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Industrial Leadership in Science Based Industries.

A co-evolution model.

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Abstract

In this paper, we seek to analyse the role of national university systems in combination with technological and market factors as sources of industrial leadership and industry growth in science-based industries. We propose a model in which national university systems and their respective national firms and industries are considered as co-evolving. National firms compete on a worldwide level and they rely on the progress of science and the availability of scientists to innovate. As the global industry develops, firms try to mold their national university systems, but they achieve different degrees of success. Apart from highlighting the role of institutional responsiveness as a source of competitive advantage, our model points to the access to essential inputs for production, the technological and strategic characteristics of firms, the international diffusion of knowledge, and the initial distribution of market demand as key sources of leadership and industry growth. The international mobility of scientists seems to foster the emergence of industrial leadership shifts.
Keywords: *Industrial leadership; innovation; diffusion; institutions; evolutionary economics.*

JEL-Code: O33; C61; B52

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1 Introduction

The development of many high-technology industries has witnessed the emergence of strong leadership positions. Thus, for example, the rise of science-based industries in Germany and other countries of continental Europe at the end of the 19^{th} century (Murmann, 2003), or the consolidation of the American technological leadership during the post-WWII era (Nelson and Wright, 1992) illustrate the relevance of industrial leadership in science-based industries. In more recent times, the rapid growth of the Asian NICs came about because these countries managed to master complex electronics-based technologies to the extent of catching up with and, later, forging ahead of previous industrial leaders in high-tech industries (Amsden, 2001).

These episodes present economic theory with serious challenges summarized in three important questions. The first question regards the need to clarify what the sources of industrial leadership in high-tech industries are. Recent contributions point to the co-evolution between universities and a number of institutional, technological and market factors as key mechanisms underlying leadership and industrial leadership shifts (Rosenberg and Nelson, 1994; Mowery and Sampat, 2005). However, despite the excellent empirical, historical and appreciative studies that support this idea, our theoretical understanding of the processes involved is still far from satisfactory (Mowery and Nelson, 1999).

The second question concerns the need to go beyond the immediate factors - capital accumulation, human capital and technical change - that usually explain growth in contemporary models. The complex techno-institutional changes, which have made the science-based industrial transformations in Western Europe, the US or South-East Asia possible, overwhelm the explicative capacity of most theoretical models, in which institutions play an exogenous and minor role. Abramovitz (1952) pointed out this shortcoming more than fifty years ago, but it still remains an open issue today (North, 1990; Nelson, 2005).

The last question regards the theory of economic development. If we pose the challenge of development as a catch-up problem - very much in the spirit of Gerschenkron (1962) or Freeman (2004) - episodes as surprising as the strