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Market structure and investment in the mobile industry[☆]

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ABSTRACT

The impact of market structure, that is the number of firms and asymmetry, on investment is an important topic in the mobile industry. However, previous literature remains ambiguous about the direction of the relationship. This paper provides an empirical evidence of the impact of market structure on investment in the European mobile industry. The empirical assessment is based on a Salop model with vertical differentiation. Consistently with the prediction of this model, we find that both the number of operators and market share asymmetry have significant effects on investment. In symmetric markets, investment per operator falls with the number of operators, with larger effects for operators that lose market share more than the average. The industry investment rises with the number of operators in the short run, but eventually falls in the long run due to significant adjustment costs of investment in the mobile industry. These findings suggest that investment should be taken into account when analysing the *welfare* effects of market structure in the mobile industry.

1. Introduction

The impact of market structure, that is the number of firms and asymmetry, on investment has become an important topic in the mobile industry in the context of market concentration as underscored by the 4-to-3 mergers cleared in Austria. The ex-post effects of these changes in market structure have fuelled an ongoing policy debate, particularly in the European Union resulting in tougher scrutiny on future entry and merger in the industry.[1] As a matter of fact, a 4-to-3 merger was cleared in Germany, whereas others have been blocked in Denmark and the United Kingdom. A key issue in the policy debate is whether or not investment in mobile networks is endogenous, that is whether it is affected by market structure.

Existing theoretical literature predicts an ambiguous effect of market structure on investment.[2] In symmetric markets, Vives (2008) finds that investment in cost-reducing innovations falls with the number of firms, provided that demand elasticity is sufficiently small. In asymmetric markets, Schmutzler (2013) shows that the effect of market structure on investment tends to be negative for less efficient firms.

In this paper, we investigate the impact of market structure on investment in the European mobile industry, taking into account adjustment costs of investment. Market structure is defined by the number of operators and their market share asymmetry. This latter is measured as the difference between an operator's market share and the average market share. Investment is measured as the logarithm of capital expenditures, excluding licence fees. We account for the adjustment costs of investment by estimating a dynamic econometric model that links investment to its lagged values. The econometric model is derived from a Salop model with vertical differentiation. Vertical differentiation stems from investment that either lowers marginal costs or increases quality, two key features of investment in mobile networks. The theoretical model predicts that investment in mobile networks depends on the number of

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[1] See the report by the OECD which highlights a positive relationship between the number of mobile operators and investment in quality (OECD, 2014), and the report by the Centre on Regulation in Europe which suggests a negative relationship between the number of mobile operators and investment (Genakos et al., 2015).

[2] See Schumpeter (1942) and Arrow (1962) for earlier analyses of the link between competition and innovation.

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operators and their asymmetry in terms of quality. More specifically, in symmetric markets, investment per operator falls with the number of operators, and this effect tends to be larger for lower-quality operators.

In accordance with the predictions of the theoretical model, we formulate a dynamic panel econometric model that links investment to the number of operators, market share asymmetry and the lagged values of investment, controlling for operator fixed effects, market characteristics and year fixed effects. The identification of the parameters relies on the Arellano–Bond estimator, a two-step system generalised method of moments estimator. We use 3-to-5 years lagged values of investment as instruments, ensuring that there is no serial correlation. We also use political ideology, mobile termination rates and population size as instruments for the number of mobile operators, market share asymmetry and market size, respectively.

Consistently with the predictions of the theoretical model, we find that investment per operator falls with the number of operators. This negative effect is larger for operators that lose market share more than the average. The industry investment tends to rise in the short run, but eventually falls in the long run due to significant adjustment costs of investment in the mobile industry. The magnitude of the long run effect amplifies the short run effect by a factor of up to 5. These findings are robust to market characteristics such as market size, consumers' income, competition from fixed lines, cash flow and retail prices.

This paper is amongst the first to show that market structure has significant effects on investment in the mobile industry. Theoretical papers such as Vives (2008) and Schmutzler (2013) find that investment in cost-reducing technologies tends to decrease with the number of firms. Boone (2000) emphasizes the role of cost efficiency gap between firms in determining how competition affects their investment incentives. Few empirical papers provide evidence for these theoretical propositions. The findings of this paper lend support to these theoretical predictions. Sacco and Schmutzler (2011) show that the relationship between competition and investment can be U-shaped. Our findings suggest a monotone effect of market structure on investment in symmetric markets. However, this relationship strongly depends on asymmetry. Beneito et al. (2015) test the effect of competitive pressure, measured by the degree of product differentiation and market size, on investment in a free entry setting, thus excluding the analysis of the effect of market structure. Consistent with their results, we also find a positive effect of market size on investment per operator.

The remaining of the paper is organised as follows. Section 2 presents the theoretical model. Section 3 outlines the empirical framework, and in particular the data, econometric model and estimation strategy. Section 4 reports and discusses the results while Section 5 concludes.

2. Theoretical background

In this section, we start by summarising the relevant findings from Vives (2008) in symmetric markets and Schmutzler (2013) in asymmetric markets. Then we focus on how market structure affects investment in the mobile industry using a Salop model with vertical differentiation as this provides a good representation of the mobile market. Salop's model is an extension of the Hotelling model often used to describe telecommunication markets characterised by price competition with horizontal and vertical differentiation (Laffont et al., 1998). The Hotelling model represents a duopoly and the Salop model extends to a more general oligopolistic market structure. In particular, it can be used to compare market outcomes when the number of firms changes. Moreover, the predictions of this theoretical model will be useful in specifying our econometric model.

Vives (2008) shows that, in a symmetric market, the number of firms impacts investment and output in the same way. He shows that, generally, an increasing number of firms decreases both production and investment in each firm. This may occur when the growth of the total market size does not compensate for the decline in per-firm market share. According to Vives, the decrease in market share, called demand effect, is a direct consequence of the rise in the number of firms, while the growth of market size is an indirect outcome (price-pressure effect). The rise in the number of firms tends to reduce prices and thus increase consumer participation and market size. In the case where the market is close to full coverage, the demand of the industry is weakly sensitive to price or market structure changes. In this case, the price-pressure effect is weak and the demand effect would likely dominate. Therefore, an increase in the number of firms has a negative impact on investment.

In our model, we assume that the market is fully covered in order to limit the price-pressure effect. This is consistent with the mobile industry where, in most countries, the penetration rate is sufficiently high such that we can expect the demand effect to dominate.[3] In the empirical model, we control for the growth of market size.

Schmutzler (2013) shows that in asymmetric markets, smaller firms are more sensitive to changes in market structure. We also verify this in both the theoretical and empirical models.

2.1. Settings of the model

All operators are located equidistantly around a circle where consumers are uniformly distributed. It is assumed that product space is totally homogeneous, thus the location of operators does not matter. The perimeter of the circle and the density of consumers are equal to unity and consumers move around the circle with a transportation cost equal to t to purchase one unit of the good from one of the operators.

We consider a restricted entry regime where the number of operators, $N > 1$, is exogenously determined by regulation. The distance between two operators is $1/N$. We also assume that the gross consumer surplus s of each operator is high enough such that the market is fully covered. The demand for operator i's variety is q_i and the demand of the industry is $Q = \sum_{i=1}^{N} q_i$, where $q_i = Q\sigma_i$. Q is a constant since the market is fully covered and σ_i is the market share of operator i. We normalise $Q = 1$ and consider the following two-stage game:

In the first stage, operators choose their investment z, which determines the level of quality of their variety. For operator i, we define the level of quality as $d_i = s_i - c_i$, where c_i represents the constant marginal cost of production and s_i is the gross surplus of purchasing from that operator ($c_i \leq s_i$). This definition reflects the fact that higher quality may result from higher consumer surplus or lower marginal cost of production. In order to choose the quality d_i, operator i invests an amount $z_i(d_i)$ increasing and convex with d_i and incurs a sunk fixed cost F to enter the market.

