case. Let $\pi^m = 2.5$, $\pi^d = 1$, $c(z) = z$ and $\sigma \in [0, 1]$. The incumbent's and the entrant's total expected profits are then given by

$$\hat{\Pi}_i = \int_0^{\bar{z}^o} \hat{\pi}_i(z) dz,$$

for $i = 1, e$, where $\bar{z}^o$ is the equilibrium coverage defined in Proposition 2. With our specific assumptions for π^m, π^d and $c(z)$, we find that $\hat{\Pi}_1(\sigma) > \hat{\Pi}_e(\sigma)$ for $\sigma \in (0, 0.46)$ and $\hat{\Pi}_1(\sigma) < \hat{\Pi}_e(\sigma)$ for $\sigma > 0.46$. When the degree of demand uncertainty σ increases, the magnitude of the market structure and total coverage distortions becomes larger; the incumbent is thus hurt more by *ex-post* co-investment, while the entrant benefits more. If the degree of uncertainty is sufficiently high, the entrant obtains a higher total expected profit than the incumbent by waiting.

In our framework, we assumed that firm 1 is the investor and that firm e can only enter via co-investment. Now, consider the case where who is the first investor and who is the co-investor is determined endogenously through a timing game. If the degree of uncertainty is low, each firm would prefer to be the first investor as it makes higher profits than the co-investor ($\hat{\Pi}_1(\sigma) > \hat{\Pi}_e(\sigma)$), and we would obtain a preemption game. By contrast, if the degree of uncertainty is high, each firm would prefer to let the other firm invest first and co-invest later (as $\hat{\Pi}_1(\sigma) < \hat{\Pi}_e(\sigma)$). Firms play a waiting game instead, delaying any investment. This delay is caused exclusively by allowing later co-investment.

In terms of welfare aggregated over all areas, the impact of *ex-post* co-investment compared to the benchmark is *a priori* ambiguous: on the one hand, welfare is reduced because there is less entry in co-investment areas and possibly lower total coverage; on the other hand, there is more entry in monopoly areas, which increases welfare. Since we are interested in situations when *ex-post* opportunism is socially harmful, we assume from now on that the overall effect of *ex-post* co-investment is negative:

Assumption 1: *Compared to the ex-ante benchmark, total welfare is lower under ex-post co-investment.*

One sufficient condition for Assumption 1 to hold is that $\bar{z}^o < \bar{z}^c$, which corresponds to Case 1 in Proposition 2. Indeed, in this case, since there are no monopoly areas, *ex-post* co-investment has no positive effect on welfare through entry in monopoly areas, only negative effects. Another sufficient condition is that the investment cost function is steep enough after $\bar{z}^c$ so that the monopoly area is very small, and therefore the welfare gains from *ex-post* co-investment are also very small.

With a specific example, we show that Assumption 1 also holds if there is a sufficiently high degree of demand uncertainty. We adopt the demand specification from Singh and Vives (1984) and local quantity competition. The inverse demand for firm $i = 1, e$ is given by $p_i = \alpha - q_i - \gamma q_j$, where $\alpha > 0$ and $\gamma \in [0, 1]$. The marginal cost is set to 0 for both firms. We set the values of α and γ such that $\pi^m = 2.5$ and $\pi^d = 1$ as in the previous example: we obtain $\alpha = 3.16$ and $\gamma = 0.72$. Total expected welfare is then given by

$$\hat{W} = \int_0^{\bar{z}^o} \left[w^m - c(z) - p^e(z)\delta^e(z)(w^m - w^d) \right] dz,$$

with $w^d = 5.54$ and $w^m = 3.75$. We find that in this numerical example, total welfare is higher with *ex-post* co-investment for $\sigma \in (0, 0.26)$ and lower for $\sigma \in (0.26, 1)$.

In the next section, under Assumption 1, we study possible *ex-ante* or *ex-post* remedies to reduce or eliminate the adverse effects of waiting.

4 Remedies

In this section, we study potential remedies which could be applied either *ex ante* or *ex post* in order to achieve the same equilibrium with *ex-post* co-investment as in the *ex-ante* benchmark, in case *ex-ante* co-investment cannot be enforced. Our objective is not to determine the optimal regulation of *ex-post* co-investment, since *ex-ante* co-investment, which we have defined in line with regulatory practice as the equal sharing of investment costs, is not necessarily optimal either. Instead, we are looking for a second-best outcome, represented by the *ex-ante* benchmark.

Note that a straightforward remedy would allow replicating fully the *ex-ante* market outcome: banning *ex-post* co-investment.[7] However, the existing regulatory framework in Europe makes it mandatory for infrastructure owners to accept late co-investment requests. Therefore, we take as a starting point that *ex-post* co-investment is possible, and look at the remedies that could reestablish the *ex-ante* outcome, in particular in terms of total coverage, and thus, improve welfare under Assumption 1.

