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Co-Investment in the Sharing of Telecommunications Infrastructures

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Abstract

This paper studies the effects of infrastructure sharing agreements on telecommunications markets. Using a theoretical two stage game model with an investment stage and a competition stage where firms compete "à la Cournot", I find that, infrastructure sharing agreements increase investment at industry level. Indeed, the sharing of infrastructures reduces costs of investment for involved operators and encourages them to invest more. This holds except if involved operators are much less efficient than their competitors (i.e., they have much higher marginal costs before investment). Furthermore, infrastructure sharing agreements generally increase both investments and consumer surplus, except if involved operators are much less efficient than their competitors or if they have very different level of efficiency. The infrastructure sharing agreement is even more effective when the most efficient operators are involved.

Keywords

Mobile Telecommunications, Network Sharing, Competition, Consumer Welfare

1. Introduction

The rapid and steady evolution of technologies in the telecommunications sector requires high and frequent investments from telecommunications operators. Such investments are not without creating difficulties for operators. Infrastructure sharing, or co-investment in new infrastructure, allows operators to reduce investment costs and keep up with technological change.

There are different ways for infrastructure sharing. Operators can share only

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passive infrastructure, but they can also share active infrastructure like the Radio access Network (RAN), which is called Ran sharing. The more they share, the more the infrastructure cost saving. However, competition authorities have raised in some cases concerns about sharing agreement. For example, in the case of Czech Republic, the European Commissioner in charge of competition policy, Margrethe Vestager, expressed concern that the recent network sharing agreement would reduce competition and thereby harms innovation EC (2019).

This article aims to study the impact of infrastructure sharing and co-investment on the market. The current rise in infrastructure sharing agreements raises several questions: What is the impact of an infrastructure sharing agreement on investment, price, subscriptions? Consumer surplus and welfare? Is there really a concern about competition and innovation? The Cerre report: "Implementing co-investment and network sharing" points out the potential benefits and anti-competitive effects of network sharing Bourreau et al. (2020). The authors find several potential benefits among which the sharing of deployment costs, leading to faster and wider coverage and higher quality and the sharing of operational costs, benefits consumers in terms of higher surplus.

In my paper, I highlight the sharing of deployment costs that reduces investment costs for operators involved in an infrastructure sharing agreement. I show that this cost reduction encourages them to invest more such that investment of the industry increases in most of cases. I assume that investment reduces operational costs, because new technologies are cheaper to operate (all other things being equal).

Although operating costs may decrease simply due to shared infrastructure, they also decrease as a result of increased investment. The CERRE report also mentions the potential drawbacks of infrastructure sharing among which a reduced incentive for unilateral investment results in lower total network investment than would otherwise be the case. This is at odds with the increased incentives to invest stemming from deployment cost reduction mentioned above. Bourreau et al. (2018) show that the overall effect is an increase in industry investment in the case of fixed networks when operators invest in coverage.

Motta Tarentino (2017) shows that it is also the case for mobile networks when market is symmetric, and operators invest in cost reduction or in quality improvement. This paper extends this last result in the case of dissymmetric markets. I find that investment at industry level increases if the involved operators are not much less efficient (have not marginal costs much higher) than their rivals. Notice that in symmetric market, operators have the same efficiency and as a result, this is consistent with Motta Tarentino (2017).

The CERRE report also points out the risk of collusion, stemming from information exchange between partners, however, I don't address this issue in this paper.

The paper is based on a theoretical model, "à la Cournot" with an investment stage. I compare two situations, on the one hand, a market with an infrastructure sharing agreement where two (among all the) operators co-invest and share their new generation infrastructure, and on the other hand, a market without sharing agreement where operators invest only in their own infrastructure. New generation infrastructures, more efficient than previous generations infrastructures, allow operators to reduce their marginal costs. The infrastructure sharing agreement reduces the cost of investment.

Operators involved in the agreement can thus reduce their marginal costs more easily. This encourages them to invest more. We find that the infrastructure sharing agreement increases the investment of involved operators, and generally the investment of the industry. I find that investment increases at industry level provided involved operators are not largely less efficient than their competitors (i.e. the marginal costs of involved operators before investment are not too high compared to those of non-involved operators).

Furthermore, we find that infrastructure sharing agreement increases subscriptions at industry level, but not equally for all operators. The number of subscriptions increases for involved operators as a whole, however, it is possible that the number of subscriptions decreases for one involved operator if it is largely more efficient than its partner. Finally, we find that infrastructure sharing agreement is beneficial for consumers, it increases consumer surplus. It also increases welfare excepted when the involved operators are largely less efficient than non-involved operators. The remainder of the paper is organized as follows: Section 2 is a literature review, section 3 presents the model, section 4 illustrates and discusses the results and section 5 concludes.

2. Literature Review

The financing of public infrastructure is one of the major concerns of political decision-makers. Several tracks can be considered, such as the tax track, like in Chen et al. (2018). For telecommunications infrastructure, co-investment in infrastructure sharing is a promising track.

Several papers deal with the issue of infrastructure sharing or co-investment, but to my knowledge, none of them deal the issue in the same way of this one. One stream of this literature investigates the impact of co-investment as an alternative to access regulation. Indeed, the different regimes of access regulation have been an important issue since the 1990s with the opening up to competition in telecommunications. Sand-Zantmann (2017) provides an overview of this literature.

In these papers, an incumbent owns the legacy network, and an entrant hesitates between building his own alternative network or leasing access to the incumbent. Nitsche & Wiethaus (2011) compare different access regulation regimes and found that the risk sharing regime is the best from a consumer point of view. In the risk sharing regime, the incumbent and the entrant invest together and thus share the investment and the risk that goes with it. In the same way, Inderst & Peitz (2014) and Bourreau et al. (2018) have compared the standard access obligation with co-investment. They found that co-investment without access obligation lead to a greater coverage and a higher welfare. In my paper there is no incumbent or entrant, but several operators who have the same status without necessarily being symmetrical. The basic setup follows Nitsche & Wiethaus (2011) with a two stages game where operators invest in infrastructure then compete à la Cournot.

