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# Defensive Strategies in the Quality Ladders

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# DEFENSIVE STRATEGIES IN THE QUALITY LADDERS[1]

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## Abstract

This paper analyses the potentially defensive behaviour of patent race winners and its effect on aggregate R&D effort. It proposes a quality-ladders model that endogenously determines leaders technology advantages and who innovates. Product market regulation can have either a positive or a negative effect on R&D intensity. The negative effect is likely to be observed in highly deregulated economies. The positive influence arises in more regulated environments and it is stronger for larger innovative jumps. These steady-state equilibrium outcomes are consistent with the puzzling patterns in data from manufacturing industries in 14 OECD countries over the 1987-2003 period.

**Key words:** Innovative leaders, quality ladders, product market regulation, R&D.

## Résumé

Dans cet article nous étudions le comportement potentiellement défensif des innovateurs et son effet sur l'effort agrégé d'innovation. Un modèle à échelles de qualité est proposé afin d'analyser l'émergence d'avantages technologiques qui, in fine, déterminent qui innove (le leader ou ses concurrents). Dans ce contexte, la réglementation de marché peut avoir un effet positif ou négatif sur l'intensité en R&D. Elle peut être négativement associée à l'effort d'innovation dans des environnements hautement dérèglementés. Par contre, en économies qui dépassent un certain seuil de réglementation, susceptible de limiter effectivement la construction de barrières stratégiques, la réglementation induit des incitations à innover. Ces prédictions sont cohérentes avec des tests empiriques menés sur un échantillon d'industries appartenant à 14 pays de l'OCDE durant la période 1987-2003.

**Mots clés :** Leaders innovants, modèle à échelles de qualité, réglementation, R&D.

**JEL Classification :** L13, O31, O33.

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# 1 Introduction

A number of pieces of empirical work on R&D surveys have shown that firms use a variety of strategies to protect the value of their innovations (Levin et al., 1987; Cohen, Nelson and Walsh, 2000; Cohen et al., 2002). We argue in this paper that this multiplicity is key for the understanding of the effect of product-market regulation (PMR) on R&D incentives. If firms have various alternative methods to keep their profits, then competitive pressures may not necessarily act as a neutral slack-reducing device. The threat of competition can in practice trigger a defensive reaction from incumbents, who will construct different types of strategic barriers to reduce the risk of losing innovation contests.[1]

Since the appropriation of innovation returns relies on the exploitation of asymmetries in private knowledge and capabilities, PMR will likely have a different effect on innovation incentives according to firms' business positions. It is then important to estimate the net effect at the aggregate level, taking into account winners' and losers' reactions in equilibrium. Industry-level data actually reveals interesting empirical patterns which motivate the theoretical discussion that follows. We analyse a sample of 14 manufacturing industries in 14 OECD countries in 1987-2003, a period marked by considerable market reform. We test the link between PMR, proxied via the regulation impact indicator (henceforth REGIMP) from the OECD, and R&D intensity. REGIMP measures the extent to which industries are constrained by administrative burdens, entry regulation and other market barriers in key input sectors, mainly network services. This type of vertical linkages makes the connexion to the theory more direct, as we shall see. Appendix A.2.1 contains details on the data construction and variables. Figure 1 presents the PMR elasticities when controling for time, country and industry fixed effects. In less-regulated markets, higher PMR reduces R&D intensity; however, the opposite is true in more-regulated environments. Moreover, this latter positive link between PMR and R&D intensity is stronger when manufacturing activities relate to the production or to

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[1] Consistent with the findings in R&D surveys, Crépon and Duguet (1997) provide evidence of negative R&D externalities amongst French manufacturing firms in narrowly-defined industries, a result interpreted by the authors as the outcome of competitors' rivalry.

the use of high-technology goods. We show in Appendix A.3 that positive slopes appear in a number of tests including more time-varying controls, fixed-effects as well as other alternative specifications. More importantly, findings pointing out ambiguities in the relationship between PMR and economic performances are indeed not new in industry-level studies.[2]

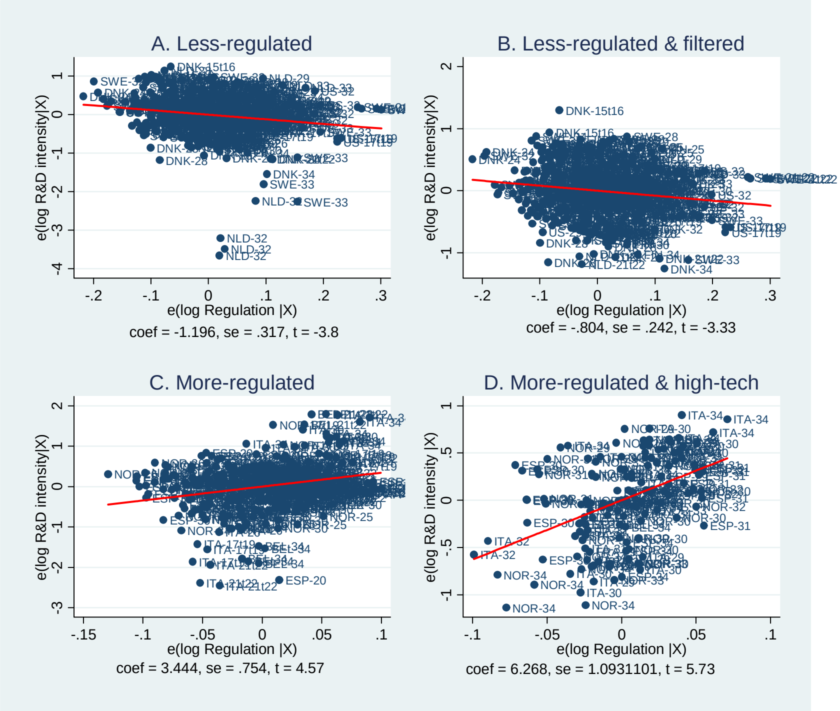

Figure 1. Regulation and R&D intensity (expected conditional residuals).

Note: All specifications are in log and control for time, country and industry fixed effects. The sample is split as follows. Graph A considers the 10% least regulated individuals (country-industry couples) over the full time period, Graph B the 10% least regultaed without visible outliers at the south of the graph, Graph C the 25% most regulated individuals and Graph D the 25% most regulated in 29-34 ISIC-Rev.3 industries.

We investigate the theoretical channels through which PMR, by setting the limits to firm strategies, may lead to such outcomes. We propose a quality-ladder model that emphasises the role of strategic behaviour in vertical innovation. In our model, each vintage is characterised by a vector composed of several quality dimensions. This vector contains information on two important aspects of quality. Its magnitude measures the *level* of quality of the vintage and we shall referred to as the *intensive* margin of quality. Its

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[2] Jamasb and Pollit (2011) make the case for the UK electricity; For evidence on positive interactions between PMR and the closennes to the technology frontier in explaining patent intensity see Amable, Demmou and Ledezma (2010), who also discuss related evidence.

direction summarises the *mix* of quality dimensions offered by the good and hence relates to what can be called the *extensive* margin of quality. To date, standard unidimensional quality-ladder representations have only focused on the former aspect. Our model underlines that a given level of quality can be potentially provided by a number of mixes of quality dimensions so that vertical innovation will also likely affect the extensive margin. In order to fend off the threat from followers, after discovering a new idea and before manufacturing, the innovator can introduce additional complexity into the good by adding new dimensions of quality.

This vectorial representation is introduced into a standard R&D race with constant returns to scale (CRS) in R&D technologies and Nash-Cournot equilibrium behaviour. By strategically manipulating the extensive margin of quality, the new successful innovative firm acquires an R&D cost advantage vis-à-vis its competitors. This advantage may be large enough to render R&D attractive to leaders despite the cannibalisation of their current rents. Incumbents may then be able to overcome the so called Arrow effect. If this is the case, the R&D investment of outsiders is not worthwhile, and their optimal strategy is not to invest. Conversely, with smaller resulting R&D cost advantages, the leader is absent from R&D races and innovation relies only on outsiders.

This is where PMR enters into the story, as it increases the costs of upgrading both the intensive and extensive quality margins. Since the new innovative firm is the sole producer that has the knowledge to implement the new idea it is also the sole producer affected by the costs related to the extensive margin. Knowledge asymmetries translate then into cost asymmetries influenced by PMR. The main result is that PMR can have either a positive or a negative effect on aggregate R&D intensity. The sign depends on whether PMR is above or below a certain threshold, which can be seen as distinguishing "liberal" from "regulated" markets. In liberal environments the equilibrium is characterised by a permanent innovative monopolist. Greater PMR here is detrimental to innovation as it distorts the innovative activity of the sole innovator (the leader). However, with PMR above the critical threshold, the economy experiences Schumpeterian leapfrogging in which leaders are continuously replaced by innovative outsiders. In this case, regulatory provisions can increase aggregate R&D since they reduce the deterrent effect on outsiders. This positive effect is stronger for larger innovations when there are considerable incentives to behave defensively, a result that can be linked to vertical innovation in high-tech industries, as in Graph D in Figure 1. Moreover, the fact that firm renewal only comes about after a certain level of PMR and that the presence of a permanent monopolist obscures a constant competitive threat, underlines the complexity of the link between PMR and competition. Appendix A.3 also offers some evidence illustrating this point. In this sense, the model sheds some light on the driving forces characterising the so-called "competitive capitalism" and "trustified capitalism" (Schumpeter, 1928).

Fairly general functional form assumptions allow us to identify the type of regulation that is consistent with the model predictions. Negative (first-order) effects of PMR on the upgrading of the extensive margin must be greater than those directly affecting the intensive margin. Pro-competitive provisions regulating, for example, mergers and acquisitions or bundling may limit the rents associated with knowledge asymmetries. However, more interestingly, and somewhat provocatively, even so-called market barriers can play this role. Theoretically speaking, all that is needed is a rule that directly or indirectly forces leaders to stay within the boundaries of the current business process and product. In a second-best context, whether on purpose or not, these rules may act as a knowledge-standardisation device and provide incentives to *some* agents who are strategically disadvantaged.[3]

The theoretical model we propose relates to particular strands of the quality-ladders and patent races literatures. A few Schumpeterian growth models have explicitly included strategic entry-deterrence in R&D activity, like the introduction of tacitness in

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[3] Contrasting with most received ideas, the link between competition and innovation is if anytihng ambiguous. Models mainly predict (i) negative relationships, as in most Schumpeterian innovation-based growth models (e.g. Grossman and Helpman 1991a, 1991b; Aghion and Howit, 1992; Segerstrom, Anant and Dinopoulos 1990); or (ii) ambiguous relationships, with for instance an inverted–U shaped relatioship (Aghion *et al.*, 2005), but also U-shaped (Tishler and Milstein, 2009) or more complex non-monotonic relationships (Boone, 2001). Examples yielding only positive links can also be constructed, as shown by Aghion, Harris and Vickers (1997) with step-by-step innovations, but tipically they do not seek generality. Also within the managerial literature highlighting positive effects of PMC on principal-agent issues arguments are not unambiguous (see Beiner, Schmid and Wanzenried, 2011 for a recent discussion).

the knowledge of production in order to prevent imitation (Thoenig and Verdier, 2003) or rent-protecting activities such as patent blocking, intellectual-property disputes and the like (Dinopoulos and Syropoulos, 2007). As in our model, leaders and followers play simultaneously in these papers. However they have identical R&D technologies, so that the above-mentioned Arrow replacement effect pertains.[4] There is, however, convincing evidence of the active role of leaders in R&D (Chandler, 1990; Malerba, Orsenigo and Peretto, 1997; Malerba et Orsenigo, 1999; Segerstrom, 2007). In the model proposed here, the participation of the leader in R&D contests is endogenous.