First, we analyze an *ex-ante* remedy, whereby the potential entrant would be required to purchase *ex ante* a co-investment option to be able to co-invest *ex post.* Second, we consider a risk premium, an *ex-post* remedy that has been envisaged by regulatory authorities. In both cases, we assume that the entrant could also co-invest *ex ante.*

4.1 Co-investment options

We first consider the case where the incumbent and the entrant can enter *ex ante* into an option contract for co-investment, which can be enforced *ex post.* More specifically, if the entrant wants to co-invest *ex post* rather than *ex ante* in a given area, it must make a payment to the incumbent *ex ante*, conditional on the incumbent actually investing in the area. Thus, instead of co-investing *ex ante*, the entrant buys an option, which it can later use (by co-investing via the payment of $c(z)/2$) or not (by staying out).

Market structure distortion

As we have seen, with *ex-post* co-investment the entrant is less likely to enter co-investment areas and more likely to enter monopoly areas, compared to the benchmark. Whereas the latter distortion is actually welfare-enhancing, the former harms welfare. Therefore, it would be welfare improving to increase entry in co-investment areas. However, a co-investment

[7] A ban on *ex-post* co-investment could even apply to only a subset of areas where it distorts investment and/or co-investment decisions.

option, once bought, has no effect on later entry, because it does not change the *ex-post* co-investment incentives of the entrant. To correct this inefficiency, we would need to subsidize the entrant; we will discuss this possibility in the subsection on the risk premium below.

Total coverage distortion

We now study to which extent co-investment options can correct the total coverage distortion. First we assume low monopoly profits, i.e. $\pi^m < 2\pi^d$. In this case, in the benchmark, there is co-investment in the areas $z \leq \bar{z}^c$, but there are no monopoly areas. If the entrant can wait for demand to realize, a total coverage distortion arises, as the incumbent covers only the areas $[0, \bar{z}^0]$, with $\bar{z}^0 < \bar{z}^c$. We look at whether, in this case, selling a co-investment option can restore total coverage up to the benchmark level $\bar{z}^c$.

Consider the areas where investment does not occur with *ex-post* co-investment, whereas it does in the *ex-ante* benchmark, i.e., areas $z \in (\bar{z}^0, \bar{z}^c)$, where $\hat{\pi}_1(z) < 0$ but $\pi_1(z) \geq 0$.

The expected value for the entrant of a co-investment option in such an area, conditional on the incumbent covering the area, is equal to the difference in expected profits for the entrant between the two cases with *ex-post* and *ex-ante* co-investment:

$$V(z) = \hat{\pi}_e(z) - \pi_e(z) = p^e(z) \left[\delta^e(z)\pi^d - \frac{c(z)}{2}\right] - \left[\pi^d - \frac{c(z)}{2}\right],$$

which simplifies to $V(z) = (1 - p^e(z))^2 \sigma \pi^d \geq 0$.

By exercising the co-investment option, the entrant gains by not making losses in the low-demand states. The option value $V(z)$ is the maximum amount that the entrant is willing to pay to wait instead of co-investing *ex ante*.

The *ex-ante* benchmark coverage can be reestablished if the incumbent's losses when the option is exercised and co-investment occurs *ex post*, can be recovered via the maximum price of the option, i.e., if $V(z) \geq -\hat{\pi}_1(z)$, or

$$\left(\pi^d - \frac{c\left(z\right)}{2}\right) + \left(\pi^m - 2\pi^d\right)\left(1 - p^e(z)\right)\delta^n(z) \geq 0.$$

The first term is positive for $z \leq \bar{z}^c$ and equal to zero at $z = \bar{z}^c$, whereas the second term is strictly negative, as $\pi^m < 2\pi^d$ and $p^e(z) < 1$ for $z \in [\bar{z}^0, \bar{z}^c]$. Therefore, this condition does not hold for z close to $\bar{z}^c$. So, it is not possible to design a co-investment option that fully restores the incumbent's infrastructure coverage in this case.

Now, consider the other case, where $\pi^m > 2\pi^d$. In the benchmark, there are monopoly areas $z \in [\bar{z}^c, \bar{z}^m]$, where the incumbent invests but the entrant does not co-invest. With *ex-post* co-investment, the total coverage distortion arises if $\pi^m < 2\left(1+\sigma\right)\pi^d$, in which case the incumbent covers only the areas $[0, \bar{z}^o]$, with $\bar{z}^o < \bar{z}^m$.