In the second stage, operators compete in price and operator i sets price p_i. The game is solved by backward induction.

The utility of a customer located at a distance x from operator i to purchase from that operator is: $U_i = s_i - tx - p_i$, and the utility from purchasing from operator $i+1$ is: $U_{i+1} = s_{i+1} - t(\frac{1}{N} - x) - p_{i+1}$. An indifferent consumer between operators i and $i+1$ is located at:

$$x = \frac{1}{2N} + \frac{(s_i - p_i) - (s_{i+1} - p_{i+1})}{2t}$$

[3] Worldwide subscription penetration rate in 2015 is close to 100% and user penetration rate is over 65%. (Worldwide cellular user forecast 2015–2020, Strategy Analytics).

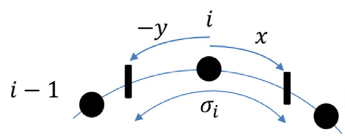

Fig. 1. Market share calculation.

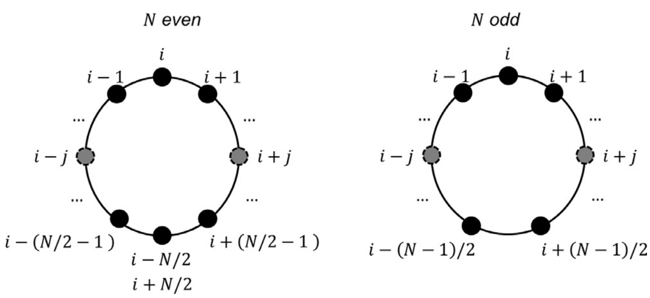

Fig. 2. Location of operators.

and between operator i and operator $i-1$ is located at:

$$-y = \frac{1}{2N} + \frac{(s_i - p_i) - (s_{i-1} - p_{i-1})}{2t}$$

The market share of operator i is $\sigma_i = x - y$ (see Fig. 1), and the corresponding profit is expressed as:

$$\pi_i = (p_i - c_i)q_i - z_i - F \tag{1}$$

2.2. Incentive to invest

The first order conditions, given the level of quality, leads to $(p_i - c_i)\frac{\partial\sigma_i}{\partial p_i} = -\sigma_i$, and $\frac{\partial\sigma_i}{\partial p_i} = \frac{\partial(x-y)}{\partial p_i} = -\frac{1}{t}$, therefore, the Nash equilibrium price is expressed as:

$$p_i^* = c_i + \sigma_i t \tag{2}$$

Profit at equilibrium is expressed as:

$$\pi_i^* = \sigma_i^2 t - z_i - F \tag{3}$$

In the first stage, operator i chooses investment z_i and the corresponding quality d_i. The first order condition leads to:

$$\frac{\partial z_i}{\partial d_i} = 2\sigma_i \frac{\partial\sigma_i}{\partial d_i} t \tag{4}$$

At equilibrium, replacing p_i^* using Eq. (2) in $\sigma_i = x - y$ and $d_i = s_i - c_i$ yields the following expression:

$$\sigma_i = \frac{1}{2N} + \frac{1}{2t}\left(d_i - \frac{d_{i+1} + d_{i-1}}{2}\right) + \frac{\sigma_{i+1} + \sigma_{i-1}}{4} \tag{5}$$

Operator i's market share, σ_i, can be expressed as a linear combination of the quality of each operator $d_i, d_{i+1}, \ldots d_N$. The impact of operator j on operator i, $(j \neq i)$ depends on its distance from operator i. Operator $i+j$ and operator $i-j$ are located at the same distance from operator i. Let β_j denotes the coefficient associated with d_{i+j} and d_{i-j}. It represents the impact of operators $i+j$ and $i-j$ on operator i's market share. β_0 is then the coefficient associated with d_i. It is expected that coefficients β_j are decreasing with j, as the impact of the operators decreases with their distance.

Notice that, for a number of operators N, $\forall j \in [0, \frac{N}{2}]$, operator $i+j$ is also operator $i-(N-j)$. In addition, when N is even, operator $i+N/2$ is also operator $i-N/2$ and when N is odd, operator $i+(N-1)/2$ and operator $i-(N-1)/2$ are neighbours. Expressions of market shares may be different depending on whether N is even or odd (see Fig. 2 below).

For a single expression whether N is even or odd, we use the floor function $\lfloor . \rfloor$ where

$$\lfloor N/2 \rfloor = \begin{cases} \dfrac{N}{2} & \text{if } N \text{ is even} \\ \dfrac{N-1}{2} & \text{if } N \text{ is odd} \end{cases}$$

With this notation, if $j \in [0, \lfloor N/2 \rfloor]$, $i+j$ and $i-j$ can represent all the operators. It is also necessary to add the coefficient γ_j defined by:

$$\gamma_j = \begin{cases} \dfrac{1}{2} & \text{if } j = 0 \text{ or } j = \dfrac{N}{2} \\ 1 & \text{otherwise} \end{cases}$$

Coefficient γ_j is useful when $j = 0$ or $j = N/2$, in both cases, operator $i+j$ is also operator $i-j$. When $j = 0$, this is operator i, when $j = N/2$, this is the farthest operator from i. Thus, $d_{i+j} = d_{i-j}$ and $d_{i+j} + d_{i-j} = 2d_{i+j}$. The coefficient for operator $i+j$ is counted twice. It is then necessary to correct it, this is the reason why, for $j = 0$ or $j = N/2$, $\gamma_j = 1/2$. (see Fig. 2)

With these notations, $j \in [0, \lfloor N/2 \rfloor]$, the linear combination can be expressed as:

$$\sigma_i = \frac{1}{N} + \frac{1}{t}\left(\sum_{j=0}^{\lfloor N/2 \rfloor} \gamma_j \beta_j (d_{i+j} + d_{i-j})\right) \tag{6}$$

In order to calculate the values associated with the coefficient denoted by β_j, we replace σ_{i+1} and σ_{i-1} in Eq. (5) by their expressions calculated using (6). This yields:

$$\begin{aligned} \sigma_i = \frac{1}{N} + \frac{1}{4t}\Bigg[&2d_i - (d_{i+1} + d_{i-1}) \\ &+ \sum_{j=0}^{\lfloor N/2 \rfloor} \gamma_j \beta_j (d_{i+j+1} + d_{i-j+1} + d_{i+j-1} + d_{i-j-1})\Bigg] \end{aligned} \tag{7}$$

The comparison between Eqs. (6) and (7) for all operators, $i \in [1, N]$ provides a system of N equations involving $\lfloor N/2 \rfloor + 1$ coefficients β_j. Although this system is overidentified, it nevertheless admits a unique solution (see proof in the Appendix):

$$\beta_0 = 1 - \frac{(2+\sqrt{3})^N + 1}{\sqrt{3}[(2+\sqrt{3})^N - 1]} \tag{8}$$

and

$$\beta_j = -\frac{(2+\sqrt{3})^{N-j} + (2+\sqrt{3})^j}{\sqrt{3}[(2+\sqrt{3})^N - 1]} \quad \text{if } j \neq 0 \tag{9}$$

For example, we can check:

$$\text{For } N = 2, \sigma_i = \frac{1}{2} + \frac{d_i - d_{i+1}}{3t}$$

$$\text{For } N = 3, \sigma_i = \frac{1}{3} + \frac{2d_i - d_{i+1} - d_{i-1}}{5t}$$

$$\text{For } N = 4, \sigma_i = \frac{1}{4} + \frac{5d_i - 2d_{i+1} - 2d_{i-1} - d_{i+2}}{12t}$$

$$\text{For } N = 5, \sigma_i = \frac{1}{5} + \frac{8d_i - 3d_{i+1} - 3d_{i-1} - d_{i+2} - d_{i-2}}{19t}$$

As expected, coefficient β_0 is positive and coefficients β_j are negative. Operator i's market share increases with its own quality, but decreases with the quality of rivals. This can be illustrated by the positive value of $\frac{\partial\sigma_i}{\partial d_i} = \frac{\beta_0(N)}{t}$ and the negative value of $\frac{\partial\sigma_i}{\partial d_{i+j}} = \frac{\beta_j(N)}{t}$. β_0 is increasing in N, however it converges quickly towards $1 - \frac{\sqrt{3}}{3}$ as N tends to infinity.

