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The role of capacity building on technology adoption under imperfect competition

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Abstract

This work studies the investment choice of firms in a two-period model when there are two different productive capacities that embody two different types of technology. One of them is more efficient (allowing to produce at a lower marginal cost), but more expensive to purchase. Firms face a financial constraint which limits their first period growth. By investing in the capacity using inefficient technology, firms grow faster but face a higher production cost in both periods. The equilibrium behavior is then to invest in a mixture of both types of capacity. This stands in contrast with the literature on technology adoption. Furthermore, under duopoly competition, there exists a symmetric equilibrium and two asymmetric equilibria with preemption, in which one of the firms overinvests in the inefficient capacity to gain a size advantage, whereas its opponent concentrates on efficient capacity. Finally, we find a counter-intuitive policy result: an increase in the purchasing price of inefficient capacity may increase its use.

Keywords: capacity choice, technology adoption, financial constraint, market structure, symmetric and asymmetric equilibria

JEL-Classification: L11, L13, D43, D24, D92

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1 Introduction

New technologies develop rapidly and firms constantly face adoption decisions. The industrial organization literature usually considers that the adoption of a new technology allows firms to decrease their marginal cost of production. This is the case when the new technology corresponds to a more efficient management technique, a new software or a new method to process inputs. However, technological progress also often takes the form of the creation of new production tools such as a new robot capable of producing a piece more quickly or a new aircraft consuming less kerosene. In that case, firms have to buy new production tools to benefit from this new technology. The cost reduction implied by the new technology is therefore only effective for the production done using these new tools, and the rest of the production of the firms remains with the same efficiency that they had before adoption.

This paper studies how the adoption of production tool technology differs from the adoption of classical marginal cost reducing technology, and how it changes the way firms compete. It shows the existence of symmetric and asymmetric equilibria in which firms may use different technologies at the same time.

For example, in the commercial aircraft market, Airbus sells the A321 model with two different engine options: current engine option (CEO) and new engine option (NEO). CEO's price is 114.9 million US dollars and NEO's price is 125.7 million US dollars.[1] NEO is more expensive to buy but it reduces the fuel burn per seat by 20 percent (and also improves payload capacity and range).[2] The problem of the airline companies is to decide to invest in which type of aircraft at which quantity. The orders and deliveries report shows airline companies ordering either the CEO, or the NEO, or even the two altogether. For instance, in 2015 Frontier Airlines ordered 10 CEOs, Air Lease Corp. ordered 30 NEOs, and ANA Holdings ordered 4 CEOs and 3 NEOs.[3] We are interested in the economic mechanisms underlying this kind of problem and observation.

When firms have no interest to delay investment, they would invest as soon as possible, and only in the capacity using the most efficient technology, i.e. the technology with the lowest inter-temporal cost (purchasing price plus the discounted cost of production). In such case, investments are done as if the technology was a cost margin reducing technology. However, when firms are financially constrained, investing in the technology with the cheapest purchasing price allows the firm to grow faster. Firms then may wish to invest in this inefficient technology in order to increase their short run profits, even though it reduces their future profits by increasing their production costs. The inefficient technology also generates a strategic effect: it permits one firm to preempt its opponent, building more capacity in the short run and reducing the future investment incentives of its opponent. These mechanisms explain why firms may use different technologies at the same time, and imply that the adoption of a production tool technology is slower than the adoption of a classic marginal cost reducing technology.

[1] New Airbus aircraft list prices for 2016, Airbus S.A.S, 12 January 2016.

[2] A321 state-of-the-art capabilities and technical details, Airbus S.A.S, retrieved on 17 January 2016

[3] Airbus orders and deliveries spreadsheet, Airbus S.A.S, 30 November 2015.

More precisely, we develop a two-period model in which firms' production is determined by their level of capacities. There are two types of capacity embodying two different types of technology. One type has a purchasing price higher than the other one, but it produces at a lower cost. This technology is also assumed to be more efficient, meaning that the inter-temporal cost of unit production is inferior for the capacity with the higher purchasing price. Firms compete *à la Cournot*. In the first period, firms are considered as entrepreneurs and have no initial capacity, but they possess an initial amount of funds in order to enter the market. Their capacity investment is then limited by their initial endowments. In the second period, firms have access to a perfect credit market and can invest as they wish in order to increase their capacities.

The monopoly faces a tradeoff between investing in the efficient capacity in the first period but growing slowly, and investing in the inefficient capacity and growing faster but facing a larger production cost in both periods. The optimal solution is then a mixture of both types of capacity, and the total capacity of the mixture does not depend on the financial constraint.

When there is a duopoly in the market, there may exist two different types of equilibrium: symmetric and asymmetric. In the symmetric equilibrium, firms invest in the same way as the monopoly, but adjusted to duopoly levels. Each firm has the same mixture of efficient and inefficient technology as its competitor, and the same market share. There may also exist other equilibria that are asymmetric, in which one of the firms overinvests in the inefficient capacity in the first period. This allows the firm to increase its total capacity above the final total capacity of the symmetric case, committing itself to a larger production for the second period. The opponent reacts to this preemption by investing less in the first period, focusing on the efficient capacity. In the second period the preempted firm is the only firm to invest, but it does not catch up its rival. The preempting firm finishes with a larger market share, producing mostly with the inefficient technology whereas the preempted firm stays smaller but more efficient.

These results lead to two unexpected recommendations for the policy maker. First, stronger competition implies an increase in the industry's level of old capacity. When the old technology generates a negative externality, the increase of competition may lead to a lower welfare if welfare loss due to the externality exceeds the usual welfare gain due to competition. Second, an increase in the price of old technology may increase its utilization. Indeed, when the price of old capacity increases, the firm has to decrease its total capacity since it is financially constrained. To avoid a too large reduction of its total capacity, the firm can substitute its investment in new capacity by old one, and an increase in the price of old technology may lead to an increase in the quantity of old capacity used. Other comparative statics are as expected.

The next subsection reviews the related literature. Section 2 presents the model framework. Section 3 studies the decision of a monopoly and Section 4 studies the duopoly behavior. Section 5 concludes.

1.1 Related literature

This work is related to several strands of literature in industrial organization, operation research and corporate investment.

In industrial organization, since the pioneering works of Reinganum (1981), Fudenberg and Tirole (1985) and Gaimon (1989), there has been a large literature studying technology adoption. Authors have considered the impact of learning, timing, uncertainty, environmental impacts and competition. However, to our knowledge, all papers consider a marginal cost reducing technology. We differ from this assumption by modeling production tool technologies.

For example, Stenbacka and Tombak (1994) study the timing of adoption of a new technology with uncertainty and they emphasize that the level of uncertainty can affect the dispersion between the equilibrium timings of adoption. Hoppe (2002) provides a survey of theoretical results and empirical evidence on the timing of adoption of new technologies. Huisman and Kort (2004) study the adoption decision in the case where firms take into account possible future technological improvements and Hoppe and Lehmann-Grube (2005) emphasize the role of R&D costs of process innovation and product innovation that generate a second-mover advantage in technology adoption games. Milliou and Petrakis (2011) investigate the timing of adoption with a focus on product market competition and they present results showing that different market features, such as the type and toughness of competition, can change the incentives for adoption. About the environmental impacts, Sanin and Zanaj (2011) study the influence of technology adoption on the prices of tradable emission permits. These few examples give a view of the diversity on the literature on technology adoption.

In operation research, our model is similar to some studies regarding the electricity generation markets. These studies question whether to invest in inefficient and cheap generation capacity (e.g. a base-load technology like coal-fired generator (CFG)) or to invest in efficient and expensive generation capacity (e.g. combined cycle gas turbines (CCGT)), knowing that there will be demand or supply uncertainties in the future. For example, Murphy and Smeers (2005), Tishler et al. (2008), Meunier (2010) and Milstein and Tishler (2012) study generation capacity mixture and expansion in different models of investment. They investigate the roles of different competition structures and show the possibilities of underinvestment or precautionary investment in electricity markets. The present work abstracts from the role of uncertainty, showing that the presence of a financial constraint is enough to induce the firms to invest in different types of capacity.

The presence of financial constraints is investigated by some studies in corporate investment literature. Fazzari et al. (1988) stress that internal funds and external finance are not perfect substitutes due to asymmetric information and capital market imperfections. They empirically show that the financial constraint is particularly active in the short run, and for the start-up ventures or small sized firms. Carpenter and Petersen (2002) discuss and empirically verify the reasons underlying the financial constraints in high-tech industry. More recently, Almeida and Campello (2007) show that firms with low level of asset tangibility are financially constrained in their investment decisions. Feichtinger et al. (2008) study the differences of disembodied and embodied technical progress when the firms have financial constraints. Differences in investment decisions in new or used capital is studied by Eisfeldt and Rampini (2007). They show that the firms are attracted to invest in used capital due to the financial constraints. The financial constraint introduced in this paper is in line with these findings: It constraints only the small firms, only in the short run. Our work contributes to this branch of literature by showing that the presence of financial constraints in imperfectly competitive markets can lead to the use of inefficient technologies as well as asymmetric outcomes in terms of technology and market shares.

2 The framework

2.1 The Model

We consider a two-period model of competition in production capacity. At each period, firms first invest in new units of capacity then determine their level of production. We assume irreversible investment and full utilization of capacity.[4] The price is determined by the total quantity of the industry. In the first period, firms start with no initial capacity and face a financial constraint which limits their investment opportunities. In the second period, firms are free to invest as they wish.

There are two different types of capacity available in the market that embody two different kinds of technology. The purchasing prices of the two capacities are p and $\tilde{p}$ and the unit costs of production by using the two capacities are c and $\tilde{c}$, respectively. We call the more efficient technology as the new technology and it has a lower cost of production ($\tilde{c} < c$) but more expensive to purchase ($\tilde{p} > p$). Thereafter we will speak of old (new) capacity to name the capacity using the old (new) technology.

We make the following assumption:

Assumption A1. *The new capacity is more efficient than the old one: $\tilde{p} + \tilde{c} < p + c$.*

Assumption A1 ensures that firms have incentives to invest in new capacity. It means that the cost of buying the capacity to produce one unit of output with new capacity is lower compared to that of old capacity. Under this assumption, a firm facing no constraint would invest only in new capacity.