Co-investment in infrastructure sharing is a kind of upstream cooperation. d'Aspremont & Jacquemin (1988) have studied the R&D cooperation that may have similar outcomes. They consider a duopoly where firms invest in R&D to reduce their marginal costs and then compete à la Cournot. However, investments in R&D have spillover effects which also reduce, albeit to a lesser extent, the competitor's marginal costs. They find, provided spillover are sufficiently high, that the situation where firms cooperate in R&D then compete in the downstream market has better outcomes in terms of investment and output than the situation where there is no cooperation. Co-investment in infrastructure sharing is quite similar to cooperation in R&D with a large spillover effect. In my article, sharing infrastructure allows operators to reduce marginal costs. They benefit from the infrastructure at a lower cost and share the operating and maintenance costs.

Some papers such as Krâmer & Vogelsang (2017) warn against the risk of collusion induced by the cooperation in infrastructure investment. This interesting question is beyond the scope of our paper, however, Bourreau et al. (2018), without fully solving the problem, cite a number of reasons which reduce the risks as well as the consequences of collusion in the event of co-investment. Anyway, empirical studies do not seem to highlight this point. Cojoc et al. (2020) present a structural model of the Ran sharing agreement in the Czech Republic between the two leading operators in the market. They found that the cost savings are passed on to consumers who benefit from lower prices and a higher download speed.

More generally, my paper rejoins the literature on the links between market structure and investment. Jeanjean (2020) shows that the cost of investment impacts the market structure that maximizes welfare. A lower cost of investment increases the investment of the industry and tends to decrease the number of firms that maximizes investment. Aimene et al. (2021) provide an example of this phenomenon. They show that the recent 4 to 3 mergers of European mobile operators tended to increase the prices of the minute of voice call while diminishing the prices of the megabyte of data. Indeed, technical progress is higher for data than for voice and therefore, cost of investment to reduce marginal costs are cheaper for data than for voice. As a result, the number of MNOs optimizing cost reduction is lower for data than for voice. Given the increasing weight of data compared to voice in mobile industry, the optimal number of MNOs tends to decrease.

Infrastructure sharing and co-investment also tend to reduce the cost of investment. However, in this case, the advantage does not benefit all the operators, but only to involved operators.

3. Theoretical Model for Analysis of Investment Incentives in Presence of Infrastructure Sharing

3.1. Setting of the Model

In this section we use a competition model where n operators compete in quantity "à la Cournot". We denote Q, the number of subscribers in the market, P, the price and c_i the marginal cost of operator i. The number of subscribers that subscribe operator i is q_i. The sum of the subscribers is $\sum_{i=1}^{n} q_i = Q$. We assume a linear inverse demand function: $P = a - bQ$, where a and b are constant parameters. We assume that operators invest in marginal cost reduction, and we assume that investment stage and competition stage are simultaneous.

We assume, as Motta & Tarantino (2017) that a decrease in marginal cost by x requires an investment $F(x)$ where F is convex. For the illustration, we choose $F(x) = x^2/2\tau$, where τ is a constant parameter ($\tau < b$), that represents the efficiency of investment. The higher τ, the lower the cost of investment to reduce the marginal cost of production. τ depends on the technical progress as well as on the type of investment. One can expect that investment in passive infrastructure corresponds to a lower τ than investment in active infrastructure like the RAN. The quadratic form of F represents the increasing marginal price of cost reduction.

Profit of operator i is written: $\pi_i = (P - c_{i0}) q_i - F_i$

Marginal cost c_i depends on the initial marginal cost c_{i0} (before investment) and the marginal cost reduction x_i, following $c_i = c_{i0} - x_i$. Profit of operator i may be rewritten:

$$\pi_i = (P - c_{i0} + x_i) q_i - \frac{x_i^2}{2\tau} \tag{1}$$

Profit maximization gives rise to two first order conditions, one for competition stage and the other for investment stage. Fist order condition for competition stage writes:

$$\frac{\partial \pi_i}{\partial q_i} = \frac{\partial P}{\partial q_i} q_i + (P - c_{i0} + x_i) = 0 \tag{2}$$

and first order condition for investment stage writes:

$$q_i - \frac{\partial F}{\partial x} = 0 \tag{3}$$

Equation (3) yields $x_i = \tau q_i$. This means that the higher the number of subscribers of operator i, the higher the incentives to invest in marginal costs reduction. Indeed, the marginal cost is multiplied by the number of subscribers and therefore, the total cost reduction is proportional to the number of subscribers.

Replacing x_i by τq_i in Equation (2), given the inverse demand function yields

$$P = c_{i0} + (b - \tau) q_i$$

where $c_{i0} - \tau q_i$ is the marginal cost reduced by investment and $b q_i$, the mark-up.

At equilibrium, price is written:

$$P=\frac{a(b-\tau)+b\sum_{i=1}^{n}c_{i0}}{(n+1)b-\tau} \tag{4}$$

and the total number of subscribers:

$$Q=\frac{na-\sum_{i=1}^{n}c_{i0}}{(n+1)b-\tau} \tag{5}$$

as a result, the number of subscribers of operator $i, \forall i\in\{1,2,\cdots,n\}$ is written:

$$q_i=\frac{a(b-\tau)+b\sum_{k\neq i}c_{k0}-(nb-\tau)c_{i0}}{((n+1)b-\tau)(b-\tau)} \tag{6}$$

3.2. Co-Investment and Infrastructure Sharing

Some operators can decide to share their new generation infrastructures. For example, some operators decided to share their 3 G, 4 G or 5 G infrastructures. To do so, they invest together in the new generation infrastructure. The infrastructure sharing may concern a part of the country or the whole country and it may concern only passive infrastructure or active infrastructure as RAN sharing.