The market share of operator i depends on the difference between the quality of operator i, d_i and the quality of the other operators weighted by the coefficients $-\beta_j/\beta_0$. In the following, we denote this weighted quality: $d_{-i} = -\frac{1}{\beta_0}\sum_{j=1}^{\lfloor N/2 \rfloor}\gamma_j\beta_j(d_{i+j}+d_{i-j})$. With this notation, the market share is expressed as:

$$\sigma_i = \frac{1}{N} + \frac{\beta_0}{t}(d_i - d_{-i}) \tag{10}$$

Market share depends only on the number of operators N and on the quality difference $d_i - d_{-i}$ between operators. Eq. (4) can thus be reexpressed as:

$$\frac{\partial z_i}{\partial d_i} = \frac{2\beta_0}{N} + \frac{2\beta_0^2}{t}(d_i - d_{-i}) \tag{11}$$

This equation shows that the incentive to invest depends on the number of operators, and the quality difference between operators $(d_i - d_{-i})$. This equation will be useful for the specification of the econometric model.

In symmetric markets, Eq. (11) becomes:

$$\frac{\partial z_i}{\partial d_i} = \frac{2\beta_0}{N} \tag{12}$$

The marginal profit from quality investment $\frac{2\beta_0}{N}$ is decreasing in N, therefore, investment in quality falls with the number of operators. In asymmetric markets, this negative effect is larger for operators with relatively lower quality, where $d_i < d_{-i}$.

2.3. Consumer surplus

This fall in quality negatively impacts consumer and social surplus. Meanwhile, an increase in the number of operators reduces market power, through the transportation cost. This highlights a static–dynamic efficiency trade-off.

Formally, the following equations correspond to the changes in consumer surplus CS and social surplus W following a change in market structure in symmetric markets. The details of the calculation are provided in the Appendix.

$$\frac{\partial CS}{\partial N} = \frac{\partial d}{\partial N} + \frac{5t}{4N^2} \tag{13}$$

$$\frac{\partial W}{\partial N} = \frac{\partial d}{\partial N}(1 - 2\beta_0) - z - F + \frac{t}{4N^2} \tag{14}$$

We know that $\beta_0 < 1 - \frac{\sqrt{3}}{3}$, thus $1 - 2\beta_0 > 0$. In addition, in symmetric markets, quality falls with the number of operators, therefore, the effect of the number of operators on the dynamic terms is negative: $\frac{\partial d}{\partial N}(1 - 2\beta_0) - z - F < 0$

Eqs. (13) and (14) suggest that the optimal market structure in the mobile industry involves a trade-off between static and dynamic efficiencies if investment in quality falls with the number of operators. In the next section we test whether this trade-off actually exists by investigating the empirical relationship between market structure and investment in the mobile industry.

3. Empirical evidence

3.1. Data and summary statistics

The empirical estimation relies on an unbalanced panel of 50 mobile operators from 17 Western European markets, observed over 10 years, from 2006 to 2015. The dataset comprises operator-level information regarding their capital expenditures, subscribers market share, average revenue per subscriber, earnings before interest, taxes, depreciation and amortisation (Ebitda), and their mobile termination rates. At the market level, we also have information about the number of mobile operators, the total number of subscribers, the penetration rate of fixed lines, socio-demographic characteristics such as gross domestic product (GDP) per capita and population size, and a political variable that aims to capture the position of the government towards the welfare-state (Volkens et al., 2016). The definitions and sources of these variables are presented in Table 1 in the Appendix.

We use this information to construct the main variables of the econometric model, namely investment, the number of mobile operators and their market share asymmetry. Investment is measured as the natural logarithm of capital expenditures in order to make it easier to interpret the estimates, and reduce variance in the residuals of the model. Capital expenditures are limited to the mobile network, but include license fees. We include year fixed effects into the econometric model in order to capture, among other things, the component of capital expenditures that stems from license fees. The number of mobile operators only includes network's owners. Mobile virtual network operators (MVNO) are not taken into account because they typically do not invest in network elements that allow traffic transportation. In particular, they do not own passive network elements such as towers and antennas, or invest in active network elements that involve frequency spectrum.

Market share asymmetry is measured as the difference between an operator's market share and the average market share, that is the inverse of the number of operators. From the theoretical model, asymmetry refers to difference in quality. However, given that quality is not observed, we rely on market shares that provide a more practical way of assessing asymmetry. This measure of asymmetry is consistent with the quality difference obtained from Eq. (10). As we discuss in Section 3.2, defining asymmetry in this way provides a simple method for interpreting the coefficient of the number of operators. This is because, in a symmetric market the difference between an operator's market share and the average market share is zero. Market share is measured in terms of operators' number of subscribers. It includes the subscribers of MVNOs hosted by mobile network operators.

The total number of subscribers, which encompasses both prepaid and postpaid subscribers, is used as a proxy for market size. Subscribers' income is proxied by GDP per capita while competition from fixed lines is proxied by the household penetration rate of fixed lines. Operators' cash flow is proxied by their accounting profit (Ebitda) and retail prices are proxied by the average revenue per user.

Table 2 provides summary statistics of these variables. The operators' market shares are very heterogeneous, ranging from 3 to 62% . The number of operators ranges from 3 to 5. Table 3 in the Appendix presents the evolution of the number of operators per market.

3.2. Econometric model

Consistent with Eq. (11), operators' incentive to invest depends on the number of operators and their asymmetry in terms of quality. The econometric model will, therefore, link operators' investment to the number of operators and the measure of asymmetry.

In addition, there are several potential sources of adjustment costs of investment in the mobile industry. For instance, given technology, increasing marginal cost of network deployment implies that operators first invest in least costly areas before moving into more costly ones. As a result, the remaining gap to the long run desired stock of capital that is closed each period gets smaller and smaller. Moreover, decreasing marginal cost of production, due to strong technological progress, makes any deviation from the steady-state level of investment costly to catch up.[4]

[4] See Koh and Magee (2006) and Amaya and Magee (2008) for the strong rate of technological progression in the Information and Communications Technologies sector.

Table 1
Variables description.

Variable	Name	Definition	Source
Capital expenditures	*capex*	Mobile capital expenditures in millions 2015 US dollars	Yankee group
Investment	*lninv or z*	Logarithm of *capex*	Constructed
Market share	*mshare*	Prepaid and postpaid *or σ*	Yankee group Subscriber market share
Asymmetry	*asym*	Market share asymmetry	Constructed
Average revenue per subscriber	*arpu*	Ratio of revenue to subscribers, in 2015 US dollars	Yankee group
Earning before taxes interest amortisation and depreciation	*cashflow*	Measure of profit	Yankee group Millions of 2015 US dollars
Mobile termination rate	*mtr*	US dollars ppp	Ovum
Number of operators	*N*	Virtual operators excluded	GSMA
Dummy for the number of operators	N_i	Equals 1 in markets with *i* operators and 0 otherwise	
Market size	*msize*	Number of subscribers	Yankee group
Fixed telephony	*ftel*	Household penetration rate	ITU
GDP per capita	*gdppc*	Constant thousands US dollars ppp	World bank
Population	*pop*	Millions	World bank
Political ideology	*welfare*	Government position towards the welfare-state	Manifesto project

Note: yearly observations from 2006 to 2015. ITU: International Telecommunications Union.

Table 2
Summary statistics.