In particular, one typical assumption which overcomes the Arrow effect is positing exogenous R&D advantages to leaders in Nash-Cournot equilibria. This is the way followed by Segerstrom and Zolnierek (1999) and Segerstrom (2007). Our explanation links these models to the above-mentioned ones by showing how leaders can acquire an R&D advantage via defensive behaviour.[5] Moreover, the model can also encompass arguments stemming from initial influential models of patent races which deeply discussed leaders' incentives to innovate (Gilbert and Newbery, 1982, 1984; Reinganum, 1983). In particular, Stackelberg-type models where the leader has a first-mover advantage also provide explanation for the persistence of the leadership (Barro and Sala-i-Martin, 2004; Chapter 7; Etro, 2004). We show that our main predictions regarding the effect of PMR on R&D intensity continue to hold in such settings. We add the insight that the effect of PMR can be ambiguous, but that this ambiguity can be understood once we identify who innovates.[6]

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[4] This is at least the usual claim (see Aghion and Howitt, 1992). However, Cozzi (2007) shows that if the R&D sector is perfectly competitive, price-taking behaviour actually leads to indeterminacy as the leader should neglect the consequences of his actions on aggregate R&D. Moreover, the author demonstrate that despite indeterminacy the equilibrium patterns are the same, so that these models can well be interpreted *as if* outsiders were the innovators.

[5] Technology advantages are not the only way to ensure that leaders innovate. Other explanations of the persistence of leadership point out assymetries in price strategies based on technology gaps (Denicolò, 2001), non-homothetic preferences (Latzer, 2011). Considering decreasing returns to scale, Etro (2004) shows that the assumption of Stackelberg leaders deciding a fixed R&D commitment suffices to reproduce the effect of a leader aggresively investing in R&D.

[6] Interested in similar issues, Grossman and Steger (2008) show that, from the leader's point of view, the erection of entry barriers and R&D are complementary activities. Despite entry blocking, this behaviour can be conducive to growth when outsiders' R&D does not generate knowledge spillovers. Though comparisons are har due to different micro-settings, this prediction is compatible with our equilibrium characterised by a permanent monopolist.

The remainder of the paper is organised as follows. Section 2 presents the general setup and Section 3 the strategic decisions. Section 4 provides steady-state equilibrium predictions and a brief discussion on the ability of the model to fit the data patterns. Finally, concluding remarks are presented.

# 2 General Framework

The formal setting is based on a semi-endogenous quality-ladder model without scale effects. The basic setup follows Li (2003), who models imperfect inter-industry substitutability and offers a simple way of removing steady-state scale effects: as quality improves, new discoveries need more R&D effort. In equilibrium the innovation rate will not depend on the amount of labour allocated to R&D but rather on the rate of population growth.[7]

## 2.1 Consumption and production

### 2.1.1 Consumers

The economy is composed of identical dynastic families whose members grow at an exogenous rate of $n > 0$. Each household member inelastically supplies one unit of labour. Without loss of generality, the initial population is set to 1, so that the population at time $t$ is $L(t) = e^{nt}$. In order to avoid notational confusion, all round brackets refer to arguments of functions.

There is a continuum of industries, indexed by $\omega$. Per capita instantaneous utility is given by

$$u\left(t\right) = \left[\int_{0}^{1} z\left(t,\omega\right)^{\frac{\sigma-1}{\sigma}} d\omega\right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

where $\sigma > 1$ is the elasticity of substitution between goods of different industries, and

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[7] This feature characterises a second wave of quality-ladder models that solve the problem of scale effects in steady-state growth (Segerstrom, 1998; Young, 1998). For a survey on the evolution of this type of Schumpeterian model, see Dinopoulos and Sener (2007).

$z(t,\omega) \equiv \sum_j \gamma^j d(j,t,\omega)$ is the sub-utility function associated with the consumption of varieties of industry $\omega$ at time $t$. Each vertically-differentiated variety represents a specific vintage of the good sold in the industry. They are ordered according to their quality which is indexed by $j$, an integer representing the "grades" in the quality ladder. The height of the grades (i.e. the size of innovation) is captured by $\gamma > 1$. Hence, consumption of each variety $j$, denoted $d(j,t,\omega)$, is weighted according to the quality it delivers.

Given perfect intra-industry substitution and the constant elasticity of substitution utility in (1), all intra-industry expenditure will focus on variety $j_\omega$ offering the lowest quality-adjusted price, the demand for which can be written as:

$$d(j_\omega,t,\omega) = \frac{\delta(j_\omega,t,\omega)}{p(j_\omega,t,\omega)^\sigma \int_0^1 \delta(j_{\omega\prime},t,\omega')\, p(j_{\omega\prime},t,\omega')^{1-\sigma}\, d\omega'} E(t) \tag{2}$$

where $E(t)$ is total expenditure at time $t$ and $\delta(j_\omega,t,\omega) \equiv \gamma^{j_\omega[\sigma-1]}$ is an alternative index of perceived quality, which takes into account the substitutability between industries.

Using a subjective discount rate of $\rho > n$, each dynastic family maximises its intertemporal utility $U = \int_0^\infty e^{-[\rho-n]t} \log u(t)\, dt$ subject to a standard dynamics of per capita assets. Solving this program leads to the optimal intertemporal expenditure rule:

$$\frac{\dot{E}(t)}{E(t)} = r(t) - \rho \tag{3}$$

### 2.1.2 Producers and price setting

The production technology is constant returns to scale with labour as the sole factor. The firm producing variety $j_\omega$ sells its output to all members of the representative household at price $p(j_\omega,t,\omega)$ and incurs a total production cost of $d(j_\omega,t,\omega)\, L(t)$, with wages being normalised to 1. The profit of this producer is then

$$\pi(j_\omega,t,\omega) = [p(j_\omega,t,\omega) - 1]\, d(j_\omega,t,\omega)\, L(t) \tag{4}$$

Following Segerstrom and Zolnierek (1999) and Barro and Sala-i-Martin (2004, ch. 7), we restrict our attention to the case of drastic innovation, so that leaders can optimally charge a markup over marginal costs $p\left(j_{\omega},t,\omega\right)=\frac{\sigma}{\sigma-1}$.[8] This rules out any asymmetry in innovation incentives stemming from price setting (Denicolò, 2001). Substituting for demand (2) in leader profits (4) yields:

$$\pi\left(j_{\omega},\omega,t\right)=\overline{\pi}\delta\left(j_{\omega},\omega,t\right) \tag{5}$$

where $\overline{\pi}\equiv\frac{p-1}{p}\frac{E(t)L(t)}{Q(t)}$ represents the basic stream of profits (those obtained at $j_{\omega}=0$) and $Q\left(t\right)\equiv\int_{0}^{1}\delta\left(j_{\omega},\omega,t\right)d\omega$ is an economy-wide index of average quality.

Before presenting the core of the model, note that: (i) only one firm produces a positive quantity in a given industry; (ii) the only difference between industries regarding the state variables is the current state-of-the-art quality level $j_{\omega}$; and (iii) all endogenous variables (except prices) depend on $t$. We will hence, from now on, drop time and industry indices to reduce notation when this does not lead to confusion.

## 2.2 Quality improvements

### 2.2.1 Quality dimensions

In the standard quality-ladder framework each new innovator climbs the quality ladder in the only possible way. Here, each vintage is characterised by an m-dimensional quality vector $\mathbf{q}\left(j_{\omega}\right)=\left\{q_{1}\left(j_{\omega}\right),q_{2}\left(j_{\omega}\right)...,q_{m}\left(j_{\omega}\right)\right\}$. The $m$ quality dimensions can be thought as particular attributes, features or components of the produced good and its related business process. The specific mix of dimensions defines the direction of the quality vector, denoted by $\alpha\left(j_{\omega}\right)$. At each quality upgrade this direction can be strategically modified by the new innovator. We capture this change as $\theta_{j_{\omega}}=\alpha\left(j_{\omega}\right)-\alpha\left(j_{\omega}-1\right)$, which is the angle between $\mathbf{q}\left(j_{\omega}\right)$ and $\mathbf{q}\left(j_{\omega}-1\right)$. Two different mixes in the same industry provide the same utility if their quality level is the same. This assumption remains consistent with the intra-industry

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[8] There is still competition within industries. Bertrand behaviour therein yields a limit-pricing strategy. The leader tries to come close to the best quality-adjusted price of its closest competitor: $p\left(j_{\omega},\omega,t\right)\rightarrow\gamma$. We hence assume that the innovation is large enough to ignore outside competition: $\gamma>\frac{\sigma}{\sigma-1}$.

sub-utility function in equation (1), where any pair of varieties are perfectly substitutable versions of the same product. It can be shown that our conclusions continue to hold if we allow for welfare effects of changes in the quality mix as long as these changes are considered as being part of the incremental vertical innovations.[9]

On the other hand this change of direction does matter crucially in the research sector. The change in the quality mix, $\theta_{j_\omega}$, is assumed to be a source of R&D advantage for the leader. As a way of protecting its business position, the firm that is successful in its R&D can make use of its private knowledge regarding the new idea and can add new quality dimensions to the current mix. The firm knows the new blueprint and will define the specific and visible features its product will have on the market. Quality of course improves with innovation, but over a different path which is strategically chosen in order to compel challengers to provide a new business solution when faced with a number of disadvantages, precisely because they are outsiders in the new business.[10] In what follows we refer to $\theta_{j_\omega}$as the *strategic technological bias* (or simply the bias) induced by the leader.[11]

The magnitude of the quality vector increases with each discovery by a factor of $\gamma$, which is the innovation size. We here retain the standard treatment: the level of quality provided by the state-of-the-art $j_\omega$ is thus $\|\mathbf{q}(j_\omega)\| = \gamma^{j_\omega}$.