Co-investment allows operators to benefit from economies of scale. In our model, if two operators invest together, say operators 1 and 2, their co-investment leading to a reduction of marginal costs by x_s is $F(x_s)=x^2/2\tau$

In such case, operators involved in co-investment maximize their joint profit in investment stage, and their own profit in competition stage. As a result, operators involved in co-investment maximize, $\forall i\in\{1,2\}$:

$$\pi_{is}=(P_s-c_{i0}+x_s)q_{is}-\frac{x_s^2}{4\tau} \tag{7}$$

at competition stage and $\forall i\in\{1,2\}$:

$$\pi_{is}+\pi_{js}=(P_s-c_{i0}+x_s)q_{is}+(P-c_{j0}+x_s)q_{js}-\frac{x_s^2}{2\tau} \tag{8}$$

at investment stage. The first order condition becomes:

$$\frac{\partial\pi_{is}}{\partial q_{is}}=\frac{\partial P_s}{\partial q_{is}}q_{is}+(P-c_{i0}+x_s)=0 \tag{9}$$

for competition stage and

$$q_{is}+q_{js}-\frac{x_s}{\tau}=0 \tag{10}$$

for investment stage. First order conditions for the operators that are not involved in co-investment remain unchanged, Equations (2) and (3).

Equation (10) yields $x_s=\tau(q_{is}+q_{js})$. Replacing x_s in Equation (9) yields $P_s=c_{i0}+(b-\tau)q_{is}-\tau q_{js}$ or $P_s=c_{j0}+(b-\tau)q_{js}-\tau q_{is}$ where $c_{i0}-\tau(q_{is}+q_{js})$ and $c_{j0}-\tau(q_{is}+q_{js})$ are the marginal costs of respectively operator i and operator *j* reduced by investment. bq_{is} and bq_{js} are the mark-up of respectively operator *i* and operator *j*. Notice that the cost reduction is higher with co-investment. For all the other operators not involved in co-investment we can still write $P_s = c_{k0} + (b-\tau) q_k$ with $k \notin \{1, 2\}$.

I assume in the following that each operator has a positive output with or without infrastructure sharing. $\forall i \in \{1, 2, \cdots, n\}$, $q_{is} \geq 0$, $q_i \geq 0$. That means that no operator is excluded from the market following the infrastructure sharing agreement.

At equilibrium when operators *i* and *j* are involved in an infrastructure sharing agreement, price is written:

$$P_s = \frac{\left(a(b-\tau)(b-2\tau) + b(b-\tau)\sum_{i=1}^{n} c_{i0} - b\tau \sum_{k \neq 1,2} c_{k0}\right)}{\left(\left((n+1)b-\tau\right)(b-\tau) - \left((n-1)b-\tau\right)\tau\right)} \tag{11}$$

and the total number of subscribers:

$$Q_s = \frac{\left(an - \sum_{i=1}^{n} c_{i0}\right)(b-\tau) - a(n-2)\tau + \tau \sum_{k \neq 1,2} c_{k0}}{\left((n+1)b-\tau\right)(b-\tau) - \left((n-1)b-\tau\right)\tau} \tag{12}$$

and as a result, the number of subscribers for involved operators is written:

$$q_{is} = \frac{\left(a(b-\tau) + b\sum_{k \neq i} c_{k0} - (nb-\tau) c_{i0}\right) b + (nb-\tau)\tau\left(c_{i0} - c_{j0}\right)}{\left(\left((n+1)b-\tau\right)(b-\tau) - \left((n-1)b-\tau\right)\tau\right) b} \tag{13}$$

with $i, j \in \{1, 2\}$

Proposition 1. *Co-investment in infrastructure sharing increases the number of subscribers at industry level and decreases the price. See proof in the appendix.*

The intuition is as follows: co-investment in infrastructure sharing reduces the investment cost for the operators involved in the sharing agreement. This encourages them to invest more and therefore, the increased investments reduce marginal costs, which decreases prices and increases subscriptions.

Proposition 2. *i. Co-investment in infrastructure sharing increases the number of subscribers of each involved operator provided they have comparable efficiency levels*, (i.e. *their marginal costs before investment are not too different*). *Co-investment may decrease the subscriptions of an involved operator if its partner is largely less efficient* (i.e. *its marginal cost before investment is much higher*).

ii. Co-investment increases the total number of subscribers of involved operators. (*But as we noticed above, not necessarily of each involved operator*). *See proof in the appendix*

Proposition 3. *Co-investment in infrastructure sharing i. increases the investment of involved operators and ii. increases investment at industry level excepted if involved operators are largely less efficient than not involved operators. See proof in the appendix.*

Lower cost of investment encourages involved operators to invest more. This holds at the industry level, unless involved operators are much less efficient than not involved ones.

Proposition 4. *i. Co-investment in infrastructure sharing increases profits of each involved operator provided they have comparable efficiency levels*, (*i.e. their marginal costs before investment are not too different*). *Co-investment may decrease the profit of an involved operator if it is largely less efficient than its partner* (i.e. *its marginal cost before investment is much higher*)

ii.At industry level, *profit increases if involved operators are not largely less efficient than not involved operators.*

Proof. i. Co-investment reduces the cost of investment and thus amplifies the cost reduction of involved operators and increases their profits. However, if an involved operator has a largely higher marginal cost before investment than its partner, the sharing agreement pushes it to invest more than the optimal level and, in this case, its profit may decrease.

ii. At industry level, co-investment increases profits provided involved operator are largely less efficient than not involved operators. Co-investment decreases the cost of investment and increases the return on investment for involved operators, therefore, infrastructure sharing agreement has a positive impact on profits, however, this positive effect may be negatively offset if involved operators are largely less efficient than not involved ones. Indeed, the impact of investment on profit depends on the efficiency level, i.e. on the marginal cost before investment. The lower the marginal cost before investment, the higher the return on investment. As a result, even if co-investment reduces the cost of investment, it may be not sufficient to compensate for the weak return on investment if involved operators are largely less efficient than not involved operators.