Variable	Obs.	Mean	Std. dev.	Min	Max
capex	391	394.69	352.57	9.30	2441.96
lninv	391	5.58	0.94	2.23	7.80
mshare	391	0.31	0.11	0.03	0.62
asym	391	0.06	0.12	−0.22	0.41
arpu	391	349.49	149.23	100.90	921.97
ebitda	391	1200.53	1207.56	−101.93	5521.24
mtr	391	5.49	4.22	0.82	16.73
N	391	4.12	0.74	3	5
msize	391	42.84	37.23	4.42	115.23
ftel	348	46.36	10.62	11.74	67.12
gdppc	391	34.48	8.50	12.35	67.67
pop	391	33.37	28.40	4.22	82.31
welfare	391	13.38	4.69	6.15	25.49
year	391	2010.58	2.93	2006	2015

Typically, when a change in market structure lowers investment, marginal cost of production is higher and next period investment, which depends on this marginal cost, tends to be lower. We model these sources of adjustment costs with a dynamic model that links investment to its one-year lag.

Formally, the econometric model is expressed as:

$$z_{ijt} = \alpha + \rho z_{ijt-1} + \theta N_{jt} + \delta \Delta_{ijt}(N_{jt}) + \lambda X_{ijt} + \mu_i + \nu_t + \epsilon_{ijt} \quad (15)$$

Where z_{ijt} denotes operator *i*'s investment in market *j* in year *t*. N_{jt} is the number of operators, which may change over time within some markets due to entry or mergers. Δ_{ijt} represents operator *i*'s level of asymmetry with respect to its rivals. Market structure is defined as the combination of the number of operators N_{jt} and their market share asymmetry Δ_{ijt}. This latter is expressed as:

$$\Delta_{ijt}(N_{jt}) = \sigma_{ijt} - \frac{1}{N_{jt}}$$

Where σ_{ijt} is operator *i*'s market share. This expression of asymmetry is consistent with the quality difference in Eq. (10) of the theoretical model. By construction, $\Delta_{ijt} = 0$ in symmetric markets, a feature that will be useful for the interpretation of coefficients θ and δ. The marginal short run effect of the number of operators on investment is expressed as:

$$\frac{\partial z_{ijt}}{\partial N_{jt}} = \theta + \delta \Delta'_{ijt}(N_{jt})$$

Coefficient θ corresponds to the effect of the number of operators on investment in symmetric markets, and more generally to the marginal effect of market structure for an operator that lose market share as the average. Coefficient δ corresponds to the additional effect due to the change in market share asymmetry. Negative $\Delta'_{ijt}(N_{jt})$ means that the operator's market share falls more than the average following an entry. This feature charac-

Table 3
Number of active operators per market.

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Austria	4	4	4	4	4	4	4	3	3	3
Belgium	3	3	3	3	3	3	3	3	3	3
Croatia										4
Denmark	4	4	5	5	5	5	5	5	5	5
Finland	3	4	4	4	4	4	4	4	4	4
France	3	3	3	3	3	3	4	4	4	4
Germany	4	4	4	4	4	4	4	4	3	3
Ireland	4	4	4	5	5	5	5	5	4	4
Italy	4	4	4	5	5	5	5	5	5	5
Netherlands	4	3	3	3	3	3	4	4	4	5
Norway	5	5	4	4	5	5	5	5	5	4
Poland	4	4	5							
Portugal	4	4	4	4	4	3	3	3	3	3
Spain	4	4	4	4					5	5
Sweden	5					5	5	5	5	5
Switzerland	4	5	4	4	4	4	3	3	3	3
UK	5	5	5	5	4	4	4	4	5	5

terises smaller or lower-quality operators. When δ is positive, then the effect of the number of operators on investment tends to be more negative for lower-quality operators.

The magnitude of the adjustment costs is captured by the coefficient ρ. It provides a way to obtain the long run effect by multiplying the short run effect by the ratio $\frac{1}{1-\rho}$.[5] ρ should be between 0 and 1 to ensure long run convergence.

X_{jt} is a control variable representing market size. We introduce additional controls such income, competition from fixed lines, cash flow and retail prices, in the robustness analysis. μ_i are time-invariant operators fixed effects of investment and ν_t are year-specific shocks to investment, such as spectrum purchase. ϵ_{ijt} represents unobserved idiosyncratic shocks affecting operators' investment that might be correlated with some explanatory variables. In the following section, we present the estimation strategy that helps overcome the bias that could stem from this correlation.

3.3. Estimation strategy

OLS estimation of Eq. (15) is likely to yield biased estimates due to several sources of endogeneity, including unobserved cost or demand parameters that jointly determine market structure and investment. For instance, regulators may allow more operators in markets where consumers have high valuation for mobile services. In addition more operators would be willing to enter a market if they are more efficient. Both mechanisms will tend to raise investment per operator and, as a result, OLS estimates of Eq. (15) will underestimate the magnitude of the effect of market structure.

The number of mobile operators can be deemed exogenous because entry and exit in mobile markets are not free. On top of the large fixed cost of network deployment, entry into mobile markets requires spectrum licences from government. This requirement constitutes a legal barrier to entry which restricts the number of mobile operators in a given market. Unlike mobile network operators, MVNOs can enter the market without purchasing a spectrum license, but they are out of the scope of this paper as they do not own networks. Exit of mobile operators is also not free due to merger control. Exit from the mobile market is typically carried out through a merger. However, most mergers require approval by competition authorities.

Nonetheless, as shown by Grajek and Roller (2012), regulatory decisions may be endogenous, in which case the number of operators may fail to be exogenous. Unfortunately, the time dimension of our panel data (10 years with gaps) is not long enough to apply the exact Granger non-causality test in heterogeneous panels, as proposed by Dumitrescu and Hurlin (2012).[6] To overcome this, we test any reverse causality from investment to the number of operators on the basis of three-stage least squares estimator. The system of simultaneous equation involves two equations, one for the number of operators and another for investment. In the tradition of the Granger non-causality test, each dependent variable is regressed over its lags, the other dependent variable and controls. The system of equations is expressed as:

$$\begin{cases} N_{jt} = \alpha_1 + \rho_{11}N_{jt-1} + \rho_{12}N_{jt-2} + \beta_1 z_{ijt} + \gamma_1 X_1 \\ \qquad + \mu_{1i} + \nu_{1t} + \epsilon_{1ijt} \\ z_{ijt} = \alpha_2 + \rho_{21}z_{ijt-1} + \rho_{22}z_{ijt-2} + \beta_2 N_{jt} + \delta_2 \Delta_{ijt}(N_{jt}) \\ \qquad + \gamma_2 X_2 + \mu_{2i} + \nu_{2t} + \epsilon_{2ijt} \end{cases}$$

To further deal with a potential endogeneity of the number of operators, we use government political ideology towards the welfare-state as an instrument. This instrument, already used by Grajek and Roller (2012), is measured by an index provided by the Manifesto Project (Volkens et al., 2016) that characterises political parties' position towards the welfare state. For instance, the index is smaller for right-wing parties. We compute the weighted average of this index at the market-year level, using the percentage vote obtained by each political party during the most recent legislative election.

Additional endogenous explanatory variables include market share asymmetry, market size and the lagged investment. The endogeneity of market share asymmetry and market size stems from the fact that they are determined by unobserved demand, cost and quality parameters. We use population size as an instrument for market size. We expect larger number of subscribers in more populated markets, while population size is predetermined. Population size affects investment only through market size because it is orthogonal to other parameters of demand such as price elasticity or quality valuation. In addition, it does not directly affect investment because it is independent from production costs.

We use mobile termination rates (MTR) as instrument for market share asymmetry.[7] MTRs are regulated wholesale prices that operators pay each other to terminate calls on their rivals' networks. In some markets, termination rates are not regulated, but freely negotiated by network operators, or operators use a bill-and-keep approach, in which case termination rates are zero. In Western European markets, MTRs are set by a regulator. They can differ from one operator to another within the same market. This asymmetry in MTRs is typically implemented in favour of the smaller operators. They are determined by an already asymmetric state of the market, due to late entry or persistent size difference between operators. They are expected to be exogenous and lower asymmetry. However, we check any reverse causality from market share asymmetry to MTR by implementing again a three-stage least squares estimator.