### 2.2.2 R&D technologies and product market regulation

**Outsiders' R&D technology:** This uses labour under CRS. R&D is governed by a Poisson stochastic process: the $\ell_i$ units of labour allocated to research over an interval of time $dt$ imply that the new discovery results with probability of $\Lambda_o(j_\omega+1)\,\ell_i dt$. The term $\Lambda_o(j_\omega+1)$ can then be interpreted as the R&D productivity of outsiders. This is

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[9] Details are given in an Online Appendix. More generally, it is difficult to postulate whether a change in the quality mix will have a positive or negative impact on consumer utility as the strategically-chosen dimensions may not necessarily fit consumers preferences. See for instance the BBC article "New phone features 'baffle users'", http://news.bbc.co.uk/2/hi/technology/7833944.stm.

[10] The incorporation of hafnium in microchip fabrication that gave Intel the upper-hand over its rivals is an illustration of how vertical innovation may qualitatively change crucial aspects of goods. See The Economist, "AMD v Intel: Oil money and hafnium", November 22nd 2007.

[11] This terminology evokes that used by Thoenig and Verdier (2003), who note similar defensive behaviour in the context of skill-biased technical change.

defined as

$$\Lambda_o\left(j_\omega+1\right)=\frac{h\left(\psi\right)b\left(\theta_{j_\omega}\right)}{\delta\left(j_\omega+1\right)} \tag{6}$$

The presence of the quality index $\delta\left(j_\omega+1\right)$ here implies that, as the quality level rises, the next R&D success becomes harder to find (Li, 2003). The two terms in the numerator of (6) represent a key departure from the existing literature. The function $h\left(\psi\right)>0$, with $h\left(0\right)=\overline{h}>0$ and $h'\left(\psi\right)<0$, captures the extent to which PMR, represented by the parameter $\psi$, may negatively affect R&D. This reflects the typical claim that tougher PMR translates into administrative burdens that hamper entrepreneurial initiatives. As this directly affects the upgrade of the norm of the quality vector we will refer to as the effect of PMR on the intensive margin of quality.

The second new term captures the negative effect of the strategic technological bias on outsiders' R&D: $b\left(\theta_{j_\omega}\right)>0$, with $b\left(0\right)=\overline{b}>0$ and $b'\left(\theta_{j_\omega}\right)<0$. This formulation implies that the complete specification of the quality dimensions is not needed as the effect of any change in the quality mix collapses to the scalar measure of the change in direction of the quality vector.[12]

The instantaneous probability of innovation $I_i$ from outsider $i's$ R&D effort is then

$$I_i=\ell_i\Lambda_o\left(j_\omega+1\right) \tag{7}$$

**Leader's R&D technology:** The leader firm is the one that has discovered the current state-of-the-art product. Therefore, it is the sole producer who knows how (and is able) to incorporate this new dimension into the good. Its probability of R&D success is then not affected by changes in the direction of the quality vector. On the other hand, just like outsiders, the leader firm is also subject to an administrative burden that may render the

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[12] In previous working-paper versions we used the normalised scalar product between $\mathbf{q}\left(j_\omega\right)$ and $\mathbf{q}\left(j_\omega-1\right)$ as a parametrisation of $b\left(\theta_{j_\omega}\right)$. Although that formulation leads to clear closed solutions, the current specification allows us to assess better the generality of the model.

process of discovery more difficult. Hence, the leader's R&D productivity is defined as

$$\Lambda_L\left(j_\omega+1\right)=\frac{h\left(\psi\right)\overline{b}}{\delta\left(j_\omega+1\right)}$$

**The path of innovation:** Figure 2 provides an illustration. We start from the quality level $j_\omega$ in a given industry. At this stage we have a horizontal vector. The good is totally based on dimension $q_1$. Once the next innovative firm succeeds in upgrading the quality level to $j_\omega+1$, it introduces a technological bias by including dimension $q_2$. The firm then produces the new vintage with a quality vector having direction $\theta_{j_\omega+1}$ far away from the previous one. By doing so, it reduces outsiders' probability of success in the next R&D race (the one leading to the $j_\omega+2$ level) by a factor of $b\left(\theta_{j_\omega+1}\right)$. Then, the next innovation occurs. This improves the quality level up to $j_\omega+2$, but the new innovative firm makes a further change in the mix to protect itself in the next contest. This process may last indefinitely.[13]

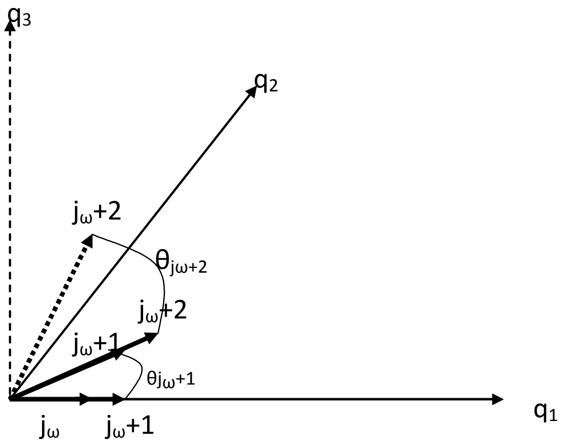

Figure 2. Innovation Path

**The technology of bias:** Each degree of departure from the current direction of the quality vector implies, for the leader, an investment decision over all quality dimensions. More specifically, the strategic technological bias can be seen as the output obtained

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[13] The figure suggests a case for the "re-discovery" of quality dimensions. Dimension $q_1$ has been dropped in the $j_\omega+2$ wave ($q_1\left(j_\omega+2\right)=0$). If some degree of obsolescence is at work, $q_1$ can eventually be re-introduced by the winner of the $j_\omega+3rd$ contest. This can conceptually substitute for an exogenous process of discovery of quality dimensions. Think for instance of the incorporation of Dolby technology in iPods.

from a variety of specific technological inputs $\mathbf{x}(j_\omega) = \{x_1(j_\omega), x_2(j_\omega), ..., x_m(j_\omega)\}$, one for each quality dimension:

$$\theta_{j_\omega} = f(\mathbf{x}(j_\omega)) \tag{8}$$

In order to simplify the presentation, let each input $k = 1...m$ be produced using labour under CRS.

$$x_k(j_\omega) = a_k(\psi, \delta(j_\omega))\, l_k \tag{9}$$

Efficiency in the production of each input, $a_k(\psi, \delta(j_\omega))$, is supposed to be negatively affected by both the PMR parameter $\psi$ and the quality level of the recently discovered vintage $\delta(j_\omega)$. Hence, we suppose that tougher regulation makes quality adaptation harder to achieve, either because it enforces current quality standards through more controls and permits, or simply because of the usual claims pointing out the administrative burden and lack of upstream dynamism. Similarly, we suppose that higher-quality goods are more difficult "to bias", an assumption that is analogous to that in Li (2003), whereby higher-quality goods are more difficult to discover. Both elements will directly determine the cost of inputs and so input prices, denoted by $w_k(j_\omega)$. It follows that, after assuming the linear homogeneity of $a_k(\cdot)$ in $1/\delta(j_\omega)$, we can write $w_k(j_\omega) = \delta(j_\omega)\overline{w}_k(\psi)$ and define $\overline{\mathbf{w}}(\psi) = \{\overline{w}_1(\psi), \overline{w}_2(\psi), ..., \overline{w}_m(\psi)\}$ as the quality-adjusted vector of input prices. Standard duality arguments allow us to specify the technology of bias as follows:

**Lemma 1** *For constant returns to scale of $x_k(\cdot)$ and decreasing returns to scale of $f(\cdot)$, there exists a (minimum) cost function of technological bias of the form*

$$c(\theta_{j_\omega}, \overline{\mathbf{w}}(\psi), j_\omega) = \overline{c}(\theta_{j_\omega}, \psi)\,\delta(j_\omega), \tag{10}$$

*so that* $\frac{\partial \overline{c}(\theta_{j_\omega},\psi)}{\partial \theta_{j_\omega}} > 0$ ,$\frac{\partial^2 \overline{c}(\theta_{j_\omega},\psi)}{\partial^2 \theta_{j_\omega}} > 0$ ,$\frac{\partial \overline{c}(\theta_{j_\omega},\psi)}{\partial \psi} > 0$ *and* $\frac{\partial^2 \overline{c}(\theta_{j_\omega},\psi)}{\partial \psi \partial \theta_{j_\omega}} > 0$.

The function $\overline{c}(\cdot)$ can be interpreted as the *quality-adjusted cost function* of upgrading the extensive margin of quality. Its properties are useful in order to characterise the leader's strategic decisions.

## 2.3 Firms' value and timing

If researchers in an outsider firm $i$ succeed in their R&D effort, the firm will sell the new vintage $j_\omega + 1$ as the leader of the industry and receive a value denoted by $v_L(j_\omega + 1)$. Free entry in the research sector implies that firms enter the R&D race up to the point where the expected value of innovation is equal to the required investment:

$$v_L(j_\omega + 1) = \frac{1}{\Lambda_o(j_\omega + 1)} \tag{11}$$

CRS in R&D technology implies that the R&D effort of outsider firm $i$ is $\ell_{io}(j_\omega + 1) = \ell_{io} \in \mathbb{R}^+$ if $v_L(j_\omega + 1) = \frac{1}{\Lambda_o(j_\omega+1)}$, otherwise is either zero or unbounded.

Let $\ell_0 = \sum_i \ell_{i0}$ be the total amount of R&D carried out by outsiders in the industry. The Bellman equation for the stochastic jumps of a potentially innovative leader facing free entry in the research sector can be written as

$$\begin{aligned} rv_L(j_\omega) &= \max_{\ell_L} \Big\{ \max_{\theta} \{ \pi_L(j_\omega) - \ell_L + I_L[v_L(j_\omega + 1) - v_L(j_\omega)] \\ &\qquad - I_o(\theta_{j_\omega}) v_L(j_\omega) - c(\theta_{j_\omega}, \overline{\mathbf{w}}(\psi), j_\omega)\} \Big\} \end{aligned} \tag{12}$$

By investing $\ell_L$ in R&D, with instantaneous probability $I_L = \ell_L \Lambda_L(j_\omega + 1)$, the leader firm will see its optimal value $v_L(j_\omega)$ jump to $v_L(j_\omega + 1)$ thanks to its own new discovery. With instantaneous probability $I_o(\theta_{j_\omega}) = \ell_o \Lambda_o(j_\omega + 1)$ it will be replaced by a successful outsider. In the meantime, the leader firm enjoys its monopolist profits of $\pi_L(j_\omega)$ and pays $\ell_L$ units of labour for new discoveries and $c(\theta_{j_\omega}, \overline{\mathbf{w}}(\psi), j_\omega)$ units of labour for defensive strategies.[14] By equalising the optimal expected return on the leader firm's stock with the return on a riskless investment of the same amount, equation (12) states the usual no-arbitrage condition stemming from an efficient stock market valuation of the leader firm.