Proposition 5. *i. Co-investment increases consumer surplus. ii. Co-investment increases welfare provided involved operators are not largely less efficient than their competitors.*

Proof. i. From proposition 1, we know that sharing agreement decreases price and increases the number of subscriptions.

ii. As infrastructure sharing agreement increases consumer surplus, it also increases welfare if profits increase at industry level. This is generally the case, excepted if involved operators are largely less efficient than uninvolved ones.

From proposition 4, we know that profit of the industry may decrease if involved operators are largely less efficient than uninvolved ones.

4. Illustration and Discussion

In this section, to illustrate the above propositions, I provide 4 examples of different configurations of infrastructure sharing agreements followed by some comments and policy implications.

In these examples, for the simulation, I assume that the number of subscriptions is in millions and the price in €. Each example simulates a four-player market in which, the operators 1 and 2 are involved in an infrastructure sharing agreement and co-invest. The two other players are uninvolved.

In the first example, the four players are quite similar, i.e., they have comparable marginal costs before investment. However, operators involved in the infrastructure sharing agreement are slightly more efficient than uninvolved operators, i.e., they have slightly lower marginal costs before investment. In the second example, the four players are quite similar, however, that time, involved operators are slightly less efficient than uninvolved ones. In the third example, involved operators are much less efficient than uninvolved ones and in the fourth example, involved operators are very different. The first operator is much more efficient than its partner in the infrastructure sharing agreement, and quite similar to uninvolved operators. in each example, $n = 4$; $a = 100$; $b = 6$ and $\tau = 1$.

In the first example, $c_{10} = 10$; $c_{20} = 11$; $c_{30} = 15$ and $c_{40} = 16$. The values, for this example and the others, were chosen arbitrarily to illustrate the model and give, as much as possible, a realistic picture of a nationwide market. Prices and marginal costs are expressed in € and subscriptions are in millions. **Figure 1** below provides the number of subscriptions with and without infrastructure sharing agreement. This figure shows that infrastructure sharing agreement increases the number of subscriptions.

At industry level, infrastructure sharing agreement increases investment from 18.52 to 36.17 million €, increases subscriptions from 12 to 12.273 million and decreases price, from 28 € to 26.36 €. Infrastructure sharing agreement increases also consumer surplus, from 432 million € to 451.91 million €, producers' surplus from 203.72 million € to 209.28 million € and total welfare from 635.72 million € to 661.19 million €.

In the second example, $c_{10} = 16$; $c_{20} = 15$; $c_{30} = 11$ and $c_{40} = 10$. **Figure 2** below, shows that, as in the first example infrastructure sharing agreement increases the number of subscriptions.

At industry level, infrastructure sharing agreement increases investment from 18.52 to 26.72 million €, increases subscriptions from 12 to 12.195 million and decreases price, from 28€ to 26.83€. Infrastructure sharing agreement increases also consumer surplus, from 432 million € to 446.18 million €, but decreases producers' surplus from 203.72 million € to 197.70 million and increases total welfare from 635.72 million € to 643.88 million €.

At industry level, the comparison shows that the first example provides better outcomes than the second both from consumers and operators points of view. In the first example, infrastructure sharing agreement generates more investment, lower prices, a higher surplus both for consumers and producers and therefore a higher welfare than in the second example. In the first example, involved operators are more efficient than uninvolved operators while it is the contrary in the second example. Most efficient operators make better use of infrastructure sharing and are able to generate more surplus for themselves and for consumers. There is therefore no risk of weakening competition with an infrastructure sharing agreement, even if only the market leaders are involved.

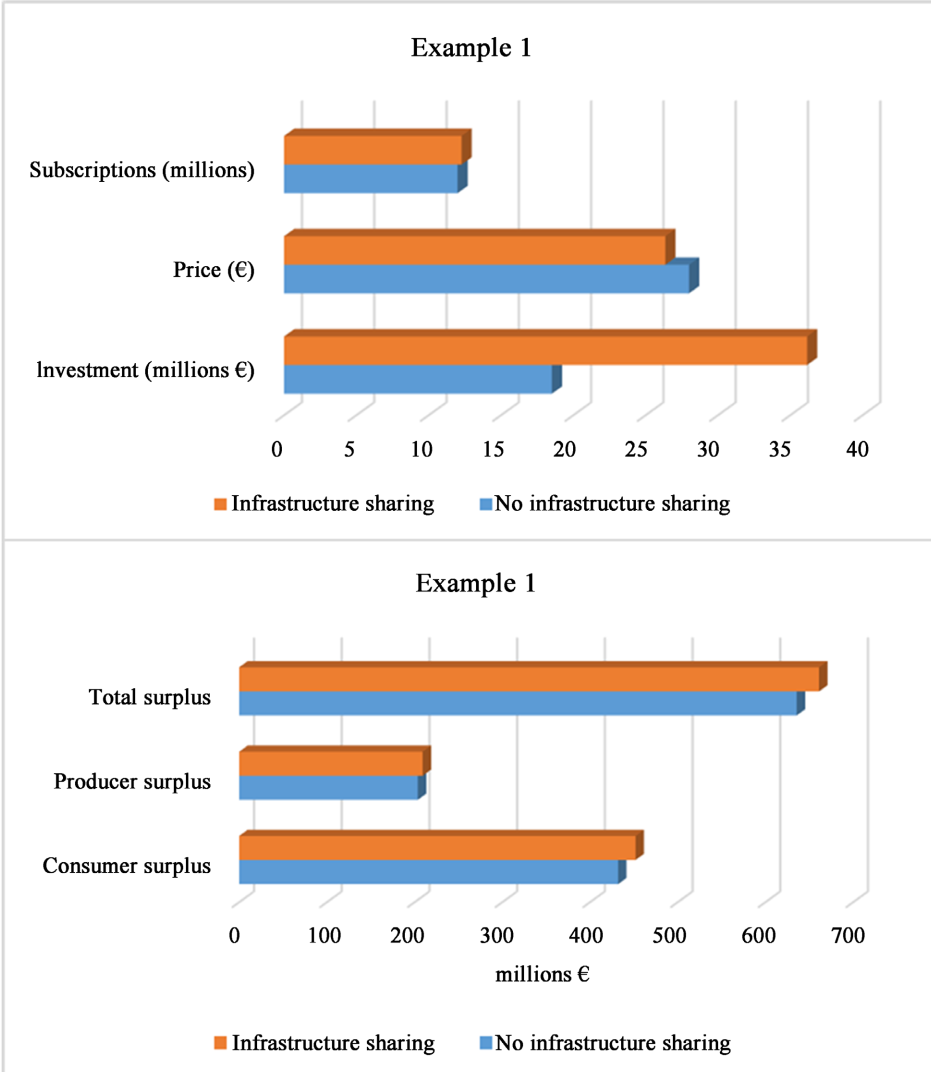
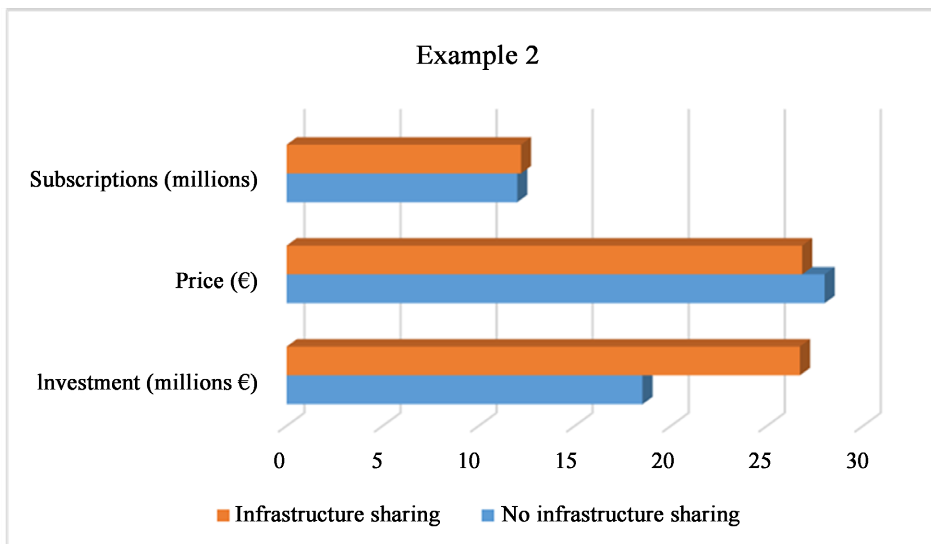