The third source of endogeneity is the one stemming from lagged investment, a standard issue in dynamic panel models.[8] This arises due to potential correlation between the lagged investment and operators' fixed effects. It generates the "Nickel bias", following Nickell (1981) who shows that the adjustment costs parameter ρ in Eq. (15) is respectively under and over-estimated by OLS estimation with and without operators' fixed effects, when the number of time periods is small.

Arellano and Bond (1991) suggest implementing the Generalised Method of Moments estimator (GMM) of Hansen (1982) on Eq. (15) in the first difference, using the lagged dependent variables as instruments as long as they are not serially correlated. This difference GMM estimator can suffer from a loss in sample size with unbalanced panel data. In this case, Arellano and Bover (1995) suggest a forward orthogonal deviations transformation to preserve sample size. Under this transformation, the average of all future available observations of investment is subtracted from its contemporaneous observation.

To improve the efficiency of the estimates, a two-step approach is implemented. It involves estimating the variance-covariance matrix of the residuals and then using it as a weighting matrix in the GMM estimation. Efficiency can be further improved by using the first differences of investment as instruments for the lagged investment (Blundell and Bond, 1995). This is done with Eq. (15) without operators' fixed effects, assuming that first differences of in-

[5] The long run effect is determined by summing all the contemporaneous effects over an infinite period. Typically, the marginal effect of market structure on investment is $\theta + \delta\Delta'_{ijt}(N_{jt})$ at date t, $\rho[\theta + \delta\Delta'_{ijt}(N_{jt})]$ at date $t+1$, $\rho^2[\theta + \delta\Delta'_{ijt}(N_{jt})]$ at date $t+2$, and so on. Thus, the long run effect is: $\sum_{k=0}^{\infty}\rho^k[\theta + \delta\Delta'_{ijt}(N_{jt})] = \frac{1}{1-\rho}[\theta + \delta\Delta'_{ijt}(N_{jt})]$.

[6] This test implements the Granger causality test on each individual in the panel and then takes the average of the Wald statistics. Dumitrescu and Hurlin (2012) show that this average converge sequentially to a normal distribution.

[7] Genakos et al. (2015) initially use MTR as an instrument for mobile market shares.

[8] See Bond (2002) for issues related to the estimation of dynamic panel models and their solutions.

Table 4
Estimation results.

	lninv						
Estimator	(1) OLS	(2) OLS	(3) FE	(4) DGMM	(5) SGMM	(6) DGMMIV	(7) SGMMIV
N	−0.111***		−0.197***	−0.167***	−0.130*	−0.224***	−0.164***
	(0.027)		(0.046)	(0.056)	(0.074)	(0.072)	(0.053)
N_4		−0.141**					
		(0.058)					
N_5		−0.229***					
		(0.060)					
asym	0.829***	0.857***	2.525***	2.772***	1.277**	2.703***	1.272***
	(0.196)	(0.210)	(0.597)	(1.029)	(0.635)	(0.916)	(0.411)
L.lninv	0.731***	0.727***	0.338***	0.715***	0.741***	0.676***	0.800***
	(0.044)	(0.046)	(0.095)	(0.097)	(0.126)	(0.094)	(0.085)
msize	0.006***	0.006***	−0.007*	0.004	0.006**	0.002	0.005**
	(0.001)	(0.001)	(0.004)	(0.011)	(0.003)	(0.009)	(0.002)
Years FE	✓	✓	✓	✓	✓	✓	✓
Operators FE			✓				
Constant	1.605***	1.293***	4.375***				
	(0.281)	(0.228)	(0.634)				
Obs.	391	391	391	342	391	342	391
R-squared	0.892	0.893	0.102				
# groups			49	47	49	47	49
# instruments				38	43	38	42
F-stat	252.52	233.91	14.87				
P-value (AR2)				0.19	0.19	0.22	0.16
P-value (AR3)				0.34	0.34	0.32	0.33
P-value (AR4)				0.18	0.18	0.17	0.18
P-value (Sargan)				0.05	0.16	0.05	0.16
P-value (Hansen)				0.23	0.01	0.3	0.11
Diff-in-Hansen tests:							
	P-value (level)				0.003		0.130
	P-value (diff)			0.38	0.004	0.500	0.120

Specifications (1) OLS, (2) OLS with dummies N_i equal 1 in markets with *i* operators. We use markets with 3 operators as the reference group. (3) Fixed-effects estimator, (4) 2-step difference GMM, (5) 2-step system GMM, (6) and (7) 2-step difference and system GMM with instrument for *N*. *L.* is the lag operator. *P*-value (level) and (diff) are the p-values for the level and difference equations. In specifications (4) and (6), observations drop from 391 to 342 due to the differentiation. Significant at 1% (***), 5% (**) and 10% (*). Standard errors in parentheses. Standard errors robust to heteroskedasticity and autocorrelation, clustered at operator level.

vestment are not correlated with operators' fixed effects. This approach, on top of the difference GMM, yields a system of two equations, one in level and another in first difference. Blundell and Bond (1995) show that this "two-step system GMM" estimator provides more efficient estimates of the parameters of the dynamic model (15).

4. Results

4.1. Main results

The main estimation results are presented in Table 4. Specification (1) is an OLS estimation of Eq. (15) without operators fixed effects. The coefficient of *N* is negative and significant, suggesting that investment per operator falls with the number of operators in symmetric markets. The positive and significant coefficient of asymmetry variable means that the effect of market structure is positively correlated with changes in asymmetry. The coefficient of the lagged investment is positive and significant, suggesting large and significant adjustment costs in the mobile industry. Market size is positively correlated with investment per operator.

Specification (2) replaces the discrete variable *N* with dummies for the number of operators in order to test the monotonicity of the relationship between market structure and investment. Three dummies N_i ($i = 3,4,5$) have been constructed respectively for markets with 3, 4 and 5 operators. N_i takes on the value 1 when a market has *i* operators, and 0 otherwise. Markets with 3 operators are used as the reference group. The outcome of this specification lends support to a monotonous and downward sloping relationship between market structure and investment. Investment per operator is predicted to be 14% and 23% lower in 4 and 5-operators markets, respectively compared to markets with 3 symmetric operators.

Specification (3) introduces operators fixed effects (FE) in order to account for unobserved and time-invariant cost and demand parameters. The main results still hold, and the magnitude of the effect of market structure becomes larger. However, there are significant changes in the coefficients of asymmetry, lagged investment and market size. As discussed in Section 3.3, these variables are likely to be endogenous. In particular, the sharp fall in the coefficient of the lagged investment reflects the Nickel bias whereby this coefficient tends to be underestimated in fixed effects estimation.

Specifications (4) and (5) account for these issues by implementing respectively Difference and System Generalised Method of Moments estimators (DGMM and SGMM) with instruments for asymmetry, lagged investment, and market size. The outcomes of these specifications accord well with a negative relationship between market structure and investment per operator, with a stronger effect for operators that lose market shares more than the average and a significant adjustment costs of investment in the mobile industry. Note that the estimation results do not include a constant term because it is differenced-out.

Specifications (6) and (7) account for the endogeneity of market structure by using government political ideology towards the welfare-state as instrument for the number of operators. The negative relationship between market structure and investment still holds, but the system GMM, that is specification (7), yields better outcomes than the difference GMM (specification (6)). Indeed, as predicted by Blundell and Bond (1995), the coefficients of the

Table 5
Complementary estimation results.