In the monopoly case, we denote k_t and $\tilde{k}_t$ the level of old and new capacity at time t. In the duopoly case, we denote k_t^i and $\tilde{k}_t^i$ the capacities of firm i, with $i \in \{A, B\}$. Let $\mathcal{K}$ be the total capacity of the industry. The profit of firm i at time t is then:

$$\Pi_t^i = (k_t^i + \tilde{k}_t^i) P(\mathcal{K}_t) - c k_t^i - \tilde{c}\tilde{k}_t^i - p(k_t^i - k_{t-1}^i) - \tilde{p}(\tilde{k}_t^i - \tilde{k}_{t-1}^i) \quad (1)$$

[4]Including the possibility of underutilization of capacity would make the model more realistic but at the cost of computational complexity. This will change our result in two different ways. If firms prefer to use their old capacity than buying new one in the long run ($\tilde{p} + \tilde{c} > c$), then assuming capacity underutilization reduces the possibility of the existence of asymmetric equilibrium given in Proposition 3, but it still may exists. If not ($\tilde{p} + \tilde{c} < c$), the firms always prefer to invest in new capacity than using their old one in the long run, therefore no preemption using old capacity is possible. In that case, the asymmetric equilibrium vanishes.

under the capacity constraints

$$k_t^i \geq k_{t-1}^i \text{ and } \tilde{k}_t^i \geq \tilde{k}_{t-1}^i. \tag{2}$$

For simplicity, assume that the price is linear, $P(\mathcal{K}) = 1 - \mathcal{K}$, and the unit production cost of new capacity is zero ($\tilde{c} = 0$).

We introduce the financial constraint of the first period as follows:

$$pk_1^i + \tilde{p}\tilde{k}_1^i \leq G \tag{3}$$

where G denotes the initial endowment of firm i. This constraint implies that the purchasing cost of capacity in the first period cannot exceed the given initial endowment.

Firm i aims to maximize its discounted total profit:

$$\Pi^i = \Pi_1^i + \delta \Pi_2^i \tag{4}$$

where $\delta \in (0,1)$ denotes the discount rate. In this setup, investments in the first period can be viewed as short run decisions while the second period represents the long run.[5] We focus on sub-game perfect equilibria. Let $\vec{K}_t = (k_t^i, \tilde{k}_t^i, k_t^j, \tilde{k}_t^j)$ be the vector of capacities at time t. By backward induction, $(\vec{K}_1^*, \vec{K}_2^*)$ is a sub-game perfect equilibrium if $\vec{K}_2^*(\vec{K}_1)$ is a mapping which verifies:

$$\left(k_2^{i*}, \tilde{k}_2^{i*}\right) = \max_{k_2^i, \tilde{k}_2^i} \Pi_2^i \left(\vec{K}_1, k_2^i, \tilde{k}_2^i, k_2^{j*}, \tilde{k}_2^{j*}\right) \text{ under (2)}, \tag{5}$$

and $\vec{K}_1^*$ verifies:

$$\left(k_1^{i*}, \tilde{k}_1^{i*}\right) = \max_{k_1^i, \tilde{k}_1^i} \Pi^i \left(k_1^i, \tilde{k}_1^i, k_1^{j*}, \tilde{k}_1^{j*}, \vec{K}_2^*(k_1^i, \tilde{k}_1^i, k_1^{j*}, \tilde{k}_1^{j*})\right) \tag{6}$$
$$\text{under (2) and (3).}$$

The sub-game perfect equilibrium path is then $(\vec{K}_1^*, \vec{K}_2^*(\vec{K}_1^*))$. In order to emphasize the role of the financial constraint, the next subsection describes firms' choices when there is no financial constraint in the first period.

2.2 The role of financial constraint

In the absence of a financial constraint, firms would invest in the first period, as any capacity installed in the first period allows to produce in both periods. The choice between old and new capacity then reduces to a simple cost-benefit analysis and firms invest only in new capacity.

Result 1. *When firms are not financially constrained, firms invest only in the most efficient capacity and only in the first period.*

[5]This two-period game is equivalent to an infinite horizon game with a discount factor β if firms' capacities are assumed to remain constant after the second period and $\delta = \frac{\beta}{1-\beta}$. In the infinite horizon game in which capacities are not assumed to remain constant after the second period, there exist equilibria equivalent to the ones defined in Proposition 2 and 3, but also other equilibria may appear due to punition scheme (as trigger strategies).

The profit of the firm in (1) can be rewritten as

$$\Pi_t^i = (k_t^i + \tilde{k}_t^i)\,[P(\mathcal{K}_t) - (\tilde{p} + \tilde{c})] + [(\tilde{p} + \tilde{c}) - (p + c)]\,k_t^i + pk_{t-1}^i + \tilde{p}\tilde{k}_{t-1}^i. \tag{7}$$

Given a constant total capacity $(k_t^i + \tilde{k}_t^i)$, the profit in (7) is decreasing in k_t^i, as $(\tilde{p} + \tilde{c} < p + c)$ due to assumption A1. Since old and new capacities are perfect substitutes in production, in this case firms have interest to invest only in new (the most efficient) capacity. Moreover, firms invest only in the first period as every unit of capacity invested in the first period is also utilized in the second period.

Accordingly, when there is no financial constraint, the introduction of different types of capacities to model the technology choice has no impact on the firm's decision as the firm always has an incentive to invest immediately and in only one type of capacity. In reality, however, firms often delay their investment decisions due to financial constraints that arise from capital market imperfections and asymmetric information, as discussed in Section 1.1. In the following, we see how the interest to delay investment generates an incentive to invest in both types of capacities.

3 Monopoly

In this section we consider that there is only one firm in the market. The investment decision of the firm is highly dependent on the financial constraint and on the differences between the two technologies. Investing only in new capacity allows to produce at lower cost (in both periods), but limits the first period production, as the new capacity is more expensive to purchase compared to the old one. On the contrary, investing only in old capacity increases the first period production, but also increases the cost of production in both periods. The optimal strategy of the firm in the first period is then to invest in a mixture of the two capacities, balancing the tradeoff between rapid growth and long run cost efficiency.

When the financial constraint is binding and the firm invests in the second period, its profit in (1) can be rewritten as a function of the total capacity and old capacity installed in the first period:

$$\Pi = \left(1 - \tilde{p} + \delta\tilde{p} - (k_1 + \tilde{k}_1)\right)\left(k_1 + \tilde{k}_1\right) + \delta\left(\frac{1 - \tilde{p}}{2}\right)^2 - (p + (1 + \delta)\,c - \tilde{p})k_1. \tag{8}$$

The first and second terms of (8) represent the profit that the firm would make if its total capacity was composed only of new capacity.[6] The third term represents the cost of using old capacity instead of new one for a given total capacity. If there were no links between the level of old capacity and total capacity, then equation (8) shows that the firm would never invest in old capacity. However, due to the financial constraint, if the firm wants to increase its total capacity, it has to reduce its level of new capacity in order to purchase more of old capacity. Rewriting (3) yields the level of old capacity as a function of the total capacity:

[6] More precisely, the first period profit is $(1 - \tilde{k}_1)\tilde{k}_1 - \tilde{p}\tilde{k}_1$ whereas the discounted second period profit is $\delta((\frac{1-\tilde{p}}{2})^2 + \tilde{p}\tilde{k}_1)$, as the capacity purchased in the first period is also used in the second one.

$$k_1 = \frac{\tilde{p}(\tilde{k}_1 + k_1) - G}{\tilde{p} - p}. \tag{9}$$

Replacing the level of old capacity in equation (8) by (9) allows to express the profit of the firm as a function of total capacity. As we consider the case in which the financial constraint is binding, all the initial endowment must be spent by investing only in old capacity, only in new capacity or in a mixture of them. Thus the total capacity belongs to the interval $\left[\frac{G}{\tilde{p}}, \frac{G}{p}\right]$. The objective of the firm then reduces to a simple one dimensional maximization problem where the decision variable is the total capacity. Let Ψ_M be the interior solution of this problem given by:

$$\Psi_M = \frac{1 - \tilde{p} - (1+\delta)\,\tilde{p}\left(\frac{c}{\tilde{p}-p} - 1\right)}{2} \tag{10}$$

This interior solution equalizes the marginal revenue of total capacity and the marginal cost of changing the composition of capacity mixture. It does not depend on the financial endowment. When Ψ_M is outside of the feasible interval, the solution lies on the boundaries:

$$\left(k_1^*, \tilde{k}_1^*\right) = \begin{cases} \left(\frac{G}{p}, 0\right) \text{ if } \Psi_M > \frac{G}{p} \\ \left(\frac{\tilde{p}}{\tilde{p}-p}(\Psi_M - \frac{G}{\tilde{p}}),\ \frac{p}{\tilde{p}-p}(\frac{G}{p} - \Psi_M)\right) \text{ elsewhere} \\ \left(0, \frac{G}{\tilde{p}}\right) \text{ if } \Psi_M < \frac{G}{\tilde{p}} \end{cases} \tag{11}$$

The above analysis assumes that the firm invests in the second period. This is the case when $\frac{1-\tilde{p}}{2} \leq \frac{G}{\tilde{p}}$. Indeed, the capacity maximizing second period profit is $\frac{1-\tilde{p}}{2}$, as the firm in the second period is not financially constrained. When the firm invests in old capacity (fully in old capacity or in a mixture), its first period total capacity is always inferior to the second period's optimal capacity.[7] When the firm uses only new capacity, it invests in the second period if its financial endowment is sufficiently low ($\frac{G}{\tilde{p}} \leq \frac{1-\tilde{p}}{2}$). In the other case, the firm invests only in the first period, only in new capacity, and to the level $\frac{G}{\tilde{p}}$.

Finally, when the firm is not financially constrained, investments are made only in the first period, only in new capacity, and to the level $\frac{1}{2}\left(1 - \frac{\tilde{p}}{1+\delta}\right)$. This behavior is optimal as long as the financial constraint is not binding $\left(\frac{G}{\tilde{p}} \geq \frac{1}{2}\left(1 - \frac{\tilde{p}}{1+\delta}\right)\right)$.

The following proposition sums up the monopoly outcome.

Proposition 1. *Assume A1. Then,*

- *If $\frac{G}{\tilde{p}} < \frac{1-\tilde{p}}{2}$, the first period decision of the monopoly is given by the pair $(k_1^*, \tilde{k}_1^*)$ described in equation (11). In the second period, the monopoly installs a total capacity $k_2^* + \tilde{k}_2^* = \frac{1-\tilde{p}}{2}$ and invests only in new capacity ($k_2^* = k_1^*$).*
- *If $\frac{1-\tilde{p}}{2} \leq \frac{G}{\tilde{p}} < \frac{1}{2}\left(1 - \frac{\tilde{p}}{1+\delta}\right)$, the first period decision of the monopoly is to invest only in new capacity, to the level $\frac{G}{\tilde{p}}$. In the second period, the monopoly does not invest.*

[7] As the first period total capacity in a mixture is $\Psi_M < \frac{1-\tilde{p}}{2}$.

- *If* $\frac{G}{\tilde{p}} \geq \frac{1}{2}\left(1 - \frac{\tilde{p}}{1+\delta}\right)$*, the first period decision of the monopoly is to invest only in new capacity, to the level* $\frac{1}{2}\left(1 - \frac{\tilde{p}}{1+\delta}\right)$*. In the second period, the monopoly does not invest.*

Proof. See Appendix. $\square$

Proposition 1 shows that the monopoly behavior is highly dependent on its financial endowment. Figure 1 illustrates the role of the financial endowment on the choice of capacities (total capacity, old capacity, and new capacity). When the financial endowment is low, the firm wishes to grow as fast as possible and thus invests only in old capacity. For a higher financial endowment, the firm balances the tradeoff between the efficiency of new capacity and the size advantage of old capacity, investing in a mixture of the two technologies. The total capacity of the firm is constant as long as it invests in both capacities. However, for a large financial endowment, the firm invests only in new capacity, and an increase in its endowment once again increases its total capacity. Finally, when the financial endowment is too high, the firm behaves as if there is no financial constraint and invests at a level that is the optimum of the problem without a financial constraint.

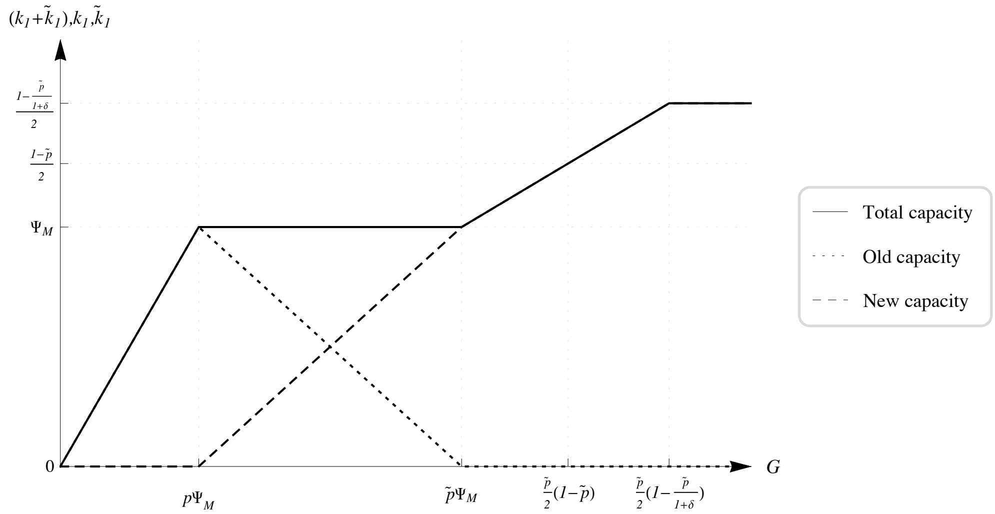

Figure 1: First period capacity investment with respect to the financial endowment

The contrast between Result 1 and Result 2 emphasizes the role of financial constraint.

Result 2. *There exists a range of financial endowment such that:*

- *The monopoly invests in a mixture of the two capacities.*
- *An increase in the initial endowment (G) increases the share of new capacity and decreases the share of old one, but does not impact the total capacity of the firm.*

The rest of the section presents the comparative static analysis done on this monopoly behavior. We focus on the range of financial endowment where the firm invests in a mixture of capacities. We consider that consumers are only affected by the price, and ignore any externality arising from the utilization of one or the other technology.

The next result exhibits the differences in outcomes when one of the technologies is not present in the market, by comparing the mixture outcome with the cases in which there is only old or only new technology in the market.

Result 3. *The profit of the firm is higher with two technologies than with only one technology. Furthermore:*

- *The introduction of a new technology is harmful for the consumer in the short run, but beneficial in the long run.*
- *The prohibition of the old technology is harmful for the consumer in the short run and neutral in the long run.*

If there is only old technology in the market, the firm would use all of its endowment to install old capacity in the first period $\left(\frac{G}{p}\right)$, before reaching a long run capacity $\left(\frac{1-c-p}{2}\right)$ that is inferior to the final total capacity of the case with two technologies $\left(\frac{1-\tilde{p}}{2}\right)$. This is due to the inefficiency of old capacity (see Assumption A1). On the contrary, the total capacity of the firm in the first period is superior with only old technology. Indeed, old capacity is cheaper than new one, and more of it can be installed with a given endowment. As consumer surplus increases with the level of production, this states Result 3.

When the old technology is prohibited, the firm invests all of its endowment in new capacity, leading to a first period level $\left(\frac{G}{\tilde{p}}\right)$ inferior to the total capacity of the two technology case (Ψ_M). In the two technology case, the long run total capacity is determined only by the features of the new technology, and the prohibition of old technology has no impact on the consumer.

The next result discusses the impact of a change in the price of old capacity. One may expect that an increase in the price of old capacity would diminish its utilization by the firm. However, our result is more ambiguous.

Result 4. *The effect of a variation in the price of old capacity (p) on the percentage and quantity of old capacity used in the technology mixture depends on p:*

- *for a low value of p, an increase in p increases the utilization of old capacity (both in the short run and in the long run),*
- *for a high value of p, an increase in p reduces the utilization of old capacity (both in the short run and in the long run).*[8]

Moreover, an increase in the price of old capacity always decreases the total capacity in the short run (and has no impact in the long run).

[8]See Appendix for the analytic thresholds.

This unexpected result comes from the fact that an increase in the price of old capacity has two effects. First, for a given total capacity, the firm wants to increase its share of new capacity and to reduce its share of old one, as the new capacity becomes relatively cheaper to purchase. This is the price effect. However, when the price of old capacity increases, the total capacity of the monopoly would reduce due to the financial constraint and the price effect (the price of new capacity remains larger than the price of old). This increases the marginal profit of total capacity (as the profit is a concave function of total capacity), and make the firm willing to invest more in old capacity, i.e. willing to sacrifice more of its long run efficiency to increase its first period size, which is the substitution effect.

When the difference between the prices of two capacities is sufficiently large, the substitution effect dominates the price effect and induces the firm to increase its investment in old capacity. In the contrary, when the prices are too close, the price effect offsets the substitution effect, and the firm increases its share of new capacity.

There is no such ambiguity for the other policy tools: the price of new capacity and the marginal cost of production using old capacity. When the price of new capacity rises, the price effect and the substitution effect incentivize the firm to increase its investment in old capacity. Indeed, the price increase leads to a decline in total capacity, which increases the marginal profit of total capacity and induces the firm to install more old capacity. The substitution effect then works in the same direction as the price effect.

Result 5. *We have:*

- *An increase in the price of new capacity ($\tilde{p}$) decreases the percentage and the quantity of new capacity used in the technology mixture, both in the short run and in the long run. Moreover, it increases the total capacity in the short run, but decreases it in the long run.*

- *An increase in the marginal cost of production using old capacity (c) decreases the percentage and the quantity of old capacity used in the technology mixture, both in the short run and in the long run. Moreover it decreases the total capacity in the short run (and has no impact in the long run).*

To complete the comparative statics of the monopoly case, we discuss the effect of the time preference of the firm (δ). When the firm is more patient (a higher δ), the firm increases its level of new capacity and reduces the level of old capacity. The firm also decreases the total capacity in the short run (and makes no change in its long run choice of capacities). Indeed, the firm values more the long run efficiency of the new technology than the short run growth provided by the old technology.

4 Equilibria in the duopoly case

In this section, there are two entrepreneurs, A and B, present in the market. Two different equilibria may arise: symmetric and asymmetric. To investigate these equilibria, let us first focus on what happens in the second period.

4.1 Behavior of firms in the second period

In this period firms are not financially constrained and thus invest only in the most efficient capacity, the new one. The investment choice of a firm depends on the level of capacity held by its rival. If the rival's total capacity of the first period is inferior to the Cournot outcome ($k_1^j + \tilde{k}_1^j < \frac{1-\tilde{p}}{3}$) then the firm increases its investment to take a larger share of the market until it reaches the Cournot outcome. In the contrary case ($k_1^j + \tilde{k}_1^j > \frac{1-\tilde{p}}{3}$), the opponent is committed itself to a large production due to the level of capacities installed in the first period, and the firm adapts its capacity according to the opponent's first period choice.

This is resumed formally as follows. Let k_1^i be the level of old capacity of firm i in the first period and $\tilde{k}_2^i$ the level of new capacity of firm i in the second period. Then the optimal investment decision of firm i is:

$$(k_2^{*i} + \tilde{k}_2^{*i}) = \left\{ \begin{array}{l} \max\left\{\frac{1-\tilde{p}}{3}, k_1^i + \tilde{k}_1^i\right\} \text{ if } k_1^j + \tilde{k}_1^j < \frac{1-\tilde{p}}{3} \\ \max\left\{\frac{1-\tilde{p}-K_1^j-\tilde{K}_1^j}{2}, \tilde{k}_1^i + k_1^i\right\} \text{ if } k_1^j + \tilde{k}_1^j > \frac{1-\tilde{p}}{3} \end{array} \right\} \tag{12}$$

where $k_2^{*i} = k_1^i$ because the firm always invests in new capacity in the second period. We summarize the optimal investment decision of the firm in the second period in the following lemma:

Lemma 1. *Assume A1. For any vector of first period capacities $\vec{K}_1$, the equilibrium of the second period is to invest only in new capacity in order to reach the total capacity given in (12).*

Proof. See Appendix. □

Lemma 1 shows that the space of total capacities can be separated in three regions, as presented in Figure 2.[9]

In the area named *the no-move zone* (which is marked by the gray mesh) firms have no interest to invest in more capacity. In fact, in that area, the marginal value of an additional capacity is positive but inferior to the price of investment. So the firm wishes to produce more, but the return does not compensate the cost of investment. As we consider that the firms start with no capacity, no equilibria will take place inside this area.

When the first period total capacity of each firm is inferior to the Cournot outcome ($\frac{1-\tilde{p}}{3}$), the equilibrium strategy of period two is, for both firms, to invest until the Cournot outcome. We name this area *the symmetric zone.* This leads to a possible symmetric equilibrium in the first period. In this equilibrium, firms invest in a mixture of old and new capacities due to the tradeoff between investing as soon as possible in the first period and focusing on long run efficiency.

When one firm has a first period total capacity larger than the Cournot outcome and its opponent has a lower capacity, the equilibrium investment choice in the second period is for the smaller

[9]The formal description of these regions can be found in Appendix.