Figure 1. Example 1.



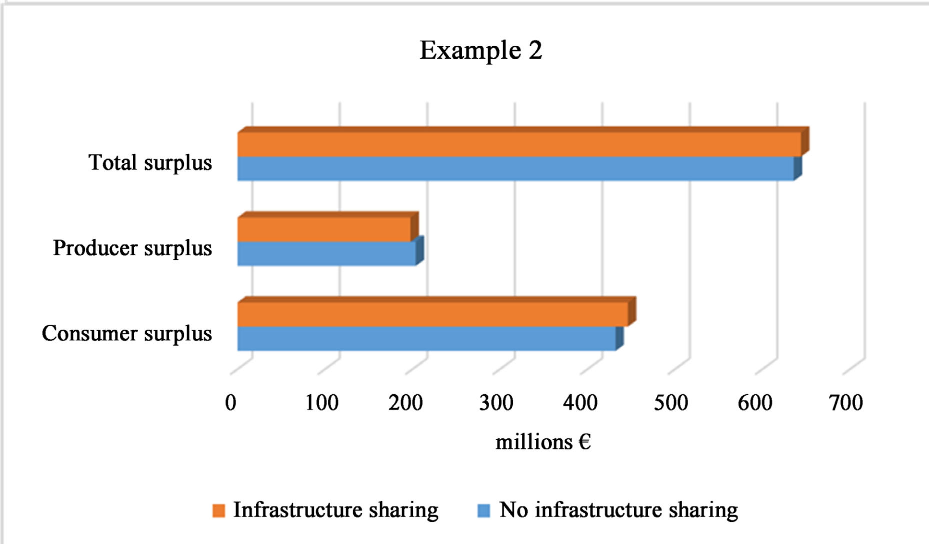


Figure 2. Example 2.

The third example illustrates the proposition 3 *ii* and shows that infrastructure sharing decreases investment only in the case where involved operators are far less efficient than uninvolved ones. And even in this case, we can notice that the impact remains moderate. In the third ex-ample, $c_{10} = 33$; $c_{20} = 32$; $c_{30} = 11$ and $c_{40} = 10$. **Figure 3** below, shows that infrastructure sharing agreement reduces investment at industry level, from 24.35 to 24.28 million €, increases subscription from 10.83 to 10.87 million, decreases price from 35.03 to 34.80 €. Infrastructure sharing agreement increases slightly consumer surplus from 351.71 to 354.29 million € but de-creases producers' surplus from 267.90 to 263.24 million € so that total welfare decreases from 619.61 to 617.53 million €. This example shows much lower results than the previous ones. Indeed, the operators involved are much less efficient than the others and are therefore not in a position to effectively use the co-investment.

The fourth example illustrates the proposition 2 where infrastructure sharing decreases the subscription of an involved operator when its partner is far less efficient. In this example, $c_{10} = 10$; $c_{20} = 30$; $c_{30} = 12$ and $c_{40} = 13$. In this case, the infrastructure sharing decreases the subscriptions of operator 1, much more efficient than operator 2 involved with it in the sharing agreement. The subscriptions of operator 2 increase sharply so that the sum of the subscriptions of the two involved operators increases.