The value of an option for the entrant in an area $z \in (\bar{z}^o, \bar{z}^m)$ corresponds to the gains from co-investing when demand turns out to be high, while *ex ante* it would not co-invest:

$$V(z) = \hat{\pi}_e(z) = p^e\left(z\right)\left[\delta^e(z)\pi^d - \frac{c\left(z\right)}{2}\right],$$

which simplifies to $V(z) = (p^e(z))^2\sigma\pi^d \geq 0$.

The incumbent's *ex-ante* coverage incentives can be reestablished by selling a co-investment option if $V(z) \geq -\hat{\pi}_1(z)$, that is, if

$$\left(\pi^m - c(z)\right) - \left(\pi^m - 2\pi^d\right)p^e\left(z\right)\delta^e(z) \geq 0. \tag{3}$$

The first term is always positive and equal to zero at $z = \bar{z}^m$, whereas the second term is strictly negative for $2\pi^d < \pi^m < 2\left(1+\sigma\right)\pi^d$ (the latter implying that $p^e\left(z\right) > 0$). Thus, as z approaches $\bar{z}^m$, this condition is not satisfied. Therefore, the co-investment option cannot restore the incumbent's investment incentives in the most outlying areas.

The following proposition summarizes our findings:

Proposition 4 *Selling a co-investment option:*

- *does not change the entrant's ex-post co-investment choices in areas covered by the incumbent;*
- *increases coverage in ex-ante co-investment areas and ex-ante monopoly areas, but cannot fully reestablish benchmark coverage.*

Because the option is bought *ex-ante*, it does not affect the entrant's co-investment incentives *ex-post*, and therefore it cannot fix the market structure distortion. Furthermore, the entrant's *ex-post* opportunism dissipates industry profits and makes it impossible to design options that fully solve the total coverage distortion.

4.2 Risk premia

In regulatory discussions, it has been proposed that late co-investors should be charged a "risk premium" on top of the co-investment fee paid by early co-investors, in order not to reward opportunistic behavior.[8] In this subsection, we study this remedy, and determine which lump-sum risk premium, defined *ex ante*, should be applied *ex post* to the late co-investor in order to achieve the benchmark outcome.

We assume that co-investment takes place *ex post*. In a given area z covered by the incumbent, after demand has been observed, the entrant decides whether to co-invest. If it co-invests, and only then, it has to pay to the incumbent, apart from half of the investment cost, an additional fee. Here, we include the possibility that the entrant receives a subsidy (i.e., a negative fee) from the incumbent. The purpose of the additional fee is to encourage the incumbent to invest in the area, while the subsidy aims at making the entrant co-invest. We maintain the assumption that the entrant can decide whether to co-invest in each single area.

[8] A risk premium for late co-investment has already been implemented in France.

We denote by $R(z)$ the additional payment made by the entrant to the incumbent if it co-invests *ex post* in an area z covered by the incumbent; its total payment is thus $R(z)+c(z)/2$. The entrant pays a risk premium if $R(z) > 0$ and receives a subsidy from the incumbent if $R(z) < 0$.[9] We assume that the payment depends on the area, but cannot be made conditional on the level of demand. Finally, the payment $R(z)$ is set by the regulator and announced before investment and co-investment decisions are taken.

Investment and co-investment decisions

We study how the premium affects the entrant's *ex-post* co-investment decision, and then, in turn, the incumbent's investment decision.

Entrant's decision. In an area z covered by the incumbent, with realized demand δ, the entrant enters via co-investment if and only if $\delta\pi^d \geq R(z) + c(z)/2$, where $R(z)$ represents the *ex-post* premium for the area, that is, if

$$\delta \geq \underline{\delta}_R(z) \equiv \min\{1+\sigma, \max\{1-\sigma, \left(R(z)+c(z)/2\right)/\pi^d\}\},$$

where $\underline{\delta}_R(z)$ is bounded from below by $1-\sigma$ and from above by $1+\sigma$. For $z \in [\underline{z}, \bar{z}]$, we have $\underline{\delta}_R(z) > \underline{\delta}(z)$ if $R(z) > 0$, and $\underline{\delta}_R(z) < \underline{\delta}(z)$ if $R(z) < 0$.

The *ex-ante* probability that the entrant enters area z is then

$$p_R^e(z) = \int_{\underline{\delta}_R(z)}^{1+\sigma} \frac{d\delta}{2\sigma} = \frac{1+\sigma-\underline{\delta}_R(z)}{2\sigma}.$$

Compared to the benchmark, the premium reduces the probability of entry in area z if it is positive, whereas it increases the probability of entry if it is negative, i.e., if it is a subsidy. This is because, in contrast to the option price that is paid *ex-ante*, the premium is paid *ex-post*, and therefore affects the co-investment decision of the entrant.

[9] Of course, the government could also subsidize the entrant's co-investment, but this is not our focus here.