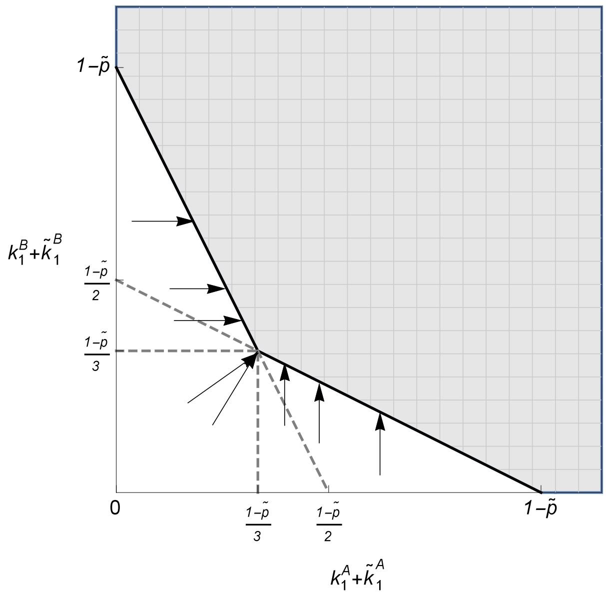

Figure 2: The second period investment regions for duopoly

firm to invest and for the larger firm to do nothing. We name this area *the asymmetric zone*. The firm may reach this area if it preempts its opponent by investing mostly in old capacity in the first period, in order to gain an advantage in the second period. This leads to the existence of an asymmetric equilibrium[10], in which one of the firm (thereafter called *the preempting or the leader*[11]) invests mainly in old capacity, in order to have a first period total capacity higher than the Cournot outcome. In this case, the best response of the other firm (thereafter called *the preempted or the follower*) is to invest less than its opponent in the first period, mostly based on new capacity, before getting closer to its rival in the second period. The preempted firm remains smaller than its opponent.

Figure 2 illustrates the different equilibrium paths corresponding to these symmetric and asymmetric outcomes in the industry. The next subsections investigate these cases in detail.

4.2 Case of symmetric equilibrium

Symmetric equilibrium can exist only if firms are not be able to reach the Cournot outcome by investing only in new capacity in the first period. In the contrary case the equilibrium is straightforward: firms invest only in the first period, and only in new capacity.

When their financial endowments are sufficiently low, firms face a tradeoff between short run growth and long run efficiency. The total capacity that the firms wish to install in the symmetric equilibrium is given by:

[10]There exists some parameter values such that the asymmetric or the symmetric equilibria do not exist.

[11]This terminology has no relation with the Stackelberg game, as firms take their action simultaneously.

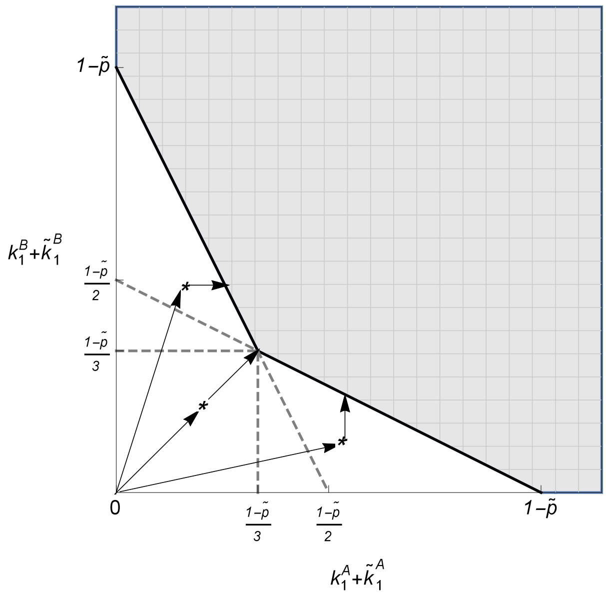

Figure 3: Potential equilibrium paths

$$\Psi_D = \frac{1-\tilde{p}-(1+\delta)\,\tilde{p}\left(\frac{c}{\tilde{p}-p}-1\right)}{3} \tag{13}$$

If the financial endowment is too low that the firms cannot reach Ψ_D then the firms invest only in old capacity at the maximum possible level. If the financial endowment is too high that the firms can reach Ψ_D using only new technology then the firms invest only in new capacity and reach a higher level than Ψ_D. We define k_1^{sym} and $\tilde{k}_1^{sym}$, the old and new capacity of the firm in the first period as:

$$\left(k_1^{sym},\tilde{k}_1^{sym}\right) = \left\{ \begin{array}{l} \left(\frac{G}{p},0\right) \text{ if } \Psi_D > \frac{G}{p} \\ \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_D-\frac{G}{\tilde{p}}\right),\ \frac{p}{\tilde{p}-p}\left(\frac{G}{p}-\Psi_D\right)\right) \text{ elsewhere} \\ \left(0,\frac{G}{\tilde{p}}\right) \text{ if } \Psi_D < \frac{G}{\tilde{p}} \end{array} \right\} \tag{14}$$

The strategy which consists for each firm to invest $(k_1^{sym},\tilde{k}_1^{sym})$ in the first period is a local equilibrium, meaning that there is no profitable deviation inside the symmetric zone. To verify that (14) is an equilibrium strategy, we have to ensure that no firm has an incentive to deviate to an asymmetric strategy profile when its opponent invests $(k_1^{sym},\tilde{k}_1^{sym})$. To characterize this profile, let $\Psi_{Asym}^{BR} = \frac{1}{2}\left[1-\frac{1}{\left(1+\frac{\delta}{2}\right)}\left(k_1^{sym}+\tilde{k}_1^{sym}+(1+\delta)\,c\frac{\tilde{p}}{\tilde{p}-p}-\delta\frac{\tilde{p}}{2}\right)\right]$, then the asymmetric strategy profile that is the best response to $(k_1^{sym},\tilde{k}_1^{sym})$ given by:

$$\left(k_1^{BRasym},\tilde{k}_1^{BRasym}\right) = \left\{ \begin{array}{l} \left(\frac{G}{p},0\right) \text{ if } \Psi_{Asym}^{BR} > \frac{G}{p} \\ \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_{Asym}^{BR}-\frac{G}{\tilde{p}}\right),\ \frac{p}{\tilde{p}-p}\left(\frac{G}{p}-\Psi_{Asym}^{BR}\right)\right) \text{ elsewhere} \end{array} \right\} \tag{15}$$

To ensure that $(k_1^{sym}, \tilde{k}_1^{sym})$ is an equilibrium, firms must be worse-off by deviating to the asymmetric best response strategy. Formally, the following condition must hold:

$$\Pi\left\{\left(k_1^{sym}, \tilde{k}_1^{sym}\right); \left(k_1^{sym}, \tilde{k}_1^{sym}\right)\right\} \geq \Pi\left\{\left(k_1^{BRasym}, \tilde{k}_1^{BRasym}\right); \left(k_1^{sym}, \tilde{k}_1^{sym}\right)\right\} \tag{16}$$

The following proposition characterizes the symmetric equilibrium in the duopoly case:

Proposition 2. *Assume A1. Then,*

- If $\frac{G}{\tilde{p}} \geq \frac{1-\tilde{p}}{3}$, there exists a unique sub-game perfect equilibrium of the game, given by: $\tilde{k}_1^{*i} = \min\left(\frac{G}{\tilde{p}}, \left(1 - \frac{\tilde{p}}{1+\delta}\right)\right)$, $\tilde{k}_2^{*i} = \tilde{k}_1^{*i}$ and $k_2^{*i} = k_1^{*i} = 0$.

- If $\frac{G}{\tilde{p}} < \frac{1-\tilde{p}}{3}$, there exists a symmetric sub-game perfect equilibrium if and only if condition (16) is true. In that case, the first period equilibrium capacities are given by (14) and the second period capacities are $\left(\frac{1-\tilde{p}}{3}, \frac{1-\tilde{p}}{3}\right)$.

Proof. See Appendix. □

Proposition 2 shows that the symmetric equilibrium strategy of the firms is similar to the one of monopoly case, but adjusted to duopoly levels. Therefore, results 2 to 5 of the monopoly hold for the symmetric equilibrium.

Result 6. *In the symmetric equilibrium of the duopoly, we have:*

- *When there is a financial constraint, the duopoly invests in a mixture of the two capacities.*
- *A decrease in the price of new capacity ($\tilde{p}$) or an increase in the marginal cost of production (c) or an increase in the discount rate (δ) reduce the percentage and the quantity of old capacity used in the industry.*
- *An increase in the price of old capacity (p) can increase or decrease the utilization of old capacity depending on the prices of capacities.*

4.3 Case of asymmetric equilibria

Besides the equilibrium previously considered, there is another possible behavior of the industry. One of the firms can overinvest in old technology, in order to increase its total capacity above the Cournot outcome, and commit itself to a larger production in the next period. In reaction to this strategy, its opponent reduces its total capacity in the first period, focusing on the efficient capacity. In the second period, the follower is the only firm to invest, only in new capacity, but it does not catch up its rival.

The equilibrium depends on the initial financial endowment available to the entrepreneurs. When this amount is too low, the firms cannot reach the Cournot outcome even by investing only in old capacity. In this case no preemption is possible. For larger amounts of financial endowment, when both firms invest in a mixture of capacity, the total capacity of the preempting firm is $\Psi_L^{nc} =$

$\frac{(1+\delta)-(1+\delta)c\frac{\tilde{p}}{\tilde{p}-p}}{(3+2\delta)}$ and the total capacity of the preempted one is $\Psi_F^{nc} = \frac{\left(1+\frac{\delta}{2}\right)-(1+\delta)^2 c\frac{\tilde{p}}{\tilde{p}-p}+\left(\frac{3}{2}+\delta\right)\delta\tilde{p}}{(3+2\delta)}$. If the firms cannot reach these outcomes then firms have to invest only in one kind of capacity, in the same way as Proposition 2. When the preempting firm invests only in old capacity, the total capacity of the preempted firm is $\Psi_F^c = \frac{1}{2}\left(1 - \frac{G}{p} - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right)$, and when the preempted firm invests only in new capacity, the preempting one installs a total capacity of $\Psi_L^c = \frac{\left(1+\frac{\delta}{2}\right)-\frac{G}{\tilde{p}}-(1+\delta)\frac{c\tilde{p}}{\tilde{p}-p}+\frac{\delta}{2}\tilde{p}}{2+\delta}$. This yields the level of capacities of the asymmetric local equilibrium (the vector of capacities such that there is no profitable deviation inside the asymmetric zone).

$$\left(k_1^L, \tilde{k}_1^L\right) = \left\{ \begin{array}{l} \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_L^{nc} - \frac{G}{\tilde{p}}\right), \frac{p}{\tilde{p}-p}\left(\frac{G}{p} - \Psi_L^{nc}\right)\right) \text{ if } \Psi_L^{nc} \leq \frac{G}{p} \text{ and } \Psi_F^{nc} \geq \frac{G}{\tilde{p}} \\ \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_L^{c} - \frac{G}{\tilde{p}}\right), \frac{p}{\tilde{p}-p}\left(\frac{G}{p} - \Psi_L^{c}\right)\right) \text{ if } \Psi_L^{nc} \leq \frac{G}{p} \text{ and } \Psi_F^{nc} < \frac{G}{\tilde{p}} \\ \left(\frac{G}{p}, 0\right) \text{ if } \Psi_L^{nc} > \frac{G}{p} \end{array} \right\}, \tag{17}$$

and

$$\left(\tilde{k}_1^F, \tilde{k}_1^F\right) = \left\{ \begin{array}{l} \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_F^{nc} - \frac{G}{\tilde{p}}\right), \frac{p}{\tilde{p}-p}\left(\frac{G}{p} - \Psi_F^{nc}\right)\right) \text{ if } \Psi_L^{nc} \leq \frac{G}{p} \text{ and } \Psi_F^{nc} \geq \frac{G}{\tilde{p}} \\ \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_F^{c} - \frac{G}{\tilde{p}}\right), \frac{p}{\tilde{p}-p}\left(\frac{G}{p} - \Psi_F^{c}\right)\right) \text{ if } \Psi_L^{nc} > \frac{G}{p} \text{ and } \Psi_F^{nc} \geq \frac{G}{\tilde{p}} \\ \left(0, \frac{G}{\tilde{p}}\right) \text{ if } \Psi_F^{nc} > \frac{G}{\tilde{p}} \end{array} \right\} \tag{18}$$