Figure 4 below, shows that, at industry level, investment increases from 21.82 to 23.56 million €, subscriptions increase from 11.55 to 11.72 million and price decreases from 30.69 to 29.69. Consumer surplus increases from 400.33 to 411.99 million €, however producers surplus decreases from 239.97 to 222.08 million € so that total welfare decreases from 640.30 to 634.07 million €. In this case, co-investment implies that involved operators choose together the amount of investment so that they maximize their joint profit. However, the large difference

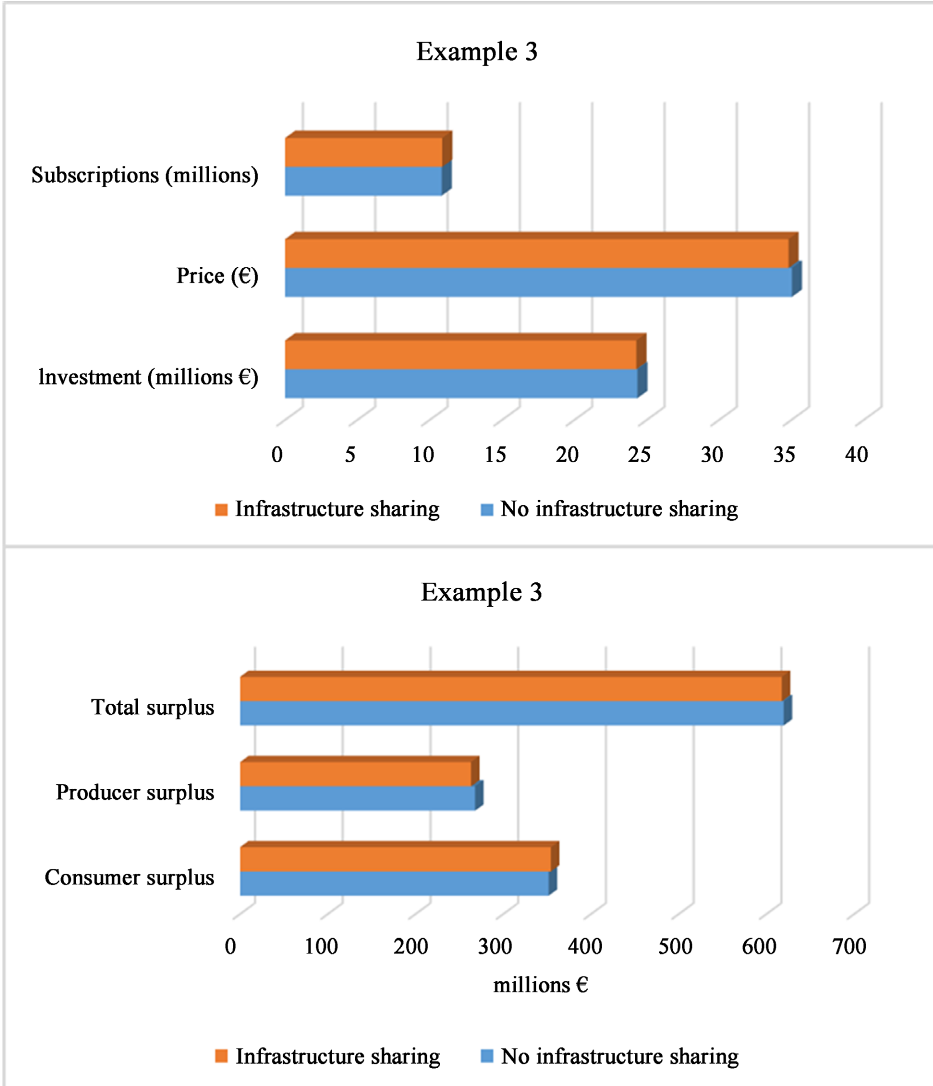
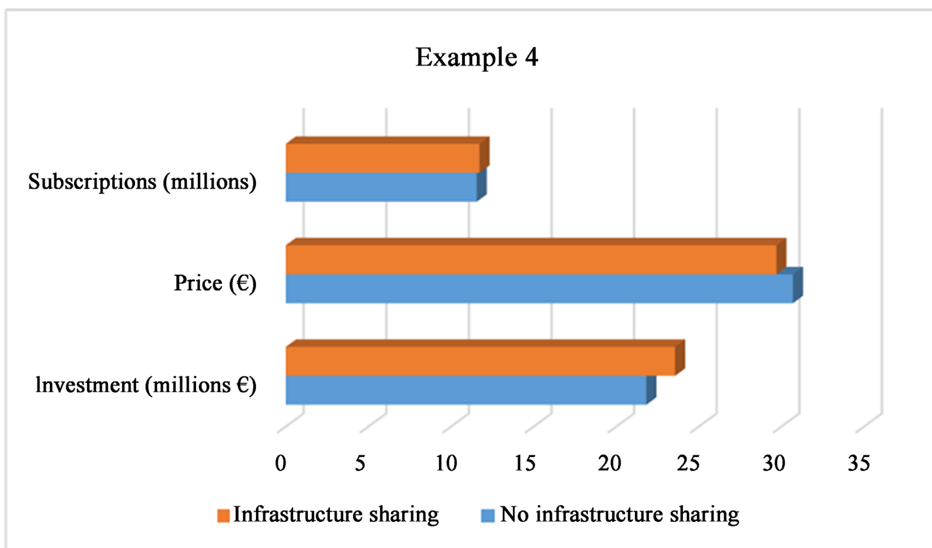


Figure 3. Example 3.



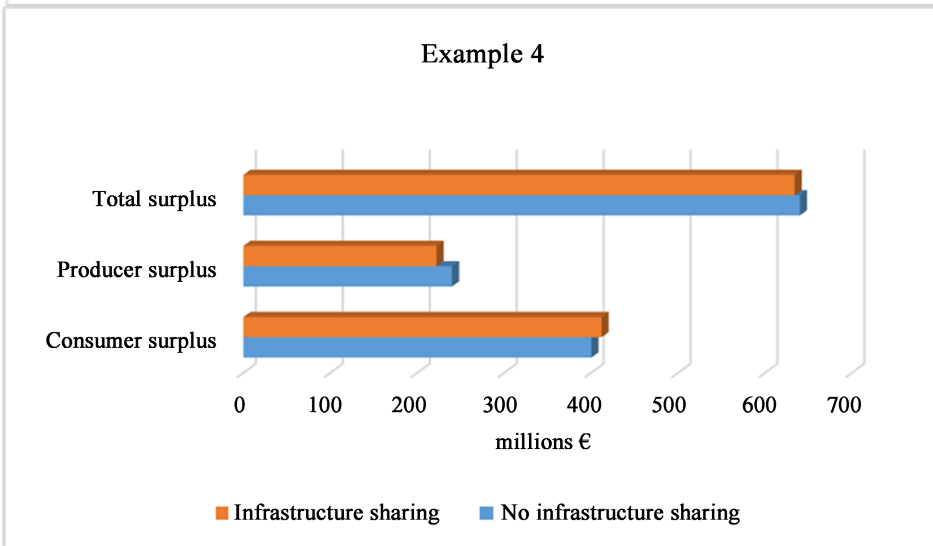


Figure 4. Example 4.