We define $\delta^e_R(z) \equiv (1+\sigma+\underline{\delta}_R(z))/2$ as the expected level of demand conditional on entry. Since the threshold level of demand that allows entry, $\underline{\delta}_R(z)$, is increasing in $R(z)$, δ^e_R is also increasing in $R(z)$: as the premium reduces the probability of entry, entry takes place in higher states of demand on average.

Incumbent's decision. Since the entrant co-invests in area z if $\delta \geq \underline{\delta}_R(z)$, the incumbent's expected profit is

$$\begin{aligned}\hat{\pi}_1(z, R(z)) &= \int_{1-\sigma}^{\underline{\delta}_R(z)} \left(\delta\pi^m - c(z)\right)\frac{d\delta}{2\sigma} + \int_{\underline{\delta}_R(z)}^{1+\sigma} \left(\delta\pi^d - c(z)/2\right)\frac{d\delta}{2\sigma} + p^e_R(z)R(z) \\ &= \pi^m - c(z) - p^e_R(z)\left[\delta^e_R(z)\left(\pi^m - \pi^d\right) - \frac{c(z)}{2} - R(z)\right], \end{aligned} \tag{4}$$

with $\hat{\pi}_1(z,0) = \hat{\pi}_1(z)$. The premium $R(z) > 0$ has a direct positive effect on the incumbent's expected profits, as a direct source of profit conditional on entry. However, the premium also has indirect negative effects, which work through the probability of entry $p^e_R(z)$, which is lower with a higher premium, and the expected level of demand conditional on entry, $\delta^e_R(z)$, which increases with the premium. Because of these contradictory direct and indirect effects, the impact of a higher premium on the incumbent's profit is *a priori* ambiguous.

The following technical lemma states the effect of the premium on the incumbent's expected profits.

Lemma 2 *The premium $R(z)$ has the following effects on the incumbent's expected profits:*

1. *If $\pi^m \geq 2\pi^d$, profits $\hat{\pi}_1(z,R)$ are strictly increasing in R, with maximum value $\pi^m - c(z)$ when $p^e_R(z) = 0$.*

2. *If $\frac{2-4\sigma}{1-\sigma}\pi^d \leq \pi^m < 2\pi^d$, profits $\hat{\pi}_1(z,R)$ are maximized at $\hat{R}(z) = \frac{(1+\sigma)(\pi^d)^2}{3\pi^d - \pi^m} - c(z)/2$, with maximum value*

$$\hat{\pi}_1(z,\hat{R}(z)) = \pi^m - c(z) + \frac{(1+\sigma)^2\left(2\pi^d - \pi^m\right)^2}{4\sigma\left(3\pi^d - \pi^m\right)}.$$

3. *If* $\pi^d < \pi^m < \frac{2-4\sigma}{1-\sigma}\pi^d$, *profits* $\hat{\pi}_1(z, R)$ *are maximized when* $p^e_R(z) = 1$, *with maximum value* $(2-\sigma)\,\pi^d - c(z)$.

Proof. See Appendix. ■

Lemma 2 shows that the incumbent's expected profits are not monotonically increasing in the premium. Therefore, setting a higher premium will not always improve firm 1's investment incentives.

We can now discuss the impact of the premium on market structure and total coverage.

Market structure distortion

Compared to the *ex-ante* benchmark, *ex-post* co-investment distorts the market structure in two ways: (i) there is more entry in monopoly areas when they exist, which happens if $\pi^m > 2\pi^d$, and (ii) there is less entry in co-investment areas.

For given coverage levels, the first distortion is actually welfare-enhancing and there is no need to correct this via a premium.

By contrast, the second distortion, which occurs because the entrant co-invests *ex-post* only when demand is high ($\delta \geq \underline{\delta}(z)$), harms welfare. If we wish to correct this distortion and replicate the *ex-ante* outcome of certain co-investment, the entrant must be paid a subsidy equal to its losses at the lowest demand state, that is, we should set:

$$R\,(z) = (1-\sigma)\pi^d - c(z)/2 \leq 0. \tag{5}$$

Since this subsidy is financed by the incumbent, it cannot exceed the latter's expected profits if investment is to occur, i.e., we must have $\pi^d - c(z)/2 + R(z) \geq 0$ or $(2-\sigma)\pi^d - c(z) \geq 0$. This condition holds at $z = \underline{z}$, since $c(\underline{z}) = 2\,(1-\sigma)\,\pi^d$, but not at $z = \bar{z}^c$, where $c(\bar{z}^c) = 2\pi^d$. Thus, for areas close to $\bar{z}^c$ the subsidy necessary to make the entrant co-invest *ex-post* with probability 1 prevents the incumbent from investing in the first place. This means that we cannot totally correct the market structure distortion with a subsidy paid by the incumbent to the entrant.