Moreover, as in the case of symmetric equilibrium, we have to ensure that firms have no incentive to deviate from the asymmetric equilibrium strategies. Let $\Psi_{sym}^{BR} = \frac{1}{2}(1 - k_1^F - \tilde{k}_1^F - (1+\delta)c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p})$. Preempting firm's best response symmetric strategy when its opponent acts following the asymmetric strategy is as follows:

$$\left(k_1^{BRsym}, \tilde{k}_1^{BRsym}\right) = \left\{ \begin{array}{l} \left(\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_{sym}^{BR} - \frac{G}{\tilde{p}}\right), \frac{p}{\tilde{p}-p}\left(\frac{G}{p} - \Psi_{sym}^{BR}\right)\right) \text{ elsewhere} \\ \left(0, \frac{G}{\tilde{p}}\right) \text{ if } \Psi_{sym}^{BR} < \frac{G}{\tilde{p}} \end{array} \right\} \tag{19}$$

The preempting firm does not have any incentive to deviate from the asymmetric strategy if

$$\Pi\left\{\left(k_1^L, \tilde{k}_1^L\right); \left(k_1^F, \tilde{k}_1^F\right)\right\} \geq \Pi\left\{\left(k_1^{BRsym}, \tilde{k}_1^{BRsym}\right); \left(k_1^F, \tilde{k}_1^F\right)\right\} \tag{20}$$

or

$$\Psi_{sym}^{BR} > \frac{1-\tilde{p}}{3} \tag{21}$$

hold true. Now we can characterize the asymmetric equilibrium with the following proposition:

Proposition 3. *Assume A1. If $\frac{G}{p} > \frac{1-\tilde{p}}{3}$, and (20) or (21) hold true, then there exists an asymmetric sub-game perfect equilibrium which consists of one firm to install $(k_1^L, \tilde{k}_1^L)$ in the first period, and for the other one to install $(k_1^F, \tilde{k}_1^F)$, before investing as described in Lemma 1.*

Proof. See Appendix. □

Even though the form of the asymmetric equilibrium differs from the symmetric one, most of the comparative static results remain valid. Indeed, results 2 to 5 of the monopoly hold for the asymmetric equilibrium.

Result 7. *In the asymmetric equilibrium of the duopoly, we have:*

- *When there is a financial constraint, the duopoly invests in a mixture of the two capacities.*
- *A decrease in the price of new capacity ($\tilde{p}$) or an increase in the marginal cost of production (c) reduce the percentage and the quantity of old capacity used in the industry.*
- *An increase in the price of old capacity (p) can increase or decrease the utilization of old capacity depending on the prices of capacities.*

However, in this case, the impact of the discount rate (δ) is ambiguous. Two effects are in place. When the discount rate increases, firms value the future more and prefer to invest more in new capacity. This is the direct effect. There is also a competition effect. When a firm decreases its total capacity, its opponent wishes to increase its own capacity to recuperate the abandoned market share. The direct effect is more important for the preempted firm than the preempting one, as it invests more in new capacity, aiming for efficiency. Therefore, the competition effect is more pronounced for the preempting firm. Consequently, when the discount rate increases, the preempting firm can increase its total capacity by investing more in old technology, while the preempted firm invests more in new capacity.[12]

4.4 Impact of competition

This subsection compares the outcomes of the monopoly and of the duopoly symmetric and asymmetric equilibria. To make a reasonable comparison, we assume that the financial endowment of the monopoly is twice the financial endowment of each firm in the duopoly. In that way, the total financial endowment of the industry remains constant. The first result compares the level of each type of capacity depending on the strength of competition.

Result 8. *The effect of competition on the level of capacities is:*

- *The level of old capacity is inferior under monopoly than under symmetric competition, and inferior under symmetric competition than under asymmetric competition (both in the short run and long run).*
- *In the long run, the level of new capacity is higher under symmetric competition than under monopoly or asymmetric competition. The comparison between monopoly and asymmetric competition is ambiguous.*

[12]The competition effect does not always dominate as the derivative of the leader's total capacity is: $\frac{\partial \Psi_L^{nc}}{\partial \delta} = \frac{\tilde{p}-p-c\tilde{p}}{(\tilde{p}-p)(3+2\delta)^2}$, and the follower's: $\frac{\partial \Psi_F^{nc}}{\partial \delta} = \frac{-\tilde{p}(c+p-\tilde{p})-(\tilde{p}-p)\frac{\partial \Psi_L^{nc}}{\partial \delta}}{(\tilde{p}-p)(3+2\delta)^2} < 0$.

The first period total capacity of the asymmetric duopoly is superior to the one of the symmetric duopoly which is superior to the one of monopoly. The difference between the monopoly and the symmetric duopoly is an expected competition effect, whereas the difference between symmetric and asymmetric duopoly is due to preemption. As firms are financially constrained in the first period, the level of old capacity increases with the strength of competition in the short run. In the long run, this result remains valid as there is no more investment in old capacity.

Due to the financial constraint, the level of new capacity in the short run decreases with the strength of competition. In the long run, the total capacity of the firm increases with the strength of competition. To install a higher total capacity than the monopoly, the symmetric duopoly invests more in the second period (and only in new) than the monopoly, and ends up with a higher level of new capacity. This result is reversed for the comparison between the asymmetric and the symmetric equilibria. The asymmetric duopoly invest so much in old capacity in the first period, that even if the total capacity is larger in the long run, its level of new capacity does not catch up the one of the symmetric duopoly. In fact, the level of new capacity of asymmetric duopoly may even be inferior to the one of the monopoly.

These results allow us to discuss the impact of competition on consumers and firms, assuming that there is no technological externality.[13]

Result 9. *For consumers, asymmetric competition is better than symmetric competition and symmetric competition is better than monopoly, both in the short run and in the long run. This ordering is reversed for the industry profit.*

The strength of competition decreases the price, as it increases the total capacity of the industry (both in the short and long run). Consumers are then better off with competition. Furthermore, the strength of competition also increases the level of old capacity, and the profit of the industry is reduced due to a higher intertemporal cost of capacity (and a lower market price).

5 Conclusion

This paper studies the adoption of a new production tool technology when firms are financially constrained. In the short run, firms face a trade-off between investing in capacity using the old technology and growing rapidly, and investing in new capacity and producing efficiently. The optimal decision of the monopoly is then to install a mixture of capacities. For the duopoly, two different types of equilibrium may arise. In the symmetric equilibrium, the duopoly also invests in a mixture to a larger total capacity than the monopoly, due to competition. The duopoly therefore installs more old capacity. In the asymmetric equilibrium, one of the firms preempts its opponent by investing more in old capacity, increasing its short run total capacity. The opponent reacts by focusing on the efficient technology and reducing its total capacity. In the long run, the preempted firm is the only investing firm, only in the new technology. It does not catch up its rival. The

[13] Consumers solely care about the price, and firms solely care about their profits.

utilization of old technology in the industry is thus higher under asymmetric equilibrium than symmetric equilibrium.

The present work does not model any externality arising from the utilization of technologies, such as pollution. However, such externalities are often in mind of the policy maker. Our results allow to stress some implications. For example, let's consider that the old technology generates more negative externality than the new one. In that case, an increase of competition may not be desirable as it increases the utilization of old technology. The welfare loss due to the externality may exceed the usual welfare gain due to competition.

When we consider policy instruments, such as taxes or subsidies on capacity prices, cost of production (carbon tax) or financial constraint, most of them work as expected. Indeed, an increase in the financial constraint does not change the total capacity of the firms (within a certain range), but it increases the share of new technology in the mixture. The consumption price does not change, but the total welfare increases due to the efficiency of new technology. In addition, increasing the old technology's marginal cost of production or reducing the price of the new technology reduces the utilization of old technology.

Finally, we show that an increase in the price of old technology may increase its utilization. Indeed, when the price of old capacity increases, the firm has to decrease its total capacity since it is financially constrained. To avoid a too large reduction of its total capacity, the firm can substitute its investment in new capacity by old one. In that case, an increase in the price of old technology may lead to an increase in the quantity of old capacity used. The policy maker should then be careful if it decides to use a tax or subsidy on the investment price of old capacity.

The present work can be extended in many directions. Capacity prices can evolve over time, due to exogenous innovation processes or endogenous learning effects. Marginal production cost of using capacities can also vary over time. These may change the technology mixture and the possibility of preemption. Moreover, in several markets, as the electricity generation market, both demand and supply uncertainties play an important role in investment decisions. One possible research direction is to combine our framework with these uncertainties. Finally, for more applied research, where the externalities of the technologies are known and measurable, our framework can be expanded for market-based policy recommendations.

Appendix

Proof of Proposition 1:

To solve the problem of the firm, we proceed by backward induction. In the second period, the firm is not financially constrained and it invests only in the most efficient technology as seen in the proof of Result 1. The problem of the firm in the second period is thus to maximize:

$$\Pi_2 = \left(1 - k_1 - \tilde{k}_2\right)\left(k_1 + \tilde{k}_2\right) - ck_1 - \tilde{p}\left(\tilde{k}_2 - \tilde{k}_1\right). \tag{A.1}$$

with respect to $\tilde{k}_2$, taking the first period choice of capacities as given, under the irreversibility constraint:

$$\tilde{k}_2 > \tilde{k}_1. \tag{A.2}$$

If the total capacity of the first period, $k_1 + \tilde{k}_1$, is inferior to $\frac{1-\tilde{p}}{2}$ the irreversibility constraint (A.2) is not binding, and the optimal level of capacity in the second period is:

$$k_2^* = k_1 \text{ and } \tilde{k}_2^* = \frac{1-\tilde{p}}{2} - k_1. \tag{A.3}$$

When $k_1 + \tilde{k}_1$ is greater than $\frac{1-\tilde{p}}{2}$, the firm is constrained by its first period total capacity and it does not invest in the second period. Thus, the discounted total profit can be written as a function of the first period total capacity:

$$\Pi = \begin{cases} (1+\delta)\left(1 - \frac{\tilde{p}}{1+\delta} - k_1 - \tilde{k}_1\right)\left(k_1 + \tilde{k}_1\right) - \left(p + (1+\delta)\,c - \tilde{p}\right)k_1, \text{ if } k_1 + \tilde{k}_1 > \frac{1-\tilde{p}}{2} \\ \left(1 - \tilde{p} + \delta\tilde{p} - k_1 - \tilde{k}_1\right)\left(k_1 + \tilde{k}_1\right) + \delta\left(\frac{1-\tilde{p}}{2}\right)^2 - (p + (1+\delta)\,c - \tilde{p})k_1, \text{ if } k_1 + \tilde{k}_1 \leq \frac{1-\tilde{p}}{2} \end{cases} \tag{A.4}$$

The problem of the firm is then to maximize (A.4) under the financial constraint (3).