	N (1)	*lninv*	*mtr* (2)	*asym*	*asym* (3)	*msize* (4)	*N* (5)
lninv	**0.393****						
	(0.186)						
L.lninv		0.194***					
		(0.055)					
L2.lninv		0.039					
		(0.050)					
N		**−0.193*****					
		(0.074)					
L.N	0.722***						
	(0.060)						
L2.N	−0.068						
	(0.054)						
asym		3.332***	**0.065**				
		(0.591)	(1.869)				
L.asym				0.849***			
				(0.055)			
L2.asym				−0.104*			
				(0.060)			
mtr				**−0.004***	**−0.007*****	0.575***	0.011
				(0.002)	(0.002)	(0.132)	(0.018)
L.mtr			0.448***				
			(0.048)				
L2.mtr			0.113***				
			(0.039)				
pop	0.175***		−0.181		0.015***	**1.001*****	0.210***
	(0.045)		(0.119)		(0.004)	(0.347)	(0.048)
welfare					−0.003***	0.157*	**−0.033*****
					(0.001)	-0.081	(0.011)
msize		−0.001		0.001			
		(0.005)		(0.001)			
Year FE	✓	✓	✓	✓	✓	✓	✓
Operators FE	✓	✓	✓	✓	✓	✓	✓
Constant	−11.814***	5.619***	−9.407***	−0.035	−1.047***	−14.851	−7.068**
	(3.051)	(0.707)	(3.020)	(0.042)	(0.266)	(22.192)	(3.040)
Obs.	336		336		391	391	391
F-stat					46.75	769.39	10.96

Specifications: (1) 3-stage least squares with *N* and *lninv* as dependent variables, (2) 3-stage least squares with *mtr* and *asym* as dependent variables, (3)–(5) are correlations between the instruments and the endogenous explanatory variables. *gdppc* as control in all specifications. The number of observations is smaller in specifications (1) and (2) due to the lagged explanatory variables. Significant at 1% (***), 5% (**) and 10% (*). Standard errors in parentheses. Standard errors robust to heteroskedasticity and autocorrelation, clustered at operator level.

SGMM are more precisely estimated. In addition, the *p*-values of the Sargan and Hansen statistics of specification (7) are greater than 10%, lending support to the validity of the set of instruments. Moreover, the *p*-value of the difference in Hansen test for this specification suggests that the additional instruments in the level equation are exogenous. Therefore, specification (7) provides the least biased causal effects of market structure on investment. This specification further suggests that market size is a positive determinant of investment per operator, in accordance with the finding by Beneito et al. (2015).

4.2. Robustness checks

Table 5 presents some complementary tests in support of the main results. Specification (1) is a non-causality test between investment and the number of operators. It estimates a system of two equations, one for investment and another for the number of operators as dependent variables, on the basis of three-stage least squares estimator. It shows that investment have a significant effect on the number of operators, but only at 5% level. Likewise, there is a negative and significant effect of the number of operators on investment. These findings do not rule out reverse causality from investment to the number of operators. However, the use of an instrument for the number of operators in specification (7) reduces any bias stemming from reverse causality. Specification (2) tests reverse causality from market share asymmetry to mobile termination rates and finds that market share asymmetry does not determine mobile termination rates, but the reverse holds.

Specifications (3)–(5) are first-stage estimates of the correlation between the instruments and the endogenous explanatory variables. Specification (3) shows a negative and significant correlation between mobile termination rates and market share asymmetry. In specification (4), market size is positively and significantly correlated with population size. Likewise, the political ideology variable is a significant predictor of the number of operators implying that countries governed by pro-welfare-state are predicted to have fewer mobile operators. The *F*-statistics provided at the bottom of the table are all larger than 10, suggesting that the instruments are not weak.

Table 6 presents results corresponding to Eq. (15) with additional controls such as income, competition from fixed lines, cash flow, and retail prices. We account for the endogeneity of the last three controls by using their 2-years lags as internal instruments. Estimation relies on the SGMMIV of specification (7) of Table 4, that is system GMM with instrument for the number of operators. It turns out that none of these additional controls has a significant effect on investment. Note that the Sargan test cannot reject the exogeneity of the instruments, unlike the Hansen test. The failure of the Hansen over-identifying test is probably due to the large

Table 6
Robustness checks.

	lninv			
	(1)	(2)	(3)	(4)
N	−0.161***	−0.138*	−0.112*	−0.114**
	(0.059)	(0.074)	(0.059)	(0.047)
asym	1.272***	0.833**	1.114**	1.149**
	(0.395)	(0.347)	(0.531)	(0.470)
L.lninv	0.811***	0.779***	0.799***	0.698***
	(0.115)	(0.085)	(0.086)	(0.053)
msize	0.005*	0.005***	0.006***	0.007***
	(0.003)	(0.001)	(0.002)	(0.001)
gdppc	−0.001			
	(0.004)			
ftel		−0.001		
		(0.002)		
cashflow			−0.00005	
			(0.00003)	
arpu				−0.0001
				(0.0001)
Year FE	✓	✓	✓	✓
Obs.	391	348	389	391
# groups	49	47	49	49
# instruments	43	43	49	48
P-value (Sargan)	0.13	0.18	0.42	0.18
P-value (Hansen)	0.10	0.00	0.00	0.00
P-value (AR2)	0.16	0.92	0.18	0.20
P-value (AR3)	0.33	0.34	0.34	0.33
P-value (AR4)	0.18	0.39	0.18	0.16

Specification (1) SGMMIV including *gdppc* as additional control and 2-to-4 year lags as internal instruments for *L.lninv*. (2) SGMMIV including *ftel* as additional control and 2 years lags as internal instruments for *ftel* and *L.lninv*. (3) SGMMIV including cashflow as additional control and 2 years lags as internal instruments for *L.lninv*and cashflow. (4) SGMMIV with *arpu* as additional control and 2 years lags as instruments for *L.lninv* and *arpu*. Significant at 1% (***), 5% (**) and 10% (*). Standard errors in parentheses are robust to heteroskedasticity and autocorrelation, clustered at operator level. Smaller observations in specifications (2) and (3) due to missing observations for *ftel* and cashflow in some markets.

number of instruments, though they do not outnumber observations. The main findings remain valid.

4.3. Discussion of the results

In this section, we discuss the marginal effect of market structure on investment from different perspectives: investment per operator, industry investment, short and long run effects. As emphasised in Section 3.2, the short run effect of market structure on investment per operator is a linear combination of the coefficients of the number of operators and asymmetry:

$$\frac{\partial z_{ijt}}{\partial N_{jt}} = \theta + \delta \Delta'_{ijt}(N_{jt})$$

$\Delta'_{ijt}(N_{jt}) = \sigma'(N) + \frac{1}{N^2}$, the variation in asymmetry, represents how much an operator's market share changes, compared to the variation in the average market share. Using Eq. (10) from the theoretical model, $\Delta'_{ijt}(N_{jt})$ can also be interpreted as the change in the quality of an operator with respect to its rivals.

We use the point estimates from specification (7) in Table 4 to evaluate the total short run marginal effect of market structure on investment per operator as a function of change in asymmetry. The outcome of this evaluation is presented in Fig. 3. The upward sloping line in this figure has a slope of $\delta = 1.27$ and intercept of $\theta = -0.16$.

Investment per operator falls by 16% as long as change in market share is identical to the variation in the average market share: $\sigma'(N) = -\frac{1}{N^2}$. This result is particularly relevant in symmetric markets where operators are identical. The magnitude of this negative marginal effect becomes larger for operators who lose more than the average: $|\sigma'(N)| > \frac{1}{N^2}$.

As illustrated by Fig. 3, the marginal effect of market structure is still negative for operators who lose slightly less than the average. More precisely, investment per operator still falls with entry when the loss in market share is less than 6 percentage points (pp) compared to the average: $0 < \Delta'_{ijt}(N_{jt}) * 100 < 6$. However, the effect of market structure is no longer significant when the loss in market share is far less than the average, typically when $6 \le \Delta'_{ijt}(N_{jt}) * 100 \le 28$.

For instance, consider the effect of a fourth entrant on the investment of an operator with 33% market share in a 3-operators market. Given the marginal effect, investment is expected to fall by 16% if market share falls to 25% with the entry. In this case, its market share loss is 8 pp, just as the average.[9] However, if market share falls to, say 32%, the entry of the fourth operator is not predicted to have a significant effect on its investment. Its market share loss is 1 pp, compared to 8 pp for the average market share. This gap is 7 pp which is larger than 6 pp.

These marginal effects are predicted to be stronger in the long run due to significant adjustment costs. The coefficient of the lagged investment in specification (7) in Table 4 is 0.8, suggesting that the short run effect is multiplied by a factor of 5 in the long run.[10] This implies that the relationship between the marginal effect of N and change in asymmetry, as depicted in Fig. 3, becomes steeper in the long run. The curve rotates counterclockwise in the long run with respect to the point where it crosses the x-axis.

The effect of market structure on industry investment, that is the total investment by all operators, strongly depends on market share asymmetry. In symmetric markets, simple calculations show that industry investment increases with the number of operators in the short run, but eventually falls in the long run.

5. Conclusion

Consistently with the prediction of the theoretical model, this paper finds that the effect of market structure on investment strongly depends on asymmetry. In particular, investment per operator falls with the number of operators in symmetric markets. This negative effect is larger for operators who lose market share more than the average. In symmetric markets, the industry investment increases with the number of operators in the short run but eventually falls in the long run.

These results are consistent with the theoretical predictions of Vives (2008) in symmetric markets and Schmutzler (2013) in asymmetric markets. They are also consistent with Genakos et al. (2015) who find a negative relationship between the number of mobile operators and their investment. The positive effect of market size on investment accords well with the findings of Beneito et al. (2015). However, our findings do not lend support to a non-monotonic relationship between competition and investment as found by Sacco and Schmutzler (2011). They are also not in line with the conclusions of a recent OECD report advocating for more mobile operators as a means to improve the quality of mobile telecommunications services (OECD, 2014).

To the extent that investment lowers marginal cost of mobile services, our findings suggest that raising the number of mobile operators could lower dynamic efficiencies. In the mobile industry, the magnitude of these dynamic efficiencies losses can be huge due to an exceptionally high rate of technological progress. According to Amaya and Magee (2008), the mobile industry is experiencing an exponential rate of technological progress of almost 50%

[9] For clarity of the illustration, we consider discrete variation in market shares.

[10] This factor is obtained as $\frac{1}{1-0.8} = 5$.

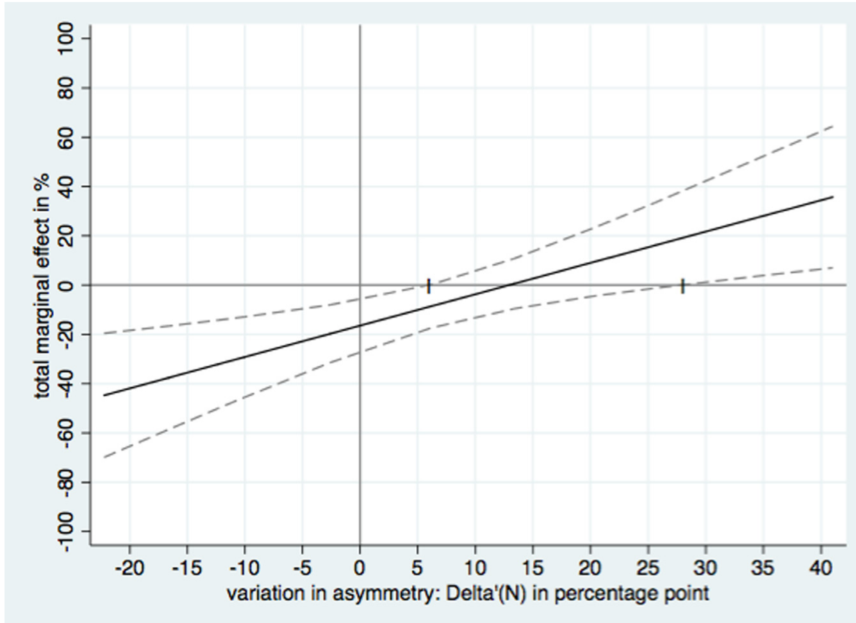

Fig. 3. Short-run marginal effect of market structure on investment per operator, note: 95% confidence interval in dashed lines. The vertical grey line at 0 corresponds to market share loss identical to the average change in market share ($1/N$).

for mobile data, which means the performance doubles every 1.4 years. Therefore, a change in the market structure of the mobile industry entails a trade-off between static and dynamic efficiencies. Merger analyses in the mobile industry should assess the magnitude of these efficiencies in order to determine the socially optimal market structure.

The empirical analysis uses capital expenditure in mobile networks as a proxy for investment in cost-reducing or quality improving technologies. To the extent that network quality is positively correlated with capital expenditures, our results remain valid. Otherwise, a fall in capital expenditure might not correspond to a fall in quality or in investment in cost-reducing technologies. Such cases may occur for instance when operators overinvest in more concentrated markets. In these cases, increasing the number of mobile operators may not entail a trade-off between static and dynamic efficiencies. Moreover, this paper has tested the hypothesis that there may be a trade-off between static and dynamic efficiencies in the mobile industry. While the strong rate of technological progress tends to suggest that dynamic efficiencies outweigh static efficiencies, it remains an empirical question to determine the exact magnitude of these efficiencies in order to characterise the optimal market structure in the mobile industry. Future work shall address these issues.

Appendix

A.1. Calculation of coefficients β_j

The comparison between Eqs. (6) and (7) for all operators, provides a system whose solutions are the coefficients β_j. We will start with relatively simple cases $N=2$ and $N=3$, to understand how the system works before moving on to the general case.

For $N=2$, the comparison between (6) and (7) is expressed as:

$$\frac{1}{2}+\frac{1}{t}(\beta_0 d_i+\beta_1 d_{i+1})=\frac{1}{2}+\frac{1}{2t}[(\beta_1+1)d_i+(\beta_0-1)d_{i+1}]$$

Notice that operator $i-1$ is also the operator $i+1$ and operator $i+2$ is also the operator $i-2$ and the operator i.

The system of equation is expressed as: $\beta_0=\frac{\beta_1+1}{2};\ \beta_1=\frac{\beta_0-1}{2}$ and the solution is $\beta_0=1/3;\ \beta_1=-1/3$.

For $N=3$, the system is expressed as: $\beta_0=\frac{\beta_1+1}{2};\ \beta_1=\frac{\beta_0+\beta_1-1}{4}$ and the solution is $\beta_0=2/5;\ \beta_1=-1/5$.

Now the general case: For $N>3$, Eqs. (6) and (7) are expressed as:

if N is odd :

$$\sigma_i=\frac{1}{N}+\frac{1}{t}\left[\beta_0 d_i+\sum_{j=1}^{(N-1)/2}\beta_j(d_{i+j}+d_{i-j})\right]$$

$$\sigma_i=\frac{1}{N}+\frac{1}{4t}\left[2d_i+(\beta_0-1)(d_{i+1}+d_{i-1})+\sum_{j=1}^{(N-1)/2}\beta_j(d_{i+j+1}+d_{i-j+1}+d_{i+j-1}+d_{i-j-1})\right]$$

if N is even :

$$\sigma_i=\frac{1}{N}+\frac{1}{t}\left[\beta_0 d_i+\sum_{j=1}^{N/2-1}\beta_j(d_{i+j}+d_{i-j})+\beta_{\frac{N}{2}}d_{i+\frac{N}{2}}\right]$$

$$\sigma_i=\frac{1}{N}+\frac{1}{4t}\left[2d_i+(\beta_0-1)(d_{i+1}+d_{i-1})+\sum_{j=1}^{N/2-1}\beta_j(d_{i+j+1}+d_{i-j+1}+d_{i+j-1}+d_{i-j-1})\right]$$
$$+\beta_{N/2}(d_{i+(N/2-1)}+d_{i-(N/2-1)})$$

Remember that when N is even, operator $i+(N/2+1)$ is also the operator $i-(N/2-1)$.