The timing of the model is as follows. At the very beginning of the technological

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[14] Equation (12) implicitly says that the current value of being a follower is zero. This is the result of Bertrand competition, free entry and zero R&D *sunk* costs to be paid before playing.

state $j_\omega$, there is a new successful innovator, R&D technologies are symmetric and the parameters of the model apply. Then, decisions are taken in two steps, as equation (12) suggests. First, the leader firm enters the product market, choosing a level of bias $\theta_{j_\omega}$ and starts production. Second, the R&D race starts. Competitors simultaneously decide their optimal level of R&D effort, taking $\theta_{j_\omega}$ as fixed. Once investments are engaged, they remain fixed during the contest. The leader firm does not change its choice of $\theta_{j_\omega}$ so that the same flow cost $c\left(\theta_{j_\omega}, \overline{\mathbf{w}}\left(\psi\right), j_\omega\right)$ is paid per-time interval $dt$. Stage 2 is essentially the Segerstrom and Zolnierek (1999) model for $\beta = 1$, using the authors' notation. A key difference here is that the relative cost advantages are endogenous thanks to stage 1. As usually, we proceed in backward induction.

# 3 Strategic Decisions

## 3.1 The R&D race

The following proposition establishes the conditions under which outsiders are completely deterred. We focus on the case where $\theta_{j_\omega} = \theta$ is constant. We shall discuss later why this should be the case of interest in the long run.

**Proposition 1** *Outsiders will not invest in R&D whenever the leader has a sufficient R&D cost advantage*

$$\frac{\Lambda_L\left(j_\omega + 1\right)}{\Lambda_o\left(j_\omega + 1\right)} = \frac{\bar{b}}{b\left(\theta\right)} > \frac{1}{1 - \gamma^{1-\sigma}} \tag{13}$$

*In this case, the leader's R&D effort can be positive, irrespective of outsiders' actions.* $\theta_p = b^{(-1)}\left(\bar{b}\left[1 - \gamma^{1-\sigma}\right]\right)$ *is then a threshold above which the equilibrium is characterised by a permanent leadership of an innovative monopolist. Below this threshold, the equilibrium features Schumpeterian leapfrogging.*

**Proof.** See Appendix A.1.1.■

The inequality stated in (13) defines a threshold that determines whether a positive R&D outlay is profitable for the leader firm. If this is the case, it can invest in R&D for any outsider threat, that is to say even if outsiders can potentially undertake R&D efforts. The resulting expected value of the next quality improvement is smaller than the R&D cost incurred by outsiders. As a result, outsiders react by expending zero R&D effort, meaning no replacement threat. This case is one of a monopolist expecting a permanent stream of profits. By way of contrast, if $\frac{\bar{b}}{b(\theta)} < \frac{1}{1-\gamma^{1-\sigma}}$, the leader cannot profitably invest in R&D along with outsiders. Innovation in this case relies on the latter and the equilibrium features Schumpeterian leapfrogging with a replacement rate of $I_o(\theta)$. In the particular case where the leader's R&D cost advantage equals the cut-off level, the identity of the innovator is unknown. These predictions are essentially the same result as stated in Theorem 1 of Segerstrom and Zolnierek (1999). A new feature here is that, the leader can, to some extent, conveniently delay its exit.

## 3.2 The strategic technological bias

At this stage, free entry potentially applies, so that the rationale of the decision of bias starts in the context of leapfrogging. In order to simplify the interpretation, define $I_{oL} \equiv I_o\frac{\bar{b}}{b(\theta)} = \ell_o \Lambda_L (j_\omega + 1)$ as the *potential threat of outsiders* - their probability of R&D success if they were to carry out research over the same innovation path as the previous vintage (i.e. if $\theta = 0$). Taking the first-order condition over (12) leads to the equalisation of marginal capital gains and the marginal cost of defensive strategies:

$$-I_{oL} b'(\theta_{j_\omega}) \, v_L(j_\omega)|_{\ell_o>0,\ell_L=0} = \frac{\partial \bar{c}(\theta_{j\omega}, \psi)}{\partial \theta_{j\omega}} \delta(j_\omega) \tag{14}$$

where right-hand side is positive since $b'(\theta_{j_\omega}) < 0$ and represents the marginal reduction of the expected capital loss in case of leapfrogging. The trade-offs are as follows. Higher-quality goods imply a greater incentive to adopt defensive strategies because they imply higher values. However, they are also more costly to bias. These effects will offset each other. Moreover, under free entry, the value obtained in quality-state $j_\omega$ must pay for the investment deployed to overcome the strategic entry barriers in the $j_\omega - 1$ R&D race, that which the current leader has won. Equation (14) then implies a dynamic relationship between $\theta_{j_\omega}$ to $\theta_{j_\omega - 1}$. The convergence of this dynamic process is ensured by the technology of bias discussed above (Lemma 1). Since the marginal quality-adjusted cost of bias is increasing, the optimal choice of $\theta_{j_\omega}$ is not unbounded. It then follows that the past technological bias is decreasingly transmitted to the current choice; we can therefore focus on the long-run relationship where $\theta_{j_\omega} = \theta$.

**Lemma 2** *Denote* $\xi_{x,y} \equiv \frac{\partial y}{\partial x}\frac{x}{y}$ *the point elasticity of a function* $y$ *with respect to (one of) its argument(s)* $x$. *The strategic technological bias set by the leader in the leapfrogging equilibrium is implicitly given by*

$$\bar{c}(\theta,\psi) = \frac{I_{oL}\,\eta(\theta,\psi)}{\bar{b}h(\psi)} \qquad \textit{with} \;\; \eta(\theta,\psi) \equiv \frac{-\xi_{\theta,b}}{\xi_{\theta,\bar{c}}} > 0 \tag{15}$$

*where* $\xi_{\theta,\bar{c}} = \xi_{\theta,\bar{c}}(\theta,\psi) > 1$, $\frac{\partial \xi_{\theta,\bar{c}}}{\partial \psi} > 0$ , $\xi_{\theta,b} = \xi_{\theta,b}(\theta) < 0$ , $\frac{\partial \eta(\theta,\psi)}{\partial \psi} < 0$. *Moreover, the appropriate second-order condition holds whenever* $\xi_{\theta b'} < \xi_{\theta \bar{c}'_1}$, *where* $\bar{c}'_1 \equiv \frac{\partial \bar{c}(\theta,\psi)}{\partial \theta}$.

Equation (15) determines an implicit relationship between the level of bias and PMR, $\theta(\psi)$, which maximises the leader's value under leapfrogging. Here, the optimal investment in the defensive strategy is larger the greater is the potential threat of outsiders, $I_{oL}$, the lower is the leader's R&D productivity net of quality difficulties, $\bar{b}h(\psi)$, and the larger is the ratio of $\theta-$ elasticities, denoted by $\eta(\theta,\psi)$. The latter can be seen as an indicator of the marginal technological incentive to invest defensively: it measures the sensitivity of outsiders' R&D productivity to the technological bias relative to that of the quality-adjusted cost of bias. We shall refer to this as the *marginal defensive incentive.* We are now able to set out the key properties of this decision.

**Proposition 2** *PMR limits defensive behaviour in the leapfrogging equilibrium (i.e.* $\theta'(\psi) < 0$*) when*

$$\xi_{\psi,\bar{c}} - \xi_{\psi,\eta} > -\xi_{\psi,h} \tag{16}$$

$$\xi_{\theta,\eta} < \xi_{\theta,\bar{c}} \tag{17}$$

*In this case, there exists an optimal level of bias given by* $\theta^* = \min\left\{\theta\left(\psi\right), \theta_p^+\right\}$ *with* $\theta_p^+$ *infinitesimally greater than* $\theta_p$*. This solution is unique if* $\eta\left(\theta, \psi\right)$ *is either independent of or monotone in* $\theta$*.*

**Proof.** See Appendix A.1.3.■

The first part of Proposition 2 formally describes the conditions under which regulation can effectively constrain the defensive strategy. This follows from the implicit differentiation of (15). Condition (16) deals with the first-order effects of regulation, $\psi$. It specifies how responsive should be the quality-adjusted costs of upgrading the extensive margin of quality to variations of PMR, i.e. how great $\xi_{\psi,\bar{c}}$ should be. Namely, such a responsiveness is specified relative to the one regarding the efficiency in the upgrading of the intensive margin, i.e. relative to $-\xi_{\psi,h}$. We shall discuss a bit more on this requirement once the full set of predictions has been presented.

The second condition, (17), covers the first- and second-order effects of the defensive strategy, $\theta$: this states that the quality-adjusted bias cost must be more sensitive to variations in $\theta$ than the marginal technological incentives to induce such a bias. The latter are measured by $\eta\left(\theta, \psi\right)$ which, as far as Proposition 2 is concerned, can be independent of (e.g. a constant elasticity function), decreasing or increasing in $\theta$.

The fact that $\theta'\left(\psi\right) < 0$ implies that for some low-enough level of PMR the leader firm can set a level of bias slightly above the threshold $\theta_p$. In this case, the threat of leapfrogging disappears and R&D becomes profitable for the leader. Any further rise in $\theta$ will only involve greater costs without changing the perceived value of an innovative leader. The equilibrium level of bias will thus be no larger than the minimum required to become the sole innovator. This is what is stated in the second part of Proposition 2.

Figure 3 depicts the determinants of the choice of $\theta$. In the graph, the right-hand side of (15) is increasing in $\theta$. For reasons that will shortly become clear, the figure illustrates the case where $\xi_{\theta,\eta} > 0$, so that the left-hand side is also increasing in $\theta$.[15] The intersection of the curves gives $\theta\left(\psi\right)$. A rise in $\psi$ clearly shifts $\bar{c}\left(\theta, \psi\right)$ upwards. The consequent change

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[15] Its concave shape is also an arbitrary illustration. What is important at this stage is that both curves intersect each other once.

in the LHS of (15) is ambiguous. This comes from conflicting forces as $\frac{\partial\eta(\theta,\psi)}{\partial\psi} < 0$ (the downward force) but $h'(\psi) < 0$ (the upward force). Even were the latter force to become stronger as $\psi$ increases, conditions (17) and (16) ensure that the upward shift in $\overline{c}(\theta,\psi)$ is large enough to move the intersection point to the left, implying a fall in $\theta(\psi)$. Conversely, lower PMR produces a stronger technological bias. A sufficiently-low level of PMR, say $\overline{\psi}$, will allow the leader to change the quality direction by an angle infinitesimally greater than $\theta_p$, which makes the next R&D race unprofitable for challengers. Therefore, the level of regulation is crucial in determining the type of equilibrium. The following corollary summarises our findings.