Total coverage distortion

A distortion in total coverage arises when $\pi^m < 2(1+\sigma)\pi^d$, in which case total coverage is lower with *ex-post* co-investment than in the benchmark. To determine whether a premium can correct this distortion, we use Lemma 2 and check whether a premium can restore investment incentives while maintaining entry.

First, if $\pi^d < \pi^m < \frac{2-4\sigma}{1-\sigma}\pi^d$, the incumbent's investment incentives are restored by subsidizing the entrant (i.e., with $R < 0$). The idea is that with sufficient product differentiation, total profits are increased by entry so that the incumbent can give up some profit for a subsidy and still be better off with co-investment due to the sharing of investment costs. This allows to raise coverage above $\bar{z}^o$, up to the area $\bar{z}^P$ given by $c(\bar{z}^P) = (2-\sigma)\pi^d$. Still, since $\bar{z}^P < \bar{z}^c$, the subsidy can only partially fix the total coverage distortion.

Second, if $\frac{2-4\sigma}{1-\sigma}\pi^d < \pi^m < 2\pi^d$, total coverage can be raised up to the area $\bar{z}^P$ where $\hat{\pi}_1(\bar{z}^P, \hat{R}(\bar{z}^P)) = 0$, that is,

$$c(\bar{z}^P) = \pi^m + \frac{(1+\sigma)^2 \left(2\pi^d - \pi^m\right)^2}{4\sigma\left(3\pi^d - \pi^m\right)}.$$

For $\pi^m < \left(2 - 2\sigma\frac{\sqrt{3-4\sigma+2\sigma^2}-1}{(1-\sigma)^2}\right)\pi^d$, this involves a subsidy, while for larger values of π^m the entrant pays a premium to the incumbent. Still, since $c(\bar{z}^P) < 2\pi^d = c\left(\bar{z}^c\right)$, the premium cannot reestablish coverage of all *ex-ante* co-investment areas.

Third, and finally, if $\pi^m \geq 2\pi^d$ there is no premium that allows to reestablish coverage at $z = \bar{z}^m$ while maintaining entry. However, in all the other *ex-ante* monopoly areas $z \in (\bar{z}^0, \bar{z}^m)$ not covered under *ex-post* investment, there is a premium $R(z)$ that is high enough such that the incumbent's expected profits become positive, since the monopoly profit can be approached arbitrarily closely if the premium is high enough, while not completely cutting off entry. Thus, coverage of all these areas can be guaranteed, though at the cost of a lower probability of entry.

The following proposition summarizes our findings:

Proposition 5 *Area-specific co-investment risk premia paid by the entrant to the incumbent:*

- *reduce the probability of entry in the areas covered by the incumbent;*
- *reestablish coverage in some but not all ex-ante co-investment areas if* $\pi^m < 2\pi^d$*;*
- *reestablish coverage in (almost) all ex-ante monopoly areas if* $\pi^m \geq 2\pi^d$*.*

One notable result is that while payments from the entrant to the incumbent are needed when services are sufficiently homogeneous (i.e., $\pi^m \geq 2\pi^d$), a subsidy to the entrant may be needed to raise coverage when services are very differentiated (i.e., $\pi^m < 2\pi^d$). This is due to a coordination failure under *ex-post* co-investment: Duopoly profits in this case are more than enough to cover investment costs *ex ante*, but the incumbent knows that the entrant will not always enter.

4.3 Combining *ex-ante* and *ex-post* remedies

As we have seen, introducing co-investment options (an *ex-ante* remedy) or a premium (an *ex-post* remedy) can partially, but not fully, restore the *ex-ante* benchmark. In this sub-section, we discuss the possibility of combining both remedies, that is, to implement co-investment options for some areas and a premium for others.

Remember that the market outcome under *ex-post* co-investment is inefficient compared to the benchmark due to two distortions: a market structure distortion and a total coverage distortion.

The market structure distortion means that, compared to the benchmark, there is more entry in monopoly areas $z \geq \bar{z}^c$ and less entry in co-investment areas $z < \bar{z}^c$. We want to correct the latter distortion but not the former, since it is actually welfare-enhancing. As we have seen, the only way to increase entry is to use subsidies (a negative premium).

By contrast, there are two ways to correct the total coverage distortion, using either options or premia. Options allow increasing investment incentives without affecting entry, whereas premia do so by decreasing entry.

Let us be more specific by focussing on the case where there are *ex-ante* monopoly areas (i.e., $\pi^m > 2\pi^d$) and a total coverage distortion (i.e., $\pi^m < 2(1+\sigma)\pi^d$). Then total coverage under *ex-post* co-investment, $\bar{z}^o$, lies between $\bar{z}^c$ and $\bar{z}^m$, which corresponds to Case 2 in Proposition 2. Let us also assume that $c(z) = z$.