Table 1. Impact of infrastructure sharing agreement.

	$c10$	$c20$	$c30$	$c40$	P	Q	Investment	Consumer Surplus	Producer Surplus	Total Surplus
Example 1	10	11	15	16	−	+	+	+	+	+
Example 2	16	15	11	10	−	+	+	+	−	+
Example 3	33	32	11	10	−	+	−	+	−	−
Example 4	10	30	12	13	−	+	+	+	−	−

The sign + or − indicates a respectively positive or negative impact of infrastructure sharing agreement compared to the situation without agreement.

of efficiency between the two involved operators complicates the choice. The most efficient operator would like to invest more than its partner. As a result, if the difference is sufficiently large, the most efficient operator invests less under co-investment agreement than alone, while the less efficient operator, by contrary invests much more. The less efficient operator thus reduces much more its marginal cost under co-investment than alone, the difference is much lower for the most efficient operator. Hence, the less efficient operator increases sharply its subscriptions while the most efficient decreases them. It is not the same for profits where the most efficient operator increases its profit.

Table 1 above summarizes the results.

5. Conclusion

This article studies the impact of infrastructure sharing agreements with co-investment on the one hand on operators and on the other hand on consumers. Co-investment reduces the cost of investment for operators involved in an infrastructure sharing agreement. This encourages them to invest more. This additional investment allows the involved operators to further reduce their marginal costs, which increases their market share and their profits. However, if together involved operators increase their market share, it is possible that one of the involved operators will see its market share decrease if its partner is much less efficient than it. At the industry level, subscriptions are increasing. Investment tends to increase, unless involved operators are significantly less efficient than non-involved operators. Consumer surplus increases as well as total welfare tends to increase unless involved operators are significantly less efficient. The infrastructure sharing agreement with co-investment is more effective when the most efficient operators are involved. Such agreements are always beneficial for consumers; however, they are not always beneficial for the operators or for total welfare, in particular when the operators involved are much less efficient than non-involved operators or when they have very different levels of efficiency.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix

Proof. of proposition 1:

We know that $\forall i \in \{1,2,\cdots,n\}$, $q_i \geq 0$. The operators involved in the sharing agreement, say *i* and *j* are such that $q_i \geq 0$ and $q_j \geq 0$. Therefore $q_i + q_j \geq 0$ with or without infrastructure sharing. Without infrastructure sharing, $q_i + q_j = \frac{2P - c_{i0} - c_{j0}}{b-\tau}$. As $b-\tau > 0$, we can write $2P > c_{i0} + c_{j0}$ or, from Equation (4):

$$\frac{2(b-\tau) + b\sum_{i=1}^{n} c_{i0}}{(n+1)b-\tau} \geq c_{i0} + c_{j0} \quad \text{which yields:}$$

$$2a(b-\tau) \geq ((n+1)b-\tau)(c_{i0}+c_{j0}) - 2b\sum_{i=1}^{n} c_{i0} \tag{14}$$

We want to show that $Q_s \geq Q$, this means that $\frac{Q_s}{Q} \geq 1$

From equations (5) and (12), we can write:

$$\frac{Q_s}{Q} = \frac{\left(an - \sum_{i=1}^{n} c_{i0}\right)((n+1)b-\tau)(b-\tau) - \left(a(n-2) - \sum_{k\neq i,j} c_{k0}\right)((n+1)b-\tau)\tau}{\left(an - \sum_{i=1}^{n} c_{i0}\right)((n+1)b-\tau)(b-\tau) - \left(an - \sum_{i=1}^{n} c_{i0}\right)((n-1)b-\tau)\tau}$$

$$\frac{Q_s}{Q} \geq 1 \ \text{ if } \ \left(a(n-2) - \sum_{k\neq i,j} c_{k0}\right)((n+1)b-\tau) \leq \left(an - \sum_{i=1}^{n} c_{i0}\right)((n-1)b-\tau)$$

This yields:

$$2a(b-\tau)(\tau-(n+1)b)\sum_{k\neq i,j} c_{k0} - ((n-1)b-\tau)\sum_{i=1}^{n} c_{i0} \geq 0$$

Using Equation (14), we can write:

$$\begin{aligned} &2a(b-\tau)(\tau-(n+1)b)\sum_{k\neq i,j} c_{k0} - ((n-1)b-\tau)\sum_{i=1}^{n} c_{i0} \\ &\geq \left(((n+1)b-\tau)(c_{i0}+c_{j0}) - 2b\sum_{i=1}^{n} c_{i0}\right)(\tau-(n+1)b)\sum_{k\neq i,j} c_{k0} \\ &\quad -((n-1)b-\tau)\sum_{i=1}^{n} c_{i0} \end{aligned}$$

Using the fact that $c_{i0} + c_{j0} = \sum_{i=1}^{n} c_{i0} - \sum_{k\neq i,j} c_{k0}$, we can check that:

$$\begin{aligned} &\left(((n+1)b-\tau)(c_{i0}+c_{j0}) - 2b\sum_{i=1}^{n} c_{i0}\right)(\tau-(n+1)b)\sum_{k\neq i,j} c_{k0} \\ &-((n-1)b-\tau)\sum_{i=1}^{n} c_{i0} = 0 \end{aligned}$$

Therefore,

$$2a(b-\tau)(\tau-(n+1)b)\sum_{k\neq i,j} c_{k0} - ((n-1)b-\tau)\sum_{i=1}^{n} c_{i0} \geq 0$$

And as a result, $Q_s \geq Q$.