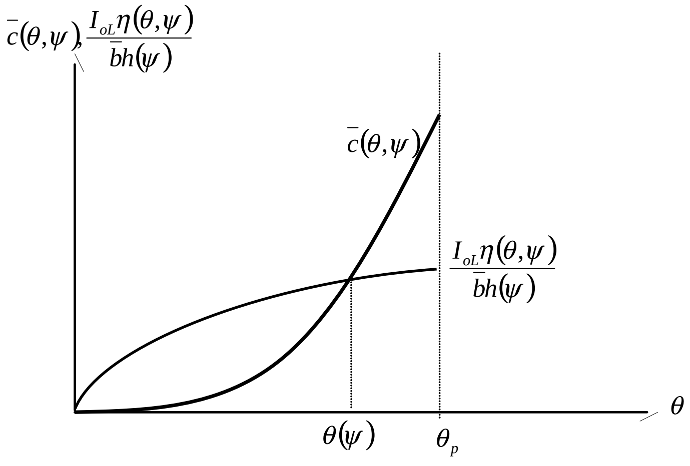

Figure 3. Optimal defensive strategy

**Corollary** *Under conditions (17) and (16), and with $\eta(\theta,\psi)$ independent of or monotone in $\theta$, there exists a unique level of PMR, denoted by $\overline{\psi}$, defining the threshold between an equilibrium with a permanent innovative leader and an equilibrium featuring Schumpeterian leapfrogging.*

**Proof.** This follows immediately from Propositions 1 and 2.■

We need now to consider the decisions described above at the macro level. In order to analyse the impact of PMR on aggregate R&D, we shall deal with marginal increases of PMR within the boundaries of each type of equilibrium separately.[16]

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[16] We do not treat the knife-edge case where the leader technology advantage is exactly at the threshold expressed in (13), so that both types of agents can be active in R&D. Neither we treat the theoretical

# 4 Global accounting and steady-state predictions

## 4.1 Schumpeterian leapfrogging

The macro equilibrium is defined by two unknowns ($E$ and $\frac{Q}{L}$) and two relationships: labour-market clearing and free entry in the research sector. Labour demand comes from research $L_r = \int_0^1 \ell_o (j_\omega + 1)\, d\omega = \frac{I_o \gamma^{\sigma-1}}{h(\psi) b(\theta(\psi))} Q$, manufacturing $L_y = \int_0^1 L\ d(j_\omega)\, d\omega = L\frac{E}{p}$ and defensive activities $L_f = \int_0^1 \overline{c}(\theta(\psi), \psi)\, \delta(j_\omega)\ \ d\omega = \overline{c}(\theta(\psi), \psi)\, Q$. We focus on the symmetric steady-state equilibrium where expenditure $E$ and outsiders' innovative potential $I_{oL}$ (and so $I_o$) are constant. Full employment requires that $L = L_y + L_r + L_f$:

$$1 = \frac{E}{p} + \frac{I_o \gamma^{\sigma-1}}{h(\psi)\, b(\theta(\psi))} \frac{Q}{L} + \overline{c}(\theta(\psi), \psi) \frac{Q}{L} \tag{18}$$

Substitution of the leader's value in the free-entry condition yields a macroeconomic relationship between the interest rate and expenditure (see the proof of Proposition 1). As we focus on constant expenditure, we use $r = \rho$ from (3) to write this second equilibrium condition.

$$E = \frac{Q}{L} \frac{p}{p-1} \left[ \frac{\rho + I_o}{h(\psi)\, b(\theta(\psi))} + \overline{c}(\theta(\psi), \psi) \right] \tag{19}$$

Clearly, in a steady-state equilibrium in which $I_{oL}$ and $E$ are constant, $\frac{Q}{L}$ is as well. Population and average quality must hence grow at the same rate of $\frac{\dot{Q}}{Q} = \frac{\dot{L}}{L} = n$. Using this result and substituting demands (2) into instantaneous utility (1), taking logs and differencing produces the usual steady-state utility growth $\frac{\dot{u}(t)}{u(t)} = \frac{n}{\sigma - 1}$ which is free of scale effects.

The change in average quality is computed by summing the expected technological jump over all industries $\dot{Q} = \int_0^1 I_o [\delta(j_\omega + 1) - \delta(j_\omega)]\, d\omega$, so that $\frac{\dot{Q}}{Q} = I_o [\gamma^{\sigma-1} - 1]$. Since population and average quality grow at the same rate, the innovation rate in equilibrium is

$$I_o = \frac{n}{[\gamma^{\sigma-1} - 1]} \tag{20}$$

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possibility of discrete changes crossing the crucial threshold level. In any case the variation of PMR will switch from one type of equilibrium to the other, fully described here.

We can now analyse aggregate R&D intensity as the share of total R&D investment over value added, $RDI_l \equiv \frac{L_r}{pL_y}$, which is a measure similar to that discussed in the empirical evidence in the introduction.[17] Using the steady-state innovation rate, the definition of $I_{oL}$, equations (15) and (19), and the expressions above for $L_r$ and $L_y$ gives

$$RDI_l = \frac{\gamma^{\sigma-1}\left[p-1\right]}{p\left\{1+\left[\gamma^{\sigma-1}-1\right]\frac{\rho}{n}+\eta\left(\theta\left(\psi\right),\psi\right)\right\}} \tag{21}$$

**Proposition 3** *PMR has a positive impact on R&D intensity if it reduces the marginal defensive incentive in equilibrium (i.e. if* $\frac{d\eta(\theta(\psi),\psi)}{d\psi}<0$*), which is if*

$$-\xi_{\theta,\eta} < \frac{\xi_{\psi,\eta}}{\xi_{\psi,\theta(\psi)}} \tag{22}$$

*This positive impact of PMR on R&D intensity rises with innovation size* $\gamma$*, if the marginal defensive incentives are strong enough in equilibrium,*

$$\eta\left(\theta\left(\psi\right),\psi\right) > \overline{\eta} \equiv \left[1+\gamma^{\sigma-1}\right]\frac{\rho}{n}-1 \tag{23}$$

**Proof.** See Appendix A.1.4.■

The effects of PMR on R&D intensity are channeled via the marginal defensive incentive, which in the leapfrogging equilibrium is evaluated at the optimal level of bias $\theta^* = \theta\left(\psi\right)$. From (21), a positive impact of PMR on R&D intensity arises when $\eta\left(\theta\left(\psi\right),\psi\right)$ falls with $\psi$. Formally, $\frac{d\eta(\theta(\psi),\psi)}{d\psi} = \frac{\partial\eta(\theta,\psi)}{\partial\theta}\theta'\left(\psi\right)+\frac{\partial\eta(\theta,\psi)}{\partial\psi}$. The first term relates to what can be called an *indirect* effect arising from the appraisal of PMR in the optimal choice of $\theta$. Under (16) and (17), $\theta'\left(\psi\right)<0$, hence the sign of this effect depends crucially on the sign of $\frac{\partial\eta(\theta,\psi)}{\partial\theta}$. The second term can be seen as a *direct* effect of PMR on the marginal defensive incentive as it relates to the extent to which PMR increases the marginal costs of upgrading the extensive margin of quality. By Lemma 2, this second effect is unambiguously negative. It follows that, if the marginal defensive incentive is

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[17] The results are similar if we consider the labour share allocated to R&D.

non-decreasing in $\theta$, i.e. $\frac{\partial\eta(\theta,\psi)}{\partial\theta} \geq 0$, PMR positively affects R&D intensity, no matter the size of the direct effect of PMR. On the other hand, if the marginal defensive incentive is decreasing in $\theta$ a positive impact of PMR can still result if the direct effect of PMR is sufficiently large relative to the indirect effect. This is what (22) summarises in terms of point elasticities.

A non-decreasing marginal defensive incentive in $\theta$ implies $\xi_{\theta,\eta} \geq 0$ a set that should be intersected with the one verifying $\xi_{\theta,\eta} < \xi_{\theta,\bar{c}}$, stated by (17) in Proposition 2. Given increasing quality-adjusted marginal cost of bias (or at least non-decreasing), this intersection, i.e. $0 \leq \xi_{\theta,\eta} < \xi_{\theta,\bar{c}}$, is likely to hold for $b''(\theta) \leq 0$, i.e. for non-decreasing *difficulty* resulting from further departures from the current quality mix. So that a number of functional forms respecting mild assumptions on the quality-adjusted cost function are then consistent with this sufficient (though not necessary) condition, namely constant-elasticity functions.[18]

Proposition 3 also highlights the potential complementarity between PMR and innovation size. Larger innovations increase R&D difficulties, but at the same time provide a longer monopolist life if the R&D is successful. The latter Schumpeterian effect is strengthened by the incentive to behave defensively. Condition (23) is more likely to hold when population growth is high relative to (though no greater than) the preference for the present or when the goods offered by different industries are only weak substitutes.

So far we have considered Nash-Cournot equilibria for leaders and followers. Different assumptions regarding the timing of the R&D race lead to different conclusions for the identity of the innovator when R&D advantages are small. For instance, as shown by Barro & Sala-i-Martin (2004, Ch. 7), the assumption of a first-mover advantage for the leader with irreversible R&D decisions yields a preemptive equilibrium in which the leader is the sole innovator and the probability of innovation is given by the free-entry condition.[19] The intuition here is that the leader firm will not consider its cannibalisation

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[18] In an online appendix we provide more details on this remark.

[19] In R&D races with Stackelberg leaders, the expected duration of R&D races is completely determined by R&D effort, not by timing advantages. Hence, leaders and followers invest simultaneously. The implicit assumption of a fixed R&D decision is then key in the argument of Barro and Sala-i-Martin (2004). Otherwhise the leader might not be credible in its R&D commitment. For instance, if outsiders are indeed

as it recognises that any R&D investment opportunity left open will be exploited by a potential entrant, so that its R&D effort will not change the innovation rate. However, the leader firm may seek to reduce the R&D effort of outsiders as much as possible by increasing its own. If its R&D advantage is not so large the leader will not go beyond the point at which outsiders are just deterred from entry.

In this equilibrium, outsiders, via the free-entry condition, continue to determine the potential for innovation. Hence, free entry still pins down the steady state equilibrium, namely the relationship between expenditure and the interest rate. The noteworthy conclusion is that Proposition 3 continues to hold. Regarding aggregate R&D intensity, as the leader is not subject to any strategic technological bias in R&D, the effect of bias in expenditure will not cancel with the one in R&D investment. R&D intensity in both types of setting can then be related in the following way

$$RDI_l|_{Stackelberg} = RDI_l|_{Nash} \frac{b\left(\theta\left(\psi\right)\right)}{\bar{b}}$$

Since $b'\left(\theta\right) < 0$ and $\theta'\left(\psi\right) < 0$ it follows that $\frac{db(\theta(\psi))}{d(\psi)} = b'\left(\theta\right)\theta'\left(\psi\right) > 0$, so that the positive impact of PMR on R&D intensity in this equilibrium also holds in a Stackelberg game and is proportionally stronger.