First, consider the market structure distortion in the areas $[\underline{z}, \bar{z}^c]$. Let $\hat{z} = c^{-1}((2-\sigma)\pi^d) = (2-\sigma)\pi^d$. The incumbent makes a positive profit with the premium given by (5) if and only if $z \leq \hat{z}$. Therefore, in the areas $z \in [\underline{z}, \hat{z}]$, it is possible to replicate the *ex-ante* benchmark with a probability 1 of entry, without undermining investment, by setting the subsidy given by (5). By contrast, in the areas $z \in [\hat{z}, \bar{z}^c]$, entry can only be partially replicated by setting the maximum subsidy such that the incumbent has an incentive to cover the area, i.e., $\hat{\pi}_1(z, R(z)) = 0$.

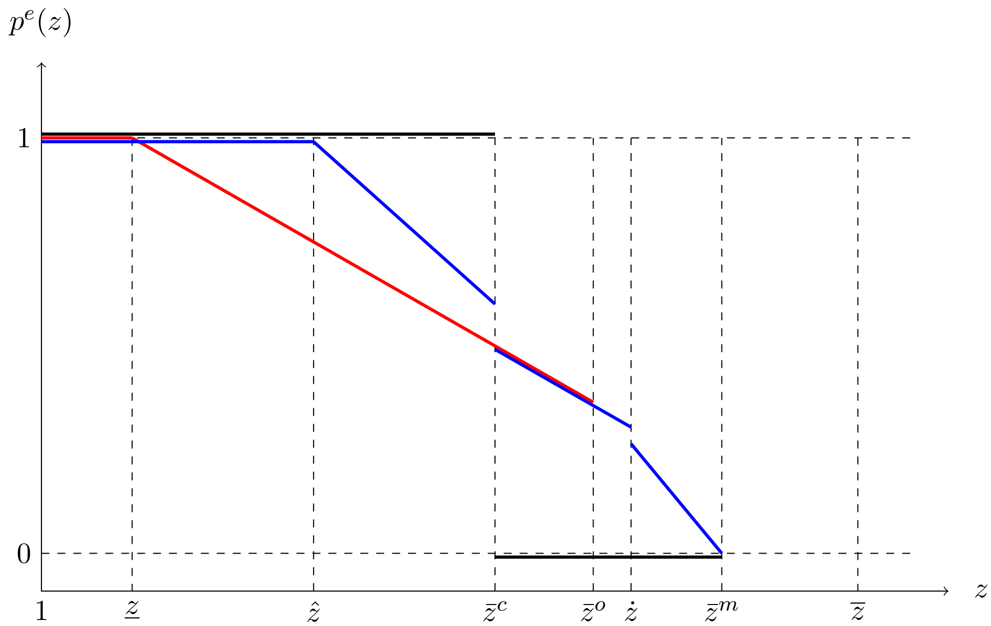
Let us now consider the total coverage distortion. With *ex-post* co-investment, the incumbent covers up to the area $\bar{z}^o \in [\bar{z}^c, \bar{z}^m)$. Since options do not distort entry, whereas the premium does, the idea is to use options to restore coverage for the largest set of areas as possible. The incumbent's profit in a given area z, including the price of the option, i.e., $\hat{\pi}_1(z) + V(z)$, which is given by (3), is decreasing in z, positive at $\bar{z}^o$ and negative at $\bar{z}^m$. Thus, there is exists a unique $\dot{z} \in (\bar{z}^o, \bar{z}^m)$ such that $\hat{\pi}_1(z) + V(z) \geq 0$ if and only if $z \leq \dot{z}$. Therefore, in the areas $[\bar{z}^o, \dot{z}]$, we can restore coverage using options, without affecting entry.

In the areas $[\dot{z}, \bar{z}^m]$, we can use a premium to restore coverage up the *ex-ante* marginal area, $\bar{z}^m$, without cutting off entry, as shown by our analysis in Sub-Section 4.3.

Thus, by combining *ex-ante* and *ex-post* remedies in different areas, total coverage is fully restored. The market structure in co-investment areas is partially, but not fully, replicated. There is still more entry in monopoly areas than in the benchmark.

As an illustration, we use the same numerical example as in Section 3, with $\pi^m = 2.5$,

$\pi^d = 1$, $c(z) = z$, and we also set $\sigma = 0.4$. Figure 1 below shows the probability of entry in the benchmark (in black), with *ex-post* co-investment (in red), and when the optimal combination of *ex-ante* and *ex-post* remedies is implemented (in blue). In the areas $z \in [\underline{z}, \bar{z}^c]$, we introduce a subsidy (i.e., a negative premium) to correct the market structure distortion and increase the probability of entry. In the areas $z \in [\bar{z}^o, \dot{z}]$, we implement options to restore coverage without affecting entry, and in the areas $z \in [\dot{z}, \bar{z}^m]$ a premium, which ensures investment, but with a lower probability of entry.