The comparison between Eqs. (6) and (7) provides four equations:

$$\beta_0=\frac{\beta_1+1}{2} \tag{16}$$

$$\beta_1=\frac{\beta_0+\beta_2-1}{4} \tag{17}$$

$$\forall j \in [2, \lfloor N/2 \rfloor - 1];\ \beta_j = \frac{\beta_{j-1} + \beta_{j+1}}{4} \tag{18}$$

if N is odd $\beta_{\frac{N-1}{2}} = \dfrac{\beta_{(N-3)/2} + \beta_{(N-1)/2}}{4}$

and if N is even $\beta_{\frac{N}{2}} = \dfrac{\beta_{N/2-1}}{2}$ (19)

For $j \in [0, \lfloor N/2 \rfloor - 3]$, Eq. (18) leads to:

$$\beta_{\lfloor \frac{N}{2} \rfloor - (j+2)} = 4\beta_{\lfloor \frac{N}{2} \rfloor - (j+1)} - \beta_{\lfloor \frac{N}{2} \rfloor - j} \tag{20}$$

Let us denote two sequences W_j and X_j such that, for $j \leq \frac{N-3}{2}$, $\beta_{\frac{N-1}{2}-j} = \beta_{\frac{N-1}{2}} W_j$ when N is odd and $\beta_{\frac{N}{2}-j} = \beta_{\frac{N}{2}} X_j$ when N is even. (This means that for $j \geq 1$; $\beta_j = \beta_{\frac{N-1}{2}} W_{\frac{N-1}{2}-j}$ if N is odd and $\beta_j = \beta_{\frac{N}{2}} X_{\frac{N}{2}-j}$ if N is even). Eq. (20) leads to $W_{j+2} = 4W_{j+1} - W_j$ and $X_{j+2} = 4X_{j+1} - X_j$. Sequences W_j and X_j are both defined by the same linear recurrence relation whose characteristic equation is: $x^2 - 4x + 1 = 0$. This equation has two positive roots: $a = 2 + \sqrt{3}$ and $b = 2 - \sqrt{3}$. It is noteworthy that $ab = 1$.

From (19), when N is odd, we have $3\beta_{\frac{N-1}{2}} = \beta_{\frac{N-3}{2}}$ and when N is even $2\beta_{\frac{N}{2}} = \beta_{\frac{N}{2}-1}$. As a result, the first terms of the sequences are $W_0 = 1$; $W_1 = 3$ and $X_0 = 1$; $X_1 = 2$. This allows us to calculate the general term of the sequences which are written in the form: $W_j = \lambda a^j + \mu b^j$ and $X_j = \lambda' a^j + \mu' b^j$.

The initial conditions are $W_0 = \lambda + \mu$; $W_1 = \lambda a + \mu b$,. Therefore, $\lambda = (\sqrt{3}+1)/2\sqrt{3}$; $\mu = (\sqrt{3}-1)/2\sqrt{3}$; in the same manner, $\lambda' = \mu' = 1/2$. The general terms of the sequence are thus expressed as:

$$W_j = \frac{(\sqrt{3}+1)a^j + (\sqrt{3}-1)b^j}{2\sqrt{3}} \text{ and } X_j = \frac{a^j + b^j}{2}.$$

When the market is symmetrical, quality d and market shares are the same for all operators: $\phi = 1/N$; thus from Eq. (6) we can write $\beta_0 = -2\sum_{j=1}^{(N-1)/2} \beta_j$ if N is odd and $\beta_0 = -2\sum_{j=1}^{N/2-1} \beta_j - \beta_{\frac{N}{2}}$ if N is even. Using the sequences W and X, this can be rewritten $\beta_0 = -2\beta_{\frac{N-1}{2}} \sum_{j=0}^{(N-3)/2} W_j$ if N is odd and $\beta_0 = -\beta_{\frac{N}{2}}(1 + 2\sum_{j=1}^{N/2-1} X_j)$ if N is even. Using the sum of geometric sequences, the expression of β_0 according to N is then:

$\beta_0 = \frac{b^{(N-1)/2} - a^{(N-1)/2}}{\sqrt{3}} \beta_{(N-1)/2}$ if N is odd and $\beta_0 = \frac{(b-1)a^{N/2} + (a-1)b^{N/2}}{2} \beta_{N/2}$ if N is even.

We know that $\beta_1 = \beta_{(N-1)/2} W_{(N-1)/2-1}$ if N is odd and $\beta_1 = \beta_{\frac{N}{2}} X_{\frac{N}{2}-1}$ if N is even. Replacing those expressions in Eq. (16) leads to $\frac{2(b^{(N-1)/2} - a^{(N-1)/2})}{\sqrt{3}} \beta_{(N-1)/2} - \beta_{(N-1)/2} \frac{(\sqrt{3}+1)a^{(N-3)/2} + (\sqrt{3}-1)b^{(N-3)/2}}{2\sqrt{3}} = 1$ if N is odd and $(b-1)a^{N/2} + (a-1)b^{N/2}\beta_{N/2} - \beta_{N/2}\frac{a^{N/2-1} + b^{N/2-1}}{2} = 1$ if N is even. This allows us to express $\beta_{(N-1)/2}$ and $\beta_{\frac{N}{2}}$ in function of N. Using $b = 1/a$ yields: $\beta_{(N-1)/2} = \frac{2\sqrt{3}a^{\frac{(N-3)}{2}}}{(9-5\sqrt{3}) - (9+5\sqrt{3})a^{N-3}}$ if N is odd and $\beta_{\frac{N}{2}} = \frac{2a^{N/2}}{(1-2a)a^{N-1} + (a-2)}$.

Those expressions can be used to calculate the general term of β_0 and β_j for $j \geq 1$ that no longer depend on N being odd or even because $\frac{b^{(N-1)/2} - a^{(N-1)/2}}{\sqrt{3}} \beta_{(N-1)/2} = \frac{(b-1)a^{N/2} + (a-1)b^{N/2}}{2} \beta_{N/2}$ and $\beta_{(N-1)/2} W_{(N-1)/2-j} = \beta_{N/2} X_{N/2-j}$. General terms are:

$$\beta_0 = 1 - \frac{a^N + 1}{\sqrt{3}(a^N - 1)}$$

$$\beta_j = -\frac{a^{N-j} + a^j}{\sqrt{3}(a^N - 1)} \text{ if } j \neq 0$$

Using $a = 2 + \sqrt{3}$ leads to the result.

A.2. Calculation of consumer surplus and social *welfare*

Consumer surplus is the sum of utility for all consumers. The utility of a consumer located at x between operator i and operator $i+1$, purchasing i's offer is $U_i = s_i - tx - p_i$. At equilibrium, $p_i^* = c_i + \sigma_i t$, thus $U_i = s_i - tx - c_i - \sigma_i t$ or $U_i = d_i - \sigma_i t - tx$. In a symmetric market $\sigma_i = 1/N$, moreover, indifferent consumer is located at $\bar{x} = 1/2N$. Half of the customers purchasing i's offer are located between operator i and operator $i+1$, the other half is located between operator i and operator $i-1$ thus $CS_i = 2\int_0^{1/2N}(d_i - \frac{t}{N} - tx)dx = \frac{d_i}{N} - \frac{5t}{4N^2}$

In a symmetric market all operators have an equal quality. $\forall$ i, $j \in \mathbb{N}$, $d_i = d_j = d$, therefore, $CS = \sum_{i=1}^{N} CS_i = N.CS_i$

Consumer surplus at the market level is thus:

$$CS = d - \frac{5t}{4N}$$

Welfare is the sum of consumer surplus and profit. Profit at the market level is expressed as $\pi = \frac{t}{N} - N(z+F)$,therefore, the welfare at the market level is expressed as:

$$W = d - \frac{t}{4N} - N(z+F)$$

Derivative of these equations according to N yields Eqs. (13) and (14).

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