When the firm is not financially constrained, it does not invest in old capacity ($k_1 = 0$ due to Result 1) and (A.4) is a concave function that is maximized at $\tilde{k}_1 = \frac{1-\frac{\tilde{p}}{1+\delta}}{2}$. Indeed, the second line of (A.4) is a concave function that is maximized at $\tilde{k}_1 = \frac{1-\tilde{p}+\delta\tilde{p}}{2} > \frac{1-\tilde{p}}{2}$. The second line of (A.4) is then increasing until $\frac{1-\tilde{p}}{2}$. The first line of (A.4) is a concave function that is maximized at $\tilde{k}_1 = \frac{1-\frac{\tilde{p}}{1+\delta}}{2} > \frac{1-\tilde{p}}{2}$ as $\delta > 0$. Therefore Π is a concave function that is maximized at $\tilde{k}_1 = \frac{1-\frac{\tilde{p}}{1+\delta}}{2}$.

When the firm is financially constrained $\left(\frac{1-\frac{\tilde{p}}{1+\delta}}{2} > \frac{G}{\tilde{p}}\right)$, (A.4) is a concave function that is maximized at $k_1 + \tilde{k}_1 = \frac{1}{2}\left(1 - \frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c + \delta\tilde{p}\right)$. The financial constraint (3) can be written as follows:

$$k_1 = \frac{\tilde{p}\left(k_1 + \tilde{k}_1\right) - G}{\tilde{p} - p}, \tag{A.5}$$

and (A.5) can be replaced in the intertemporal profit (A.4):

$$\Pi = \begin{cases} (1+\delta)\left(1 - \frac{c\tilde{p}}{\tilde{p}-p} - \left(k_1 + \tilde{k}_1\right)\right)\left(k_1 + \tilde{k}_1\right) + \frac{p+(1+\delta)c-\tilde{p}}{\tilde{p}-p}G \text{ if } k_1 + \tilde{k}_1 > \frac{1-\tilde{p}}{2} \\ \left(1 + \delta\tilde{p} - \frac{(1+\delta)c\tilde{p}}{\tilde{p}-p} - \left(k_1 + \tilde{k}_1\right)\right)\left(k_1 + \tilde{k}_1\right) + \delta\left(\frac{1-\tilde{p}}{2}\right)^2 + \frac{p+(1+\delta)c-\tilde{p}}{\tilde{p}-p}G, \text{ if } k_1 + \tilde{k}_1 \leq \frac{1-\tilde{p}}{2} \end{cases} \tag{A.6}$$

The first line of (A.6) is a concave function that is maximized at $k_1^* + \tilde{k}_1^* = \frac{1}{2}\left(1 - \frac{c\tilde{p}}{\tilde{p}-p}\right) < \frac{1-\tilde{p}}{2}$ due to Assumption A1. So the first line of (A.6) is decreasing for the values greater than $\frac{1-\tilde{p}}{2}$. The second line of (A.6) is a concave function that is maximized at $k_1^* + \tilde{k}_1^* = \frac{1}{2}\left(1 - \frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c + \delta\tilde{p}\right) \leq \frac{1-\tilde{p}}{2}$ due to Assumption A1. Therefore, Π is a concave function maximized at $k_1^* + \tilde{k}_1^* = \frac{1}{2}\left(1 - \frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c + \delta\tilde{p}\right)$. Using (A.5), we can determine the technology mixture associated with this level of total capacity. If $\frac{1}{2}\left(1 - \frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c + \delta\tilde{p}\right) > \frac{G}{p}$ then the firm invests only in old capacity to a level $\frac{G}{p}$, as the firm cannot have a negative amount of one capacity. For the same reason, if $\frac{1}{2}\left(1-\frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c+\delta\tilde{p}\right)<\frac{G}{\tilde{p}}$ then the firm invests only in new capacity. This establishes (11) when $\frac{G}{\tilde{p}}<\frac{1-\frac{\tilde{p}}{1+\delta}}{2}$. Finally, the firm does not invest in the second period when $\frac{G}{\tilde{p}}<\frac{1-\tilde{p}}{2}$.

Proof of Lemma 1:

In the second period the profit of firm i is:

$$\Pi_2^i=\left(k_2^i+\tilde{k}_2^i\right)\left(1-\left(k_2^i+\tilde{k}_2^i+k_2^j+\tilde{k}_2^j\right)\right)-ck_2^i-p\left(k_2^i-k_1^i\right)-\tilde{p}\left(\tilde{k}_2^i-\tilde{k}_1^i\right). \tag{A.7}$$

As in the case of monopoly, firm i invests only in new technology and $k_2^i=k_1^i$, as in Result 1. Then, maximizing the above profit with respect to the level of new capacity in the second period yields the best response of firm i as follows:

$$\tilde{k}_2^i+k_1^i=\max\left\{\frac{1-\tilde{p}-\left(k_2^j+\tilde{k}_2^j\right)}{2},\tilde{k}_1^i+k_1^i\right\}. \tag{A.8}$$

If the first period capacities of both firms is inferior to $\frac{1-\tilde{p}}{3}$, the equilibrium is $\frac{1-\tilde{p}}{3}$ (the Cournot outcome). If they are both superior to $\frac{1-\tilde{p}}{3}$ then the equilibrium is not to invest for both firms. When the capacity of firm j is superior to $\frac{1-\tilde{p}}{3}$ and the capacity of firm i is inferior to $\frac{1-\tilde{p}}{3}$, firm j does not invest and firm i invests only if $\tilde{k}_1^i+k_1^i<\frac{1-\tilde{p}-\left(\tilde{k}_1^j+k_1^j\right)}{2}$.

Proof of Propositions 2 and 3:

Lemma 1 separates the set of first period capacities in three regions with different firm behaviors in the second period (see Figure 1):

- the no-move zone:

$$\left\{\left(k_1^A,\tilde{k}_1^A,k_1^B,\tilde{k}_1^B\right)\mid \tilde{k}_1^i+k_1^i\geq\frac{1-\tilde{p}-\left(k_1^j+\tilde{k}_1^j\right)}{2}\text{ for each }i\in\{A,B\}\right\}, \tag{A.9}$$

- the symmetric zone:

$$\left\{\left(k_1^A,\tilde{k}_1^A,k_1^B,\tilde{k}_1^B\right)\mid \tilde{k}_1^i+k_1^i<\frac{1-\tilde{p}}{3}\text{ for each }i\in\{A,B\}\right\}, \tag{A.10}$$

- the asymmetric zone:

$$\left\{\left(k_1^A,\tilde{k}_1^A,k_1^B,\tilde{k}_1^B\right)\mid \frac{1-\tilde{p}}{3}\leq\tilde{k}_1^i+k_1^i<\frac{1-\tilde{p}-\left(k_1^j+\tilde{k}_1^j\right)}{2}\text{ for each }i\in\{A,B\}\right\}. \tag{A.11}$$

The aim is to determine the sub-game perfect equilibria of the game. In the first step, we search for potential equilibria in each region, i.e. if there are some vectors of capacity without any profitable deviation inside the region. In the second step, we verify if potential equilibria are Nash by studying the possibility of a deviation to other regions.

Case 1: No-move zone

When the first period capacities are inside the no-move zone, firms do not invest in the second period and their profits are therefore:

$$\Pi^i = (1+\delta)\left(1 - \frac{\tilde{p}}{1+\delta} - k_1^i - \tilde{k}_1^i - k_1^j - \tilde{k}_1^j\right)\left(k_1^i + \tilde{k}_1^i\right) - (p + c - \tilde{p})\, k_1^i. \tag{A.12}$$

If the firms are not financially constrained, the equilibrium is then to invest only in new capacity, and to the level $\tilde{k}_1^i = \frac{1}{3}\left(1 - \frac{\tilde{p}}{1+\delta}\right)$. The firms are financially constrained when $\frac{1}{3}\left(1 - \frac{\tilde{p}}{1+\delta}\right) \geq \frac{G}{\tilde{p}}$. This states the first part of proposition 2 when $\frac{G}{\tilde{p}} > \frac{1}{3}\left(1 - \frac{\tilde{p}}{1+\delta}\right)$.

If the firms are financially constrained, we can rewrite their profit by using (A.5):

$$\Pi^i = (1+\delta)\left(1 - \frac{\tilde{p}}{1+\delta} - k_1^i - \tilde{k}_1^i - k_1^j - \tilde{k}_1^j\right)\left(k_1^i + \tilde{k}_1^i\right) - (p + c - \tilde{p})\,\frac{\tilde{p}\left(k_1 + \tilde{k}_1\right) - G}{\tilde{p} - p} \tag{A.13}$$

and the equilibrium total capacity is therefore $k_1^i + \tilde{k}_1^i = \frac{1}{3}\left(1 - \frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c + \delta\tilde{p}\right) = \Psi_D$. There are several possibilities.

- When $\frac{G}{\tilde{p}} \geq \frac{1-\tilde{p}}{3}$, $\frac{G}{\tilde{p}} \geq \Psi_D$ as $1 - \frac{(1+\delta)\tilde{p}}{\tilde{p}-p}c + \delta\tilde{p} < 1 - \tilde{p}$ due to Assumption A1. In that case firms never reach the optimal mixture, as they cannot invest in a negative amount of old capacity. Firms then invest only in new capacity to the level $\frac{G}{\tilde{p}}$. This states the first part of Proposition 2 when $\frac{1}{3}\left(1 - \frac{\tilde{p}}{1+\delta}\right) \geq \frac{G}{\tilde{p}} \geq \frac{1-\tilde{p}}{3}$.

- When $\frac{1-\tilde{p}}{3} > \frac{G}{\tilde{p}} \geq \Psi_D$, firms invest only in new capacity to the level $\frac{G}{\tilde{p}}$. However $\frac{G}{\tilde{p}} < \frac{1-\tilde{p}}{3}$, and firms optimal first period capacity does not belong to the no-move zone.

- When $\frac{G}{p} \geq \Psi_D > \frac{G}{\tilde{p}}$, firms invest in a mixture of capacity, to a level of total capacity Ψ_D and firms optimal first period capacity does not belong to the no-move zone.