Ex-ante co-investment: black; *ex-post* co-investment: red; combination of remedies: blue.

Figure 1: Probability of entry under three scenarios.

To compare the three scenarios in terms of total welfare, we use the same Singh and Vives (1984) demand specification as in Section 3, and the same numerical example where the local welfare in duopoly and monopoly areas are $w^d = 5.54$ and $w^m = 3.75$, respectively. We find that total welfare over all areas is $W^b = 9.83$ in the *ex-ante* benchmark, $W^{\text{ex-post}} = 9.39$ with *ex-post* co-investment, and $W^{\text{remedies}} = 10.06$ with the combination of remedies. Therefore, introducing a combination of *ex-ante* and *ex-post* remedies increases total welfare, compared to the outcome under *ex-post* co-investment. It even leads to higher welfare than in the benchmark, because the possibility of *ex-post* co-investment stimulates entry in monopoly areas.

5 Conclusion

In this paper, we have studied the impact of co-investment on the roll-out of network infrastructures under demand uncertainty. Compared to a benchmark where the incumbent and the entrant both take their (co-)investment decisions under uncertainty, we have shown that if the entrant can wait to co-invest until after the level of demand has become known, it can opportunistically cherry-pick which areas to enter. Two distortions then arise. First, there is less entry in *ex-ante* co-investment areas and more entry in *ex-ante* monopoly areas (market structure distortion). Second, the incumbent's investment incentives are reduced, and total coverage tends to be lower than in the benchmark (total coverage distortion).

We considered two possible remedies to correct these distortions when co-investment takes place *ex post*: (i) a co-investment option purchased *ex ante* by the entrant from the incumbent, and (ii) a risk premium paid *ex post* by the entrant. We showed that the co-investment option does not affect entry, and that it cannot fully reestablish total coverage. By contrast, a negative premium (i.e., a subsidy from the incumbent to the entrant) can partially correct the market structure distortion, and a positive premium can also reestablish total coverage in most cases, but at the cost of less entry. Finally, we discussed the possibility to combine the use of options and risk premia in different areas, and showed through a numerical example that it can improve welfare compared to both the *ex-ante* and *ex-post* co-investment outcomes.

From a policy perspective, our findings show that options can be complementary to a risk premium to cope with the opportunism induced by allowing late co-investment. Our results suggest that they would constitute a relevant remedy in areas with intermediate costs where the risk of opportunistic entry may discourage investment.

In our analysis, we considered only one potential entrant. It would be interesting to extend our framework to multiple entrants and study the mechanism through which co-investment options are sold in this case, as well as their potential foreclosure effects among co-investors and access seekers. One could also consider a market for the trade of co-investment options. We leave these topics to future research.

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Appendix

Proof of Proposition 2.

First, note that the profit function of firm 1 is continuous in $z \geq 0$. For $z \in [0, \underline{z}]$, $\hat{\pi}_1(z) = \pi^d - c(z)/2$ is strictly decreasing in z, with $\hat{\pi}_1(\underline{z}) = \sigma\pi^d > 0$. Thus, the incumbent will at least cover all the areas $[0, \underline{z}]$. For $z \geq \overline{z}$, $\hat{\pi}_1(z) = \pi^m - c(z)$ is strictly decreasing from $\hat{\pi}_1(\overline{z}) = \pi^m - 2(1+\sigma)\pi^d$, and the incumbent covers the areas $[\overline{z}, \bar{z}^m]$ if $\bar{z}^m \geq \overline{z} \Leftrightarrow \hat{\pi}_1(\overline{z}) \geq 0$. Finally, for $z \in (\underline{z}, \overline{z})$ the derivative of profits is

$$\frac{d\hat{\pi}_1(z)}{dz} = \left[(1-3\sigma)\,\pi^d + \underline{\delta}(z)\left(\pi^m - 3\pi^d\right)\right]\frac{\underline{\delta}'(z)}{2\sigma},$$

where $\underline{\delta}'(z) > 0$. Therefore, the derivative of $\hat{\pi}_1(z)$ has the sign of the term in brackets.