## 4.2 The permanent monopolist equilibrium

In the permanent monopolist case, where the leader carries out innovation of $I_L$, labour-market clearing and a positive finite R&D outlay imply respectively that

$$1 = \frac{E}{p} + \frac{I_L \gamma^{\sigma-1}}{h\left(\psi\right)}\frac{Q}{L} + \bar{c}\left(\theta_p^+, \psi\right)\frac{Q}{L} \qquad E = \frac{p}{p-1}\frac{Q}{L}\left[\frac{r}{\left[1-\gamma^{1-\sigma}\right]h\left(\psi\right)\bar{b}} + \bar{c}\left(\theta_p^+, \psi\right)\right] \quad (24)$$

where the defensive investment is evaluated at $\theta^* = \theta_p^+$, which no longer depends on $\psi$. Despite the absence of free entry, there exists a relationship between expenditure and the

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absent from the R&D race, the leader's investment is not optimal for a small R&D advantage. Segerstrom and Zolnierek (1999) make a similar remark. In previous working paper versions we assumed first-mover advantage and took credibility issues into account. Consequently we interpreted the equilibrium with a small R&D advantage in a similar fashion to that presented here.

interest rate (see the proof of Proposition 1). The leader actually chooses to "enter" the R&D race when the potential value to be gained equals the R&D investment plus the destruction of the current value.

The same steady-state properties as before apply in this equilibrium, so that the observed innovation rate is $I_L = \frac{n}{\gamma^{\sigma-1}-1}$.[20] We can then analyse the steady-state R&D intensity in the permanent monopolist equilibrium:

$$RDI_p = \frac{n\left[p-1\right]}{p\left\{\rho + \left[1-\gamma^{1-\sigma}\right]\bar{b}h\left(\psi\right)\bar{c}\left(\theta_p^{+},\psi\right)\right\}} \tag{25}$$

**Proposition 4** *PMR reduces R&D intensity in the permanent monopolist equilibrium whenever*

$$\xi_{\psi,\bar{c}} > -\xi_{\psi,h} \tag{26}$$

**Proof.** See Appendix A.1.5.■

As regulation increases, but not by enough to ensure continuous monopolistic replacement, resources that could potentially be employed in R&D are allocated to defensive activities: R&D thus falls. Condition (26) implies $\xi_{\psi,\bar{c}} - \xi_{\psi,\eta} > -\xi_{\psi,h}$ stated in condition (16) since $\xi_{\psi,\eta} < 0$. Proposition 4 is then consistent with Proposition 2.

## 4.3 Fitting the evidence

In summary, the model suggests an explanation for the contrasted empirical patterns motivating the paper in the following context:

1. The *technology of bias* features decreasing returns to scale.
2. Either the *marginal defensive incentive* is non-decreasing in the level of bias, although more than compensated by marginal cost, or, there is a strong enough impact of PMR on the quality-adjusted cost of upgrading the *extensive margin* of quality.[21]

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[20] This similarity in innovation rates comes from the semi-endogenous growth dynamic structure of the model. It follows that R&D efforts in each type of equilibrium are different.

[21] This potentially allows for CRS in the technology of bias.

3. The *marginal defensive incentive* is large enough in equilibrium.

4. The first-order effects of PMR on the quality-adjusted cost of upgrading the *extensive margin* of quality are greater than the first-order effects of PMR affecting efficiency in upgrades of the *intensive margin.*

These statements follow directly from the conditions stated in Lemma 1, Propositions 2-4 and the second-order optimality requirements. For the reasons discussed above, these statements leave enough room for a number of different functional forms. They suggest industries where technological vertical innovation is characterised by a certain form of path dependency, in which the costs of departing from current standards are technologically and/or institutionally important.

Statement 4 is crucial as it identifies the type of regulation which can reduce the strategic acquisition of a technology advantage by leaders and at the same time be detrimental for R&D effort in an equilibrium with a permanent leadership of an innovative monopolist; cf. conditions (16) and (26). The model does take into account the usual view that PMR increases innovation costs. It suggests, however, that after all, when innovation relies on followers, PMR can yield incentives to innovate by reducing their technology disadvantages, which is the case when the sensitivity of innovation costs to PMR is larger for the extensive margin of quality. This restriction is actually general enough to encompass a number of regulatory practices which might have immediate negative effects on R&D activities. PMR which purposely seeks technological standardisation and facilitates knowledge accumulation and diffusion is likely to be consistent with our model. However, the key insight is that even the costs induced by *some* provisions which are usually seen as inducing lack of dynamism or administrative burdens can, in practice, play a similar role if they are less constraining when innovative firms retain the mix of features already offered by their good than when they significantly change them. It is in this sense that the model offers an explanation of the controversial empirical patterns depicted in Figure 1. The indicators used actually measure the impact of administrative restrictions in upstream sectors that induce rigidities in downstream business operations. Their effects are thus captured by the micro setup of the technology of bias, where upgrades in the quality mix involve investments in specific upstream inputs.

Private knowledge is also important for our results. It implies that the cost of upgrading the extensive margin is borne by leaders only, whereas that of the intensive margin is borne by both player types. The negative effects of PMR on efficiency in upgrades of the intensive margin are, after all, not crucial if what matters for preemption is relative R&D efficiency. Knowledge asymmetries thus entail a heterogeneous effect of PMR in reducing the advantage of leaders. The overall effect on R&D intensity, however, depends on who innovates.[22] If the leader is the innovator, PMR will consume resources that could be allocated to research; if the followers innovate, PMR will reduce their technology disadvantage and imply a greater incentive to undertake R&D investment.

# 5 Conclusion

This paper has considered the consequences of defensive strategies on R&D effort and market structure in a simple quality-ladder model. Among the multiplicity of leaders' available strategies, defensive behaviour may increase the challengers' R&D cost beyond the pure technology dynamics. Institutions which constrain this set of strategies and reduce the resulting deterrent effects may increase the resources devoted to innovation. This effect is however likely to be observed only above a certain threshold level of regulation, and may be stronger when technology jumps are larger. All of these features are consistent with a number of patterns in data on R&D expenditure in OECD industries. Further research should provide deeper empirical scrutiny of the model's mechanisms, particularly by turning to data on firm demographics.

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[22] More precisely, it depends on who determines the potential for innovation (see the discussion of Proposition 3).

# A Appendix

## A.1 Proofs

### A.1.1 Proof of Proposition 1

Equation (12) shows that the leader has an incentive to carry out R&D when

$$\Lambda_L\left(j_\omega+1\right)\left[v_L\left(j_\omega+1\right)-v_L\left(j_\omega\right)\right]>1 \tag{27}$$

When free entry applies, so that outsiders can potentially invest in R&D , $v_L\left(j_\omega+1\right)=\frac{1}{\Lambda_o\left(j_\omega+1\right)}$. Likewise, $v_L\left(j_\omega\right)=\frac{1}{\Lambda_o\left(j_\omega\right)}=\frac{\gamma^{1-\sigma}}{\Lambda_o\left(j_\omega+1\right)}$. We work here with the stable value of $\theta_{j_\omega}=\theta$. Substituting these into inequality (27) yields $\frac{\bar{b}}{b(\theta)}>\frac{1}{1-\gamma^{1-\sigma}}$.

Under this condition, the participation of the leader in R&D activities occurs no matter what level of R&D effort can be potentially deployed by outsiders. A positive R&D outlay of the leader is indeed sufficient for zero R&D effort of outsiders. In order to show this, we analyse the resulting leader's value *allowing* $I_o\left(\theta\right)$ to be potentially positive. In equilibrium $I_o\left(\theta\right)$ will actually turn out to be zero as the free-entry condition will no longer hold. From (12), it follows that a positive finite R&D effort of the leader only results when $-\ell_L+\ell_L\Lambda_L\left(j_\omega+1\right)\left[v_L\left(j_\omega+1\right)-v_L\left(j_\omega\right)\right]=0$, so that

$$v_L\left(j_\omega+1\right)-v_L\left(j_\omega\right)=\frac{1}{\Lambda_L\left(j_\omega+1\right)} \tag{28}$$

This result combined with (12) and the quality-adjusted profit and cost from equations (5) and (10) yields

$$v_L\left(j_\omega\right)=\frac{\left[\overline{\pi}-\overline{c}\left(\theta,\psi\right)\right]\delta\left(j_\omega\right)}{r+I_o\left(\theta\right)} \tag{29}$$

In order for finite R&D to pertain, the interest rate in this equilibrium must satisfy (28). Using (29) we get

$$r=\left[\overline{\pi}-\overline{c}\left(\theta,\psi\right)\right]\left[1-\gamma^{1-\sigma}\right]h\left(\psi\right)\bar{b}-I_o\left(\theta\right) \tag{30}$$

On the other hand, outsiders will not undertake research if the value of becoming an innovative leader does not cover the investment:

$$v_L\left(j_\omega+1\right) < \frac{1}{\Lambda_o\left(j_\omega+1\right)} \tag{31}$$

which can be rewritten using (30) and (29) for $j_\omega+1$, leading to $\frac{1}{1-\gamma^{1-\sigma}} < \frac{\bar{b}}{b(\theta)}$. Thus, if the leader firm is able to overcome the loss stemming from cannibalisation, outsiders will not carry out R&D. Therefore, we have $I_o\left(\theta\right)=0$, so that the value perceived by the leader becomes $v_L\left(j_\omega\right)|_{\ell_o=0,\ell_L>0} = \frac{[\overline{\pi}-\overline{c}(\theta,\psi)]\delta(j_\omega)}{r}$. The resulting equilibrium interest rate should verify here

$$r_p = \left[\overline{\pi}-\overline{c}\left(\theta,\psi\right)\right]\left[1-\gamma^{1-\sigma}\right]h\left(\psi\right)\bar{b} \tag{32}$$

where $p$ stands for permanent leadership equilibrium.[23]

If $\frac{\bar{b}}{b(\theta)} < \frac{1}{1-\gamma^{1-\sigma}}$ we have $\ell_L=0$. From equation (12) the leader value under leapfrogging is then $v_L\left(j_\omega\right)|_{\ell_o>0,\ell_L=0} = \frac{[\overline{\pi}-\overline{c}(\theta,\psi)]\delta(j_\omega)}{r+I_o(\theta)}$. In this case the free-entry condition (11) ensures a positive finite R&D outlay and gives the equivalent of (32) in this equilibrium

$$r_l = \left[\overline{\pi}-\overline{c}\left(\theta,\psi\right)\right]h\left(\psi\right)b\left(\theta\right)-I_o\left(\theta\right) \tag{33}$$

where $l$ stands for leapfrogging.

### A.1.2 Proof of Lemma 2

Consider free entry (11) evaluated for $j_\omega$ in order to substitute for $v_L\left(j_\omega\right)|_{\ell_o>0,\ell_L=0}$ in (14) and multiply both sides by $\frac{\theta}{\overline{c}(\theta,\psi)}$. This leads to (15). The sign of elasticities follows immediately from the cost function (Lemma 1) and outsiders' R&D technology.