- When $\Psi_D > \frac{G}{p}$, firms invest only in old capacity, to a level of total capacity $\frac{G}{p}$. Since $\frac{G}{p} < \Psi_D < \frac{1-\tilde{p}}{3}$, firms optimal first period capacity does not belong to the no-move zone.

Case 2: Symmetric zone

Assume that the first period capacities are inside the symmetric zone. Then, firms invest to a level $\frac{1-\tilde{p}}{3}$ in the second period, and only in new capacity. The intertemporal profit of firm i is then:

$$\Pi^i = \left[\left(1 - k_1^i - \tilde{k}_1^i - k_1^j - \tilde{k}_1^j - \tilde{p} + \delta\tilde{p}\right)\left(k_1^i + \tilde{k}_1^i\right) - \left((1+\delta)\,c + p - \tilde{p}\right) k_1^i\right] \\ + \delta\left[\left(1 - 2\tilde{k}_C\right)\tilde{k}_C - \tilde{p}\tilde{k}_C\right]. \quad \text{(A.14)}$$

If firm i is not financially constrained, its best response in the first period is $\tilde{k}_1^i = \frac{1}{2}\left(1 - \tilde{p} + \delta\tilde{p} - k_1^j - \tilde{k}_1^j\right)$ (and no investment in old capacity). If both firms are not constrained at the equilibrium, then $\tilde{k}_1^{i*} = \frac{1}{3}\left(1 - \tilde{p} + \delta\tilde{p}\right) > \frac{1-\tilde{p}}{3}$. In this case the first period capacities do not belong to the symmetric zone anymore. This rules out the possibility of any equilibrium in the symmetric zone such that none of the firms is financially constrained.

Let then i be the firm which is financially constrained. Using (A.5) we can rewrite its profit as follows:

$$\Pi^i = \left[\left(1 - k_1^i - \tilde{k}_1^i - k_1^j - \tilde{k}_1^j - \frac{(1+\delta)\,c\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right)\left(k_1^i + \tilde{k}_1^i\right)\right] + \frac{(1+\delta)\,c + p - \tilde{p}}{\tilde{p}-p}G \\ + \delta\left[\left(1 - 2\tilde{k}_C\right)\tilde{k}_C - \tilde{p}\tilde{k}_C\right]. \quad \text{(A.15)}$$

This leads the following best response:

$$k_1^i + \tilde{k}_1^i = \frac{1}{2}\left[1 - k_1^j - \tilde{k}_1^j - (1+\delta)\,c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right]. \quad \text{(A.16)}$$

As the firm cannot invest in a negative amount, the complete best response of firm i is then:

$$k_1^i + \tilde{k}_1^i = \left\{\begin{array}{c} \frac{G}{p} \text{ if } \frac{1}{2}\left(1 - k_1^j - \tilde{k}_1^j - (1+\delta)\,\tilde{p}\frac{c}{\tilde{p}-p} + \delta\tilde{p}\right) > \frac{G}{p} \\ \frac{1}{2}\left(1 - k_1^j - \tilde{k}_1^j - (1+\delta)\,\tilde{p}\frac{c}{\tilde{p}-p} + \delta\tilde{p}\right) \text{ elsewhere} \\ \frac{G}{\tilde{p}} \text{ if } \frac{1}{2}\left(1 - k_1^j - \tilde{k}_1^j - (1+\delta)\,\tilde{p}\frac{c}{\tilde{p}-p} + \delta\tilde{p}\right) < \frac{G}{\tilde{p}} \end{array}\right\} \quad \text{(A.17)}$$

In the case where both of the firms are financially constrained, the equilibrium is

$$k_1^i + \tilde{k}_1^i = \left\{\begin{array}{c} \frac{G}{p} \text{ if } \frac{1}{3}\left(1 - (1+\delta)\,\tilde{p}\frac{c}{\tilde{p}-p} + \delta\tilde{p}\right) > \frac{G}{p} \\ \frac{1}{3}\left(1 - (1+\delta)\,\tilde{p}\frac{c}{\tilde{p}-p} + \delta\tilde{p}\right) \text{ elsewhere} \\ \frac{G}{\tilde{p}} \text{ if } \frac{1}{3}\left(1 - (1+\delta)\,\tilde{p}\frac{c}{\tilde{p}-p} + \delta\tilde{p}\right) < \frac{G}{\tilde{p}} \end{array}\right\}. \quad \text{(A.18)}$$

To verify that firm j is also financially constrained, suppose that it is not. In that case, its best response would be:

$$\tilde{k}_1^j = \frac{1}{2}\left(1 - \tilde{p} - k_1^i - \tilde{k}_1^i\right), \quad \text{(A.19)}$$

leading to a total capacity in the industry:

$$k_1^i + \tilde{k}_1^i + k_1^j + \tilde{k}_1^j = \frac{1}{3}\left(2 - (1-\delta)\,\tilde{p} - (1+\delta)\,\frac{c\tilde{p}}{\tilde{p}-p}\right). \tag{A.20}$$

The capacity of the unconstrained firm at the equilibrium is therefore:

$$\tilde{k}_1^j = \frac{1}{3}\left(1 - (2+\delta)\,\tilde{p} + (1+\delta)\,\frac{c\tilde{p}}{\tilde{p}-p}\right), \tag{A.21}$$

This can be rewritten as:

$$\tilde{k}_1^j = \frac{1}{3}\left(1 - \tilde{p} + (1+\delta)\,\tilde{p}\left(\frac{c}{\tilde{p}-p} - 1\right)\right). \tag{A.22}$$

However, $\frac{1}{3}(1-\tilde{p}) > \frac{G}{\tilde{p}}$ and $c + p > \tilde{p}$ by assumption. Thus $\tilde{k}_1^j > \frac{G}{\tilde{p}}$, which is impossible.

The study of no-move zone and symmetric zone proves Proposition 2.

Case 3: Asymmetric zone

When the first period capacities of firms are inside the asymmetric zone, the profit of the firms are:

- for the preempting firm,

$$\begin{aligned}\Pi^L = &\left(\left(1 - k_1^L - \tilde{k}_1^L\right)\left(1 + \frac{\delta}{2}\right) - \tilde{p} + \delta\frac{\tilde{p}}{2} - \left(k_1^F + \tilde{k}_1^F\right)\right)\left(k_1^L + \tilde{k}_1^L\right)\\ &- (p + (1+\delta)\,c - \tilde{p})\,k_1^L,\end{aligned} \tag{A.23}$$

- and the preempted firm:

$$\begin{aligned}\Pi^F = &\left(1 - k_1^F - \tilde{k}_1^F - k_1^L - \tilde{k}_1^L - \tilde{p} + \delta\tilde{p}\right)\left(k_1^F + \tilde{k}_1^F\right) - (p + (1+\delta)\,c - \tilde{p})\,k_1^F\\ &+ \delta\left(\frac{1 - \tilde{p} - k_1^L - \tilde{k}_1^L}{2}\right)^2.\end{aligned} \tag{A.24}$$

The scheme of the proof is the following: first we assume that both firms are financially constrained and we express the best response of the leader and of the follower. Then we verify that there is no possible equilibrium such that one of the firm is not financially constrained.

Assume that both firm are financially constrained. Then, using (A.5), its profit can be rewritten:

$$\begin{aligned}\Pi^L = &\left(\left(1 - k_1^L - \tilde{k}_1^L\right)\left(1 + \frac{\delta}{2}\right) - \frac{(1+\delta)\,c\tilde{p}}{\tilde{p}-p} + \delta\frac{\tilde{p}}{2} - \left(k_1^F + \tilde{k}_1^F\right)\right)\left(k_1^L + \tilde{k}_1^L\right)\\ &+ \frac{p + (1+\delta)\,c - \tilde{p}}{\tilde{p}-p}G.\end{aligned} \tag{A.25}$$

This give us a best response:

$$k_1^L + \tilde{k}_1^L = \frac{1}{2}\left[1 - \frac{1}{(1+\frac{\delta}{2})}\left(k_1^F + \tilde{k}_1^F + (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} - \delta\frac{\tilde{p}}{2}\right)\right]. \tag{A.26}$$

As the firm cannot invest a negative amount of capacity, the complete best response function is:

$$k_1^L + \tilde{k}_1^L = \left\{ \begin{array}{l} \frac{1}{2}\left[1 - \frac{1}{(1+\frac{\delta}{2})}\left(k_1^F + \tilde{k}_1^F + (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} - \delta\frac{\tilde{p}}{2}\right)\right] \text{ elsewhere} \\ \frac{G}{p} \text{ if } \frac{G}{p} < \frac{1}{2}\left[1 - \frac{1}{(1+\frac{\delta}{2})}\left(k_1^F + \tilde{k}_1^F + (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} - \delta\frac{\tilde{p}}{2}\right)\right] \end{array} \right\}. \tag{A.27}$$

Remark than we did not include the possibility for the leader to have a total capacity equal to $\frac{G}{\tilde{p}}$. This is because the equilibrium total capacity of the leader has to be higher than the follower's total capacity in an equilibrium in the asymmetric zone. It is therefore not necessary to take into account a best response possibility for the leader to have a total capacity of $\frac{G}{\tilde{p}}$. For the same reason, the total capacity of the follower has to be inferior to $\frac{G}{p}$.

Similarly, using (A.5), the profit of the preempted firm can be rewritten:

$$\Pi^F = \left(1 - k_1^F - \tilde{k}_1^F - k_1^L - \tilde{k}_1^L - \frac{(1+\delta)\, c\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right)\left(k_1^F + \tilde{k}_1^F\right) + \frac{p + (1+\delta)\, c - \tilde{p}}{\tilde{p}-p} G$$
$$+ \delta\left(\frac{1 - \tilde{p} - k_1^L - \tilde{k}_1^L}{2}\right)^2, \tag{A.28}$$

which leads to the best response:

$$k_1^F + \tilde{k}_1^F = \frac{1}{2}\left[1 - k_1^L - \tilde{k}_1^L - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right]. \tag{A.29}$$

The complete best response function of the follower is thus:

$$k_1^F + \tilde{k}_1^F = \left\{ \begin{array}{l} \frac{1}{2}\left(1 - k_1^L - \tilde{k}_1^L - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right) \text{ if } \frac{G}{\tilde{p}} < \frac{1}{2}\left(1 - k_1^L - \tilde{k}_1^L - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right) \\ \frac{G}{\tilde{p}} \text{ if } \frac{G}{\tilde{p}} > \frac{1}{2}\left(1 - k_1^L - \tilde{k}_1^L - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right) \end{array} \right\}. \tag{A.30}$$

These can be rewritten as follows:

$$k_1^F + \tilde{k}_1^F = \left\{ \begin{array}{l} \frac{1}{2}\left(1 - k_1^L - \tilde{k}_1^L - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p}\right) \text{ if } \left(k_1^L + \tilde{k}_1^L\right) < 1 - 2\frac{G}{\tilde{p}} - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p} \\ \frac{G}{\tilde{p}} \text{ if } \left(k_1^L + \tilde{k}_1^L\right) > 1 - 2\frac{G}{\tilde{p}} - (1+\delta)\, c\frac{\tilde{p}}{\tilde{p}-p} + \delta\tilde{p} \end{array} \right\}. \tag{A.31}$$

Combining (A.27) and (A.31) yields Proposition 3.