If $Q_s \geq Q$, then $P \geq P_s$ because $P - P_s = b(Q_s - Q) \geq 0$

Proof. of proposition 2:

In the following we denote q_{is} the number of subscribers of operator *i* when there is co-investment with an infrastructure sharing agreement and q_i, the number of subscribers of operator *i* when there is no agreement.

i. Equations (6) and (13) provide respectively the expressions of the number of subscribers of operator *i*, respectively without agreement q_i and with agreement, q_{is} if *i* is involved. The difference $q_{is} - q_i$ is written:

$$q_{is} - q_i = \frac{\left(\left(a(b-\tau)+b\sum_{k\neq i} c_{k0} - (nb-\tau)c_{i0}\right)\left((n-1)b-\tau\right)b + \left((n+1)b-\tau\right)(b-\tau)(nb-\tau)\left(c_{i0}-c_{j0}\right)\right)\tau}{\left(\left((n+1)b-\tau\right)(b-2\tau)+2b\tau\right)\left((n+1)b-\tau\right)(b-\tau)b} \quad (15)$$

with $i, j \in \{1,2\}$

thus $q_{is} \geq q_i$ if

$$c_{j0} - c_{i0} \leq \frac{\left(a(b-\tau)+b\sum_{k\neq i} c_{k0} - (nb-\tau)c_{i0}\right)\left((n-1)b-\tau\right)b}{\left((n+1)b-\tau\right)(b-\tau)(nb-\tau)}$$

using Equation (6), this expression yields:

$$c_{i0} - c_{j0} \leq \frac{q_i\left((n-1)b-\tau\right)b}{nb-\tau}$$

and same manner, we can also write:

$$c_{j0} - c_{i0} \leq \frac{q_j\left((n-1)b-\tau\right)b}{nb-\tau}$$

This means that if the difference between c_{i0} and c_{j0} is not too large, then $q_{is} \geq q_i$ and $q_{js} \geq q_j$, the co-investment increases the subscriptions to the involved operators. Otherwise, if the difference is large enough, it is possible that $q_{is} < q_i$ and $q_{js} < q_j$,

ii. Co-investment increases the total number of subscribers of involved operators if $q_{is} + q_{js} \geq q_i + q_j$ with $i, j \in \{1,2\}$

$$q_{is} + q_{js} - (q_i + q_j) = \frac{\left(a(b-\tau)+b\left(c_{i0}+c_{j0}+2\sum_{k\neq i,j} c_{k0}\right)-(nb-\tau)\left(c_{i0}+c_{j0}\right)\right)\left((n-1)b-\tau\right)\tau}{\left(\left((n+1)b-\tau\right)(b-2\tau)+2b\tau\right)\left((n+1)b-\tau\right)(b-\tau)}$$

that can be rewritten, using Equation (6)

$$q_{is} + q_{js} - (q_i + q_j) = \frac{\left(q_i+q_j\right)\left((n-1)b-\tau\right)\tau}{\left(\left((n+1)b-\tau\right)(b-2\tau)+2b\tau\right)}$$

this expression is positive, as a result $q_{is} + q_{js} \geq q_i + q_j$ The agreement increases the total number of subscribers of involved operators.

From proposition (1), we know that $P_s \leq P$, as a result, $q_{ks} \leq q_k$. The infrastructure sharing agreement decreases the subscriptions of the not involved operators.

From proposition (1), we know that $P_s \leq P$, as a result, $q_{ks} \leq q_k$. The infrastructure sharing agreement decreases the subscriptions of the not involved operators.

Proof of proposition 3:

iii. Investments of involved operators without infrastructure sharing agreement are given by:

$$F_i = \frac{x_i^2}{2\tau} \text{ and } F_j = \frac{x_j^2}{2\tau}$$

From equation (3), we have $x_i = \tau q_i$ and $x_j = \tau q_j$. As a result, $F_i = \frac{\tau q_i^2}{2}$ and $F_j = \frac{\tau q_j^2}{2}$.

With infrastructure sharing and co-investment, each operator invests $F_{is} = F_{js} = \frac{x_s^2}{4\tau}$, from Equation (10), we have $x_s = \tau\left(q_{is} + q_{js}\right)$. As a result, involved firms invest:

$$F_{is} + F_{js} = \frac{\tau\left(q_{is} + q_{js}\right)^2}{2}$$

From proposition (2), we know that $q_{is} + q_{js} \geq q_i + q_j$. As a result, $\tau\left(q_{is} + q_{js}\right)^2 \geq \tau\left(q_i + q_j\right)^2 \geq q_i^2 + q_j^2$, therefore, $F_{is} + F_{js} \geq F_i + F_j$. Co-investment encourage involved operators to invest more. If, moreover, we have $q_{is} \geq q_i$ and $q_{js} \geq q_j$, then $F_{is} \geq F_i$ and $F_{js} \geq F_j$.

iv. At industry level, $F = \frac{q_i^2 + q_j^2 + \sum_{k \neq i,j} q_k^2}{2}$ and $F_s = \frac{\left(q_{is} + q_{js}\right)^2 + \sum_{k \neq i,j} q_{ks}^2}{2}$

If involved operators are more efficient than the others, that is to say, their marginal cost before investment are lower, they have a higher number of subscriptions. Since the infrastructure-co-investment increases the subscriptions of involved operators and decreases the subscriptions of the others, as a result, $F_s \geq F$. Indeed, $F_s > \frac{q_{is}^2 + q_{js}^2 + \sum_{k \neq i,j} q_{ks}^2}{2}$ and the co-investment increases the heterogeneity of the squared terms which increases the sum.

If, by contrary, involved operators are sufficiently less efficient than the others, it is possible that $F_s < F$. In that case, the co-investment reduces the heterogeneity of the squared terms which decreases the sum.