Appropriate second order condition (SOC) implies $-\frac{I_{0L}}{h(\psi)b(\theta)}\frac{1}{\bar{b}}b''\left(\theta\right) < \frac{\partial^2\overline{c}(\theta,\psi)}{\partial\theta^2}$. Using (15), this can be rewritten as $-\frac{\overline{c}(\theta,\psi)}{\eta(\theta,\psi)}\frac{b''(\theta)}{b(\theta)} < \frac{\partial^2\overline{c}(\theta,\psi)}{\partial\theta^2}$, which after developing $\eta\left(\theta,\psi\right)$ leads to $\xi_{\theta,b'} < \xi_{\theta,\overline{c}_1'}$. Hence the latter implies, at least locally, the SOC.

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[23] In order to simplify notation, it is implicitly understood that $\psi$ and $\theta$ are not the same in each type of equilibrium.

### A.1.3 Proof of Proposition 2

Differentiation of (15) with respect to $\psi$ considering the implicit relationship $\theta(\psi)$ leads to

$$\theta^{'}(\psi) = \frac{I_{0L}\eta(\theta,\psi)\,h'(\psi) + \bar{b}h(\psi)^2 \frac{\partial \bar{c}(\theta,\psi)}{\partial \psi} - I_{0L}h(\psi)\frac{\partial \eta(\theta,\psi)}{\partial \psi}}{-\bar{b}h(\psi)^2 \frac{\partial \bar{c}(\theta,\psi)}{\partial \theta} + I_{0L}h(\psi)\frac{\partial \eta(\theta,\psi)}{\partial \theta}} \tag{34}$$

Condition (16) ensures a positive numerator. Multiplying the whole expression by $\frac{\psi}{I_{0L}\eta(\theta,\psi)h(\psi)} > 0$ and using (15), we have

$$\frac{h'(\psi)\,\psi}{h(\psi)} + \frac{\bar{b}h(\psi)\,\psi}{I_0\eta(\theta,\psi)}\frac{\partial \bar{c}(\theta,\psi)}{\partial \psi} - \frac{\psi}{\eta(\theta,\psi)}\frac{\partial \eta(\theta,\psi)}{\partial \psi} > 0 \Leftrightarrow \xi_{\psi,\bar{c}} - \xi_{\psi,\eta} > -\xi_{\psi,h}$$

Similarly, condition (17) implies a negative denominator. Using (15), we observe that a negative denominator needs to verify

$$\frac{\partial \eta(\theta,\psi)}{\partial \theta} < \frac{\eta(\theta,\psi)}{\bar{c}(\theta,\psi)}\frac{\partial \bar{c}(\theta,\psi)}{\partial \theta} \Leftrightarrow \xi_{\theta,\eta} < \xi_{\theta,\bar{c}}$$

Hence, with (16) and (17) $\theta^{'}(\psi) < 0$.

### A.1.4 Proof of Proposition 3

**The impact of PMR on R&D intensity under leapfrogging** Partial derivative of R&D intensity with respect to PMR gives

$$\begin{aligned}\frac{\partial RDI_l(\psi)}{\partial \psi} &= -\frac{[p-1]\,\gamma^{\sigma-1}\frac{d\eta(\theta(\psi),\psi)}{d\psi}}{p\left[\frac{[\gamma^{\sigma-1}-1]}{n}\rho + 1 + \eta(\theta(\psi),\psi)\right]^2} > 0 \Longleftrightarrow \frac{d\eta(\theta(\psi),\psi)}{d\psi} < 0 \\ &\Longleftrightarrow \frac{\partial \eta(\theta,\psi)}{\partial \theta}\theta^{'}(\psi) + \frac{\partial \eta(\theta,\psi)}{\partial \psi} < 0 \Longleftrightarrow -\xi_{\theta,\eta} < \frac{\xi_{\psi,\eta}}{\xi_{\psi,\theta(\psi)}}\end{aligned}$$

So that $\frac{d\eta(\theta(\psi),\psi)}{d\psi} < 0$ is ensured by (22). The last equivalence comes after multiplying the previous inequality by $\frac{\psi}{\eta(\theta,\psi)} > 0$ and its first term by $\frac{\theta}{\theta} = 1$ (recall that $\theta^{'}(\psi) < 0$ by Proposition 2).

**Complementarity between the size of innovation and PMR** Cross-partial derivative of R&D intensity with respect to PMR and innovation size yields

$$\frac{\partial^2 RDI_l}{\partial\gamma\partial\psi}=\frac{n^2\left[p-1\right]\gamma^{\sigma+1}\left[\sigma-1\right]\Omega\frac{d\eta(\theta(\psi),\psi)}{d\psi}}{p\left[\gamma^\sigma\rho+\gamma\left[n\left[1+\eta\left(\theta\left(\psi\right),\psi\right)\right]-\rho\right]\right]^3}$$

where $\Omega\equiv\left[1+\gamma^{\sigma-1}\right]\rho-n\left[1+\eta\left(\theta\left(\psi\right),\psi\right)\right]$. The denominator is positive as $\sigma>1$. Moreover, under (22) $\frac{d\eta(\theta(\psi),\psi)}{d\psi}<0$. Hence, $\frac{\partial^2 RDI_l(\gamma,\psi)}{\partial\gamma\partial\psi}>0$ when $\Omega<0$, which is the case whenever $\eta\left(\theta\left(\psi\right),\psi\right)$ is sufficiently high

$$\Omega<0\Longleftrightarrow\frac{\rho}{n}\left[1+\gamma^{\sigma-1}\right]-1<\eta\left(\theta\left(\psi\right),\psi\right)$$

### A.1.5 Proof of Proposition 4

The partial derivative of $RDI_P$ is

$$\frac{\partial RDI_P}{\partial\psi}=-\frac{\bar{b}\,n\left[p-1\right]\left[\bar{c}\left(\theta_p^+,\psi\right)h'\left(\psi\right)+h\left(\psi\right)\frac{\partial\bar{c}\left(\theta_p^+,\psi\right)}{\partial\psi}\right]}{p\left[1-\gamma^{1-\sigma}+\rho+\bar{b}\bar{c}\left(\theta_p^+,\psi\right)h\left(\psi\right)\right]^2}$$

The sign of this expression depends crucially on the sign of the right-hand bracket in the numerator, which is positive if $\xi_{\psi,\bar{c}}>-\xi_{\psi,h}$ . In this case $\frac{\partial RDI_P}{\partial\psi}<0$.

## A.2 Data

### A.2.1 Variables and data sources

The data set used for the empirical motivation contains information for 14 manufacturing industries in 14 OECD countries over the 1987-2003 period. Appendix A.2.2 presents a summary of the sample. The R&D series come from the OECD's Analytical Business Enterprise Research and Development (ANBERD) dataset (Vol. 2006 release 01). The sample period is mainly limited by R&D data availability. *R&D intensity* is measured as the ratio of business R&D expenditure to value added. Value added series were obtained from the 60-Industry database of the Groningen Growth and Development Centre

(GGDC), which fills missing values in OECD STAN from alternative sources and checks for consistency with national accounts.[24]

We use the regulation impact indicator (*REGIMP*) computed by the OECD (see Conway and Nicoletti, 2006).[25] For each industry, country and time period, this captures the "knock-on" effects associated with regulation in key input sectors: (i) network sectors supplying energy, transport and communication (post, telecoms, electricity, gas, airlines, rail and road); (ii) retail distribution and professional business services; and (iii) finance. Information on regulatory practices in these sectors are collected for relevant areas of regulation. This indicator is coded from 0 to 6 in ascending order of restrictiveness or anti-competitiveness. This coding is the base to compute what the OECD calls low-level indicators. To construct aggregate indicators for each sector, a bottom-up approach is implemented using weights reflecting information availability and the nested structure of the areas included in the aggregate indicator. The information on regulation in networks is the most comprehensive in terms of periods (1975-2003) and provides scores for areas such as entry regulation, public ownership, vertical integration and market structure. Information on regulation in retail and business services (price control and constraints on business operations) is available for 1998 and 2003.[26] Regulation in the financial sector comes from De Serres et al. (2006), who provide information on regulatory practices in the banking system and financial instruments over the 2002-2003 period. Indicators of regulation in all of these input sectors are then associated to each industry, country and year by the means of a weighted sum, where the weight coefficients are derived from harmonised input/output matrices describing the use of these sectors as intermediate inputs.

REGIMP is then available in the form of time series by country and industry, and hence exhibits time-series cross-section (TSCS) variability compatible with our R&D-intensity variable. As regulation in upstream sectors certainly has consequences for downstream

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[24] http://www.ggdc.net/databases/60_industry.htm. GGDC series on value-added have been filtered. OECD STAN's value added information has been kept for outliers (in terms of labour productivity), which mostly belong to industry 30 (office machinery).

[25] http://www.oecd.org/eco/pmr.

[26] Recent data upgrades also provide information for 2008, but this is not used in our dataset.

operations, this indicator turns out to be a good proxy for the restrictions induced by PMR. Conway and Nicoletti (2006) report that in the late 1990s roughly 80% of the output of business services was used as an intermediate input in other sectors of the economy, and that finance, electricity, post and telecommunication sectors accounted for between 50%-70% of the intermediate inputs in the production processes.

Two other controls are used in the tests presented in Table 1. For each country, industry and period *R&D externalities* are proxied by the R&D intensity in the same industry in other countries. This variable is thus also available in TSCS data format. This helps to take into account knowledge externalities as well as potential strategic complementarities in R&D investments at the international level. The second control is the indicator of intellectual property right protection proposed by Ginarte and Park (1997) and updated by Park (2008). This captures the degree of intellectual property right (*IPR*) protection in 122 countries for 1960-2005, at five-year intervals. It consists of five categories measuring the scope of IPR protection, participation in international agreements related to IPR, duration of protection, enforcement mechanisms and restrictions on patent rights. The main drawback here is the availability over time. Given the clear upward trend, close to linear in most series, we apply an interpolation in order to increase data availability.

Finally we also use GGDC information on the *average age of firms*. GGDC constructs these market-structure indicators by aggregating information from company accounts using the AMADEUS database. The data relies on information from roughly 120,000 companies in the EU-25. Countries that are present in our sample are those with the best coverage. Information is only available from 1997 onwards.

### A.2.2 Sample summary

**List of countries:** Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Japan, the Netherlands, Norway, Spain, Sweden, the UK, and the US.

**List of industries (ISIC Rev 3 Code):** (15-16) Food products, beverages and tobacco; (17-19) Textiles, wearing apparel and leathers; (20) Wood and products of wood and cork; (21-22) Pulp, paper, paper products, printing and publishing; (24) Chemicals and chemical products; (25) Rubber and plastic products; (26) Other non-metallic mineral products; (28) Fabricated metal products, except machinery and equipment; (29) Machinery and equipment, nec; (30) Office, accounting and computing machinery; (31) Electrical machinery and apparatus, nec; (32) Radio, television and communication equipment; (33) Medical, precision and optical instruments, watches and clocks; (34) Motor vehicles, trailers and semi-trailers.