For $\pi^m \leq 3\pi^d$, the term in brackets is weakly decreasing in $z \in [\underline{z}, \overline{z}]$, which implies that $\hat{\pi}_1(z)$ is either first increasing then decreasing, or always increasing or decreasing. By contrast, for $\pi^m > 3\pi^d$, this term is increasing in z, which means that $\hat{\pi}_1(z)$ is either always increasing or decreasing, or first decreasing and then increasing, in which case it has a local minimum at $\hat{z}$ with $\delta(\hat{z}) = \frac{3\sigma-1}{\pi^m/\pi^d-3}$. The latter case occurs if and only if $\underline{z} \leq \hat{z} \leq \overline{z}$, or equivalently $\frac{2+6\sigma}{1+\sigma} \leq \pi^m/\pi^d \leq \frac{2}{1-\sigma}$, which implies that $\hat{\pi}_1(\hat{z}) > 0$ and therefore also that $\hat{\pi}_1(z) > 0$ for all $z \in [\underline{z}, \overline{z}]$.

Thus, for all values of π^m there will be a unique $\bar{z}^o > \underline{z}$ such that $\hat{\pi}_1(\bar{z}^o) = 0$, and we have $\hat{\pi}_1(\bar{z}^o) > 0$ for $z < \bar{z}^o$ and $\hat{\pi}_1(\bar{z}^o) < 0$ for $z > \bar{z}^o$. The incumbent covers the areas $[0, \bar{z}^o]$, where $\bar{z}^o$ is defined by

$$c(\bar{z}^o) = \frac{2\pi^d}{3\pi^d - \pi^m}\left((1-3\sigma)\,\pi^d + \sqrt{(1-\sigma)^2\left(2\pi^d - \pi^m\right)^2 + 4\sigma\pi^d\left(2(1+\sigma)\,\pi^d - \pi^m\right)}\right).$$

For $\pi^m < \frac{4-\sigma}{2-\sigma}\pi^d$, we have $\hat{\pi}_1(\bar{z}^c) = \frac{1}{4}(2-\sigma)\,\pi^m - \frac{1}{4}(4-\sigma)\,\pi^d < 0$, thus $\bar{z}^o < \bar{z}^c$. For $\frac{4-\sigma}{2-\sigma}\pi^d < \pi^m < 2(1+\sigma)\pi^d$, we have $\hat{\pi}_1(\overline{z}) < \hat{\pi}_1(\bar{z}^m) < 0 < \hat{\pi}_1(\bar{z}^c)$, with $\bar{z}^c < \bar{z}^o < \bar{z}^m < \overline{z}$, while for $\pi^m \geq 2(1+\sigma)\pi^d$, we have $\hat{\pi}_1(\bar{z}^m) = 0$, with $\bar{z}^0 = \bar{z}^m \geq \overline{z}$. ■

Proof of Lemma 2.

We have

$$\frac{\partial \hat{\pi}_1}{\partial R} = \frac{(1+\sigma)\pi^d + \left(\pi^m - 3\pi^d\right)\underline{\delta}_R(z)}{2\sigma\pi^d},$$

and $\partial^2\hat{\pi}_1/\partial R^2 \leq 0$ (i.e., profits are concave in R) if and only if $\pi^m \leq 3\pi^d$. If $\pi^m > 2\pi^d$, profits are increasing in R since

$$\frac{\partial \hat{\pi}_1}{\partial R} \geq \frac{(1+\sigma) - \underline{\delta}_R(z)}{2\sigma} \geq 0,$$

as $\underline{\delta}_R(z) \leq 1+\sigma$. Firm 1's expected profit is thus maximized when $\underline{\delta}_R(z) = 1+\sigma$, i.e., $p^e_R(z) = 0$, where $\hat{\pi}_1 = \pi^m - c(z)$.

For $\pi^m < 2\pi^d$, the candidate for an interior maximum is $\hat{R} = \frac{(\sigma+1)\left(\pi^d\right)^2}{3\pi^d - \pi^m} - c\left(z\right)/2$, with expected profits

$$\hat{\pi}_1\left(z, \hat{R}\right) = \pi^m - c\left(z\right) + \frac{\left(\sigma+1\right)^2\left(2\pi^d - \pi^m\right)^2}{4\sigma\left(3\pi^d - \pi^m\right)}.$$

This candidate is the maximizer if $1-\sigma \leq \left(\hat{R} + c(z)/2\right)/\pi^d \leq 1+\sigma$, or $\frac{2-4\sigma}{1-\sigma}\pi^d \leq \pi^m \leq 2\pi^d$.

Finally, for $\pi^m < \frac{2-4\sigma}{1-\sigma}\pi^d$, firm 1's profits are maximized if $\left(R + c(z)/2\right)/\pi^d = 1-\sigma$, i.e., when $p^e_R(z) = 1$, with expected profits

$$\pi^m - c(z) - 1\left[1\left(\pi^m - \pi^d\right) - \left(1-\sigma\right)\pi^d\right] = \left(2-\sigma\right)\pi^d - c\left(z\right).$$

■