We now have to verify that the financial constraint is binding for both firms. Due to the same reason for the symmetric zone, at least one firm is financially constrained. As the leader produces more than the follower, the leader is necessarily financially constrained. Furthermore, if the preempted firm is not financially constrained, the maximization of its profit gives the following best response:

$$k_1^F + \tilde{k}_1^F = \tilde{k}_1^F = \frac{1}{2}\left[1 - k_1^L - \tilde{k}_1^L - (1-\delta)\,\tilde{p}\right]. \tag{A.32}$$

However, as the preempting firm does not invest in the second period, the second period profit of the preempted firm is

$$\pi_2^F = \left(1 - k_1^L - \tilde{k}_1^L - k_1^F - \tilde{k}_2^F\right)\left(k_1^F + \tilde{k}_2^F\right) - \tilde{p}\left(\tilde{k}_2^F - \tilde{k}_1^F\right) - ck_1^F, \tag{A.33}$$

which leads to a second period optimal capacity of the preempted firm:

$$\left(k_1^F + \tilde{k}_2^F\right) = \frac{1}{2}\left(1 - k_1^L - \tilde{k}_1^L - \tilde{p}\right), \tag{A.34}$$

which is inferior to the first period best response given by (A.32), meaning that the preempted firm does not invest in the second period. This contradicts the fact that the potential equilibrium is in the asymmetric zone.

Proof of Result 4:

Most of the results are directly obtained by taking the derivatives of capacity amounts given in propositions. However, the effect of the price of old capacity is less straightforward. The following proves the result for the monopoly.

The percentage of old capacity is given by:

$$\%_{Old} = \frac{k_1^*}{k_1^* + \tilde{k}_1^*} = \frac{\tilde{p}}{\tilde{p} - p}\frac{\Psi_M - \frac{G}{\tilde{p}}}{\Psi_M}. \tag{A.35}$$

The derivative of the percentage is positive if and only if:

$$\frac{\partial \%_{Old}}{\partial p} > 0 \Leftrightarrow (\Psi_M)^2 > \frac{G\,(1+\delta\tilde{p})}{2\tilde{p}}. \tag{A.36}$$

This condition can be rewritten:

$$\frac{\partial \%_{Old}}{\partial p} > 0 \Leftrightarrow p < \tilde{p} - \frac{c\,(1+\delta)\,\tilde{p}}{1 + \delta\tilde{p} - \sqrt{2\frac{G(1+\delta\tilde{p})}{\tilde{p}}}}. \tag{A.37}$$

The same approach works for the quantity of old capacity:

$$\frac{\partial k_1^*}{\partial p} > 0 \Leftrightarrow p < \tilde{p} - \frac{2c\,(1+\delta)\,\tilde{p}}{2G - \tilde{p} - (\tilde{p})^2}. \tag{A.38}$$

The same approach can be used to prove this result for the symmetric duopoly. For the asymmetric duopoly, the proof is given in the following.

In the asymmetric equilibrium, the total capacity of the industry can be written as:

$$\Psi_L^{nc} + \Psi_F^{nc} = \frac{6\Psi_D + 3\delta\Psi_D + \delta\left(\frac{1}{2} - \frac{1}{2}\tilde{p}\right)}{3 + 2\delta}. \tag{A.39}$$

The percentage of old capacity in the industry is therefore:

$$\%_{old} = \frac{\frac{\tilde{p}}{\tilde{p}-p}\left(\Psi_L^{nc} + \Psi_F^{nc} - \frac{2G}{\tilde{p}}\right)}{\Psi_L^{nc} + \Psi_F^{nc}}. \tag{A.40}$$

The derivative of the total capacity according to the price of the old capacity is decreasing as $\frac{\partial \Psi_D}{\partial p} < 0$. Furthermore, the derivative of the old percentage gives:

$$\frac{\partial \%_{old}}{\partial p} = \frac{\tilde{p}}{(\tilde{p} - p)^2} - \frac{4G\,(3 + 2\delta)\,(4 + \delta\,(3 + \tilde{p}\,(3 + 2\delta)))}{(4(c\tilde{p} + p - \tilde{p}) + 3\delta\,(p + 2c - 1 - \tilde{p}) + 2\tilde{p}(c + p - \tilde{p})\delta^2)^2}. \tag{A.41}$$

Asymmetric equilibrium exists only when condition (21) exists. When the total capacity of the follower is Ψ_F^{nc}, this condition can be rewritten:

$$\frac{1}{2}\left(1 - \Psi_F^{nc} - (1 + \delta)\,\frac{c\tilde{p}}{\tilde{p} - p} + \delta\tilde{p}\right) > \frac{1 - \tilde{p}}{3}. \tag{A.42}$$

This is equivalent to:

$$c < \frac{\tilde{p} - p}{\tilde{p}}\frac{1 + \frac{3}{2}\delta + \tilde{p}}{(1 + \delta)\,(2 + \delta)}. \tag{A.43}$$

We will see that this condition implies that

$$4(c\tilde{p} + p - \tilde{p}) + 3\delta\,(p + 2c - 1 - \tilde{p}) + 2\tilde{p}(c + p - \tilde{p})\delta^2 \tag{A.44}$$

is negative. Indeed, by using (A.43) in (*A*.44) we obtain:

$$(A.44) < -\,(\tilde{p} - p)\,(2 + \tilde{p}\,(2 + \delta)\,(2\delta - 1)) \tag{A.45}$$

Since $2 + \tilde{p}\,(2 + \delta)\,(2\delta - 1) < 0$ for any $\tilde{p} < 1$ and $\delta \geq 0$, (A.44) is negative. This implies that $\frac{\partial \%_{old}}{\partial p} > 0$ if and only if:

$$\begin{aligned}&4(c\tilde{p} + p - \tilde{p}) + 3\delta\,(p + 2c - 1 - \tilde{p}) + 2\tilde{p}(c + p - \tilde{p})\delta^2\\ &-(\tilde{p} - p)\sqrt{\frac{4G\,(3 + 2\delta)\,(4 + \delta\,(3 + \tilde{p}\,(3 + 2\delta)))}{\tilde{p}}} < 0\end{aligned} \tag{A.46}$$

Therefore,

$$p < \frac{4(\tilde{p} - c\tilde{p}) + 3\delta\left(1 + \tilde{p} - 2c\right) + 2\tilde{p}(\tilde{p} - c - p)\delta^2 + \tilde{p}\sqrt{\frac{4G(3+2\delta)(4+\delta(3+\tilde{p}(3+2\delta)))}{\tilde{p}}}}{\left(4 + 3\delta + 2\tilde{p} + \sqrt{\frac{4G(3+2\delta)(4+\delta(3+\tilde{p}(3+2\delta)))}{\tilde{p}}}\right)}. \tag{A.47}$$

As the total capacity is decreasing, the ambiguity of the percentage proves the ambiguity of the total capacity.

Proof of Result 9:

Let $\tilde{k}_2^M$ be the level of new capacity in second period for the monopoly:

$$\tilde{k}_2^M = \frac{1 - \tilde{p}}{2} - \frac{\tilde{p}}{\tilde{p} - p}\left(\Psi_M - \frac{2G}{\tilde{p}}\right).$$

Let $\tilde{k}_2^S$ be the level of new capacity in second period for the symmetric duopoly:

$$\tilde{k}_2^S = \frac{2\left(1 - \tilde{p}\right)}{3} - 2\frac{\tilde{p}}{\tilde{p} - p}\left(\Psi_D - \frac{G}{\tilde{p}}\right).$$

Then, $\tilde{k}_2^M < \tilde{k}_2^S$ if and only if:

$$\frac{1 - \tilde{p}}{2} - \frac{\tilde{p}}{\tilde{p} - p}\Psi_M < \frac{2\left(1 - \tilde{p}\right)}{3} - 2\frac{\tilde{p}}{\tilde{p} - p}\Psi_D$$

As $\Psi_D = \frac{2}{3}\Psi_M$, this is always the case.

Let $\tilde{k}_2^{As}$ be the level of new capacity in second period for the asymmetric duopoly:

$$\tilde{k}_2^{As} = \frac{1 - \tilde{p} - \Psi_L}{2} - \Psi_F - \frac{\tilde{p}}{\tilde{p} - p}\left(\Psi_L - \frac{G}{\tilde{p}}\right) - \frac{\tilde{p}}{\tilde{p} - p}\left(\Psi_F - \frac{G}{\tilde{p}}\right)$$

The difference between the level of new capacity for the asymmetric duopoly and for the symmetric duopoly is given by:

$$\tilde{k}_2^{As} - \tilde{k}_2^S = \frac{\left(1 + \delta\right)\left(3 + 2\delta\right)\tilde{p}^2 - p\delta - \tilde{p}p\left(3 + 2\delta\right) - \frac{c\tilde{p}}{\tilde{p} - p}\left(1 + \delta\right)\left(\tilde{p}\left(3 + 2\delta\right) - 3p\right)}{6\left(\tilde{p} - p\right)\left(3 + 2\delta\right)}.$$

Due to assumption A1, $\frac{c}{\tilde{p} - p} > 1$, therefore:

$$\tilde{k}_2^{As} - \tilde{k}_2^S < \frac{-p\delta - \tilde{p}p\left(3 + 2\delta\right) + 3p\tilde{p}\left(1 + \delta\right)}{6\left(\tilde{p} - p\right)\left(3 + 2\delta\right)},$$

so:

$$\tilde{k}_2^{As} - \tilde{k}_2^S < \delta\frac{p\tilde{p} - p}{6\left(\tilde{p} - p\right)\left(3 + 2\delta\right)}.$$

As $\tilde{p} < 1$ (if not, no firm will enter in the market),

$$\tilde{k}_2^{As} < \tilde{k}_2^S.$$

The difference between the level of new capacity for the asymmetric duopoly and for the monopoly is given by:

$$\tilde{k}_2^{As} - \tilde{k}_2^M = \frac{p\left(\frac{c\tilde{p}}{\tilde{p}-p} - 1\right)(1+\delta)}{6\left(\tilde{p}-p\right)(3+2\delta)}.$$

If the cost of adding and using during a single period a capacity is similar for the old and new technology ($c + p \simeq \tilde{p}$), then $\tilde{k}_2^{As} < \tilde{k}_2^M$ as $\tilde{p} < 1$. When the cost difference is important, $\tilde{k}_2^{As} > \tilde{k}_2^M$. ■

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