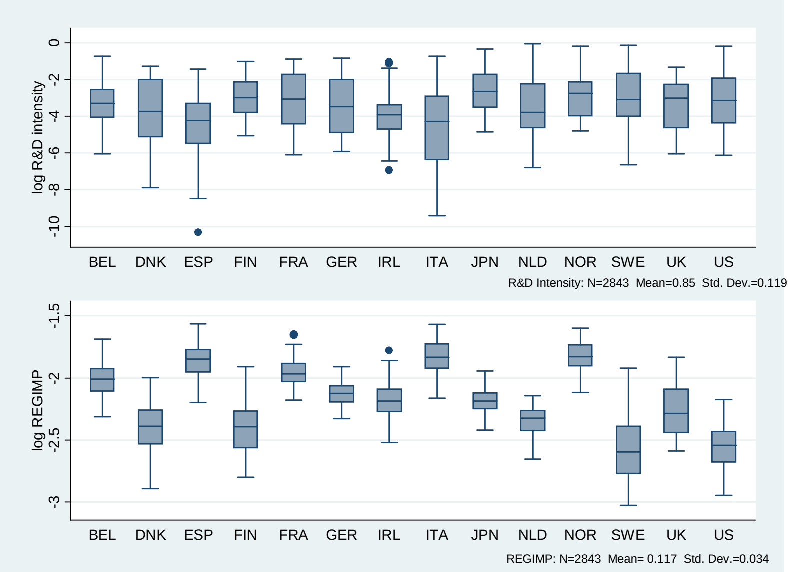

Figure 4. Box plots of R&D and regulation measures aggregated by country

## A.3 Further evidence

Table 1 completes the evidence presented in Figure 1. It tests whether findings on positive slopes resist additional control variables and specifications. We include an indicator of intellectual property rights (IPR) from Ginarte and Park (1997) and updated by Park (2008), which is time-varying at the national level,[27] and a measure of R&D externalities, calculated for a given country-industry pair in a given year as the R&D intensity in the same industry in other countries. These variables help to control for technological features which are time-varying at both country and industry levels. The table also

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[27] An interpolation is applied to produce annual data (See the Appendix).

considers a differential effect of regulation on innovation in high-tech industries, and addresses heteroskedasticity, endogeneity and fixed-effect vector decomposition. Overall, the previous results remain robust across the variety of different specifications.[28]

A more parsimonious way to demonstrate the heterogeneity of the PMR effect is via quantile regressions. Figure 5 shows the results controlling for country, industry and time fixed effects, as well as the IPR and R&D externality variables. This graph shows the REGIMP elasticity from regressions of different quantiles of the conditional distribution of R&D intensity. This suggests that PMR may well be at the root of both low and high levels of innovative activity, measured in terms of (conditional) R&D intensity. The horizontal lines show the elasticity estimate and confidence interval from standard OLS regressions. The latter clearly obscures significant aspects of the relationship between PMR and R&D intensity.

The second graph in the figure shows the results from an alternative specification exploiting the panel structure of the data through within-group regressions. Apart from the unobserved individual fixed effects and time-period dummies, this specification also includes a quadratic term in REGIMP. The estimated coefficients and t-statistics on the level and square terms are, respectively, -1.376 (-3.96) and 5.321 (4.71). The graph illustrates this convex relationship by plotting the marginal effect of REGIMP and the associated confidence intervals for different sample values of REGIMP. The pattern is similar to that obtained previously: in less-regulated country-industry markets PMR seems to exert a negative effect, which becomes positive in more-regulated markets. The marginal effect of REGIMP close to the mean is small in absolute value.

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[28] It should also be noticed that this aggregate empirical approach also runs a smaller risk of endogeneity since, at this level, the focus is on *de jure* dimensions of competition rather than *de facto* measures (e.g. the concentration index or profitability measures), as is usually the case with firm-level data.

Table 1. The impact of PMR on R&D intensity.

| | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] |
|---|---|---|---|---|---|---|---|---|---|
| ln(REGIMP) | -0.889*** | -1.204*** | 0.336*** | 0.429*** | 0.342** | -0.125 | -0.184 | -0.184 | -0.183 |
| | (0.095) | (0.211) | (0.111) | (0.138) | (0.142) | (0.270) | (0.332) | (0.466) | (0.167) |
| ln(IPR) | | | | | 0.686** | | 0.629* | 0.629 | 0.630*** |
| | | | | | (0.270) | | (0.319) | (0.967) | (0.129) |
| ln(R&D externalities) | | | | | -0.059 | | 0.168* | 0.168 | 0.168*** |
| | | | | | (0.063) | | (0.089) | (0.132) | (0.036) |
| High-tech | | | | | | - | - | 4.260*** | - |
| | | | | | | - | - | (1.117) | - |
| ln(REGIMP)×High-tech | | | | | | 0.863** | 1.186*** | 1.186** | 1.180*** |
| | | | | | | (0.380) | (0.411) | (0.530) | (0.151) |
| Unobserved fixed-effects | No | $c, t$ | $c, i, t$ | $c, i, c\times t, i\times t$ | $c\times i, t$ | $c\times i, t$ | $c\times i, t$ | $c\times i, t$ | $c\times i, t$ |
| Method-VCE type | OLS-HMK | OLS-HMK | OLS-HW | OLS-HW | OLS-HW | Within-HW | Within-HW | FEVD-HMK | IV-Within-GLS |
| Number of Obs | 2843 | 2843 | 2843 | 2843 | 2154 | 2843 | 2154 | 2154 | 2154 |
| Marginal Effect of PMR | | | | | | 0.738* | 1.002** | 1.002* | 0.997*** |
| on High-tech | | | | | | (0.410) | (0.444) | (0.514) | (0.213) |

Note: *, **,*** denote significance at the 10%, 5% and 1% levels respectively. The dependent variable is R&D intensity (in logs). All specifications include an intercept. As a starting point, Column [1] reports a simple OLS regression that does not control for omitted-variable bias. Country ($c$), industry ($i$) and time ($t$) fixed effects are included successively in the following regressions. Column [3] shows the importance of controlling for permanent industry factors affecting R&D effort. Column [4] interacts country and industry indicators with time indicators as a way of controlling for unobserved national- and industry-level trends. Column [5] considers two plausible time-varying controls: a national-level indicator of intellectual property rights (IPR) and a measure of R&D externalities, computed by given country, industry and year as the ratio of R&D expenditures to value added in the rest of the world by industry and year. Columns [6]-[9] exploit the panel data structure and focus on different effects of PMR in High-tech industries. High-tech is a dummy identifying industries 30-33 ISIC Rev-3. The coefficient of ln(REGIMP) is the elasticity of PMR in non-high-tech industries and that of the interaction term, ln(REGIMP)×High-tech, the effect of PMR on R&D intensity in high-tech relative to non-high-tech industries. In absolute terms, the overall marginal effect of PMR on high-tech industries is given by the sum of both. This marginal effect is presented at the bottom of the table. Estimation acronyms are as follows. "OLS" stands for ordinary least squares; "Within" for the within-group estimator for fixed-effect models, "IV-Within" for two-stage least square within estimators (the interaction term is treated as endogenous and instrumented by its own lags 1 and 2 to address potential reversal causality); and FEVD indicates the use of fixed-effect vector decomposition to estimate the coefficient of High-tech, which is eliminated by the within-group transformation (see Plümper and Troeger, 2007). The estimates of the unexplained part of unit fixed effects, not-reported, is 1, as expected when accounting for panel heteroskedasticity. Different type of variance-covariance estimation are used, starting from standard homoskedasticity assumptions (HMK), Hubert-White (HW) standard error correction and GLS based estimates.

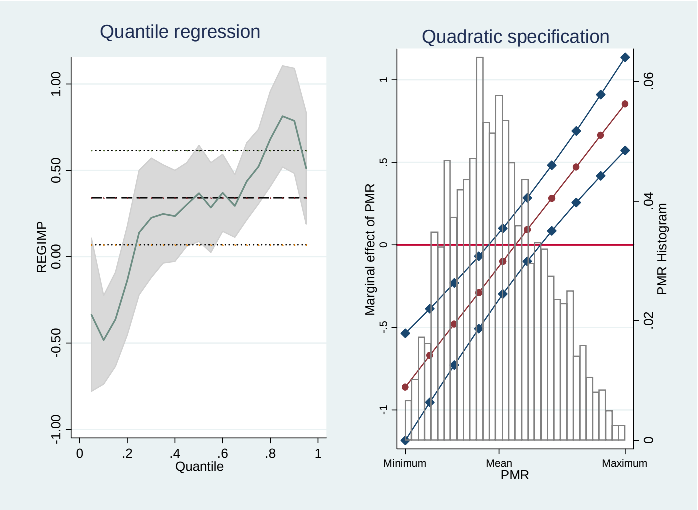

Figure 5. Regulation and R&D intensity: quantile regressions and a quadratic specification.

Finally we show some evidence on the assumption of incumbents' strategies to delay or to avoid their replacement. Table 2 illustrates this using data on firm demographics collected by GGDC from the AMADEUS database. The table shows the results from log-log estimations where the dependent variable is the average age of firms in a given country and industry and the main explanatory variable is our proxy of PMR (REGIMP). The underlying correlations can be understood by analysing how PMR may, intentionally or not, reduce the scope for defensive behaviour.

Table 2. The impact of PMR on the average age of firms

| | | | | |
|---|---|---|---|---|
| ln(REGIMP) | -0.330*** | -0.196*** | -0.150*** | -0.060* |
| | (0.031) | (0.055) | (0.051) | (0.032) |
| ln(IPR) | | | 0.545*** | 0.663*** |
| | | | (0.189) | (0.118) |
| ln(R&D externalities) | | | 0.024*** | 0.041*** |
| | | | (0.006) | (0.004) |
| log(N) | | | | -0.700*** |
| | | | | (0.028) |
| log(H) | | | | 0.008* |
| | | | | (0.005) |
| Unobserved fixed effects | No | $t, c\times i$ | $t, c\times i$ | $t, c\times i$ |
| Method | OLS | Within | Within | Within |
| Number of Obs | 875 | 875 | 482 | 482 |

Note: *, **,*** denote significance at the 10%, 5% and 1% levels, respectively. The dependent variable is the average age of firms in the country-industry (in logs). All specifications include an intercept. The elasticity estimated is significantly negative in a simple bivariate OLS regression (column [1]), a result that remains robust to a within-group estimation of a model including individual (country-industry) and time fixed effects (Column [2]), additional controls for intellectual property rights and R&D externalities (Column [3]), as well as controls for market structure such as the number of firms (N) and the Herfhindahl index (H) of concentration (Column [4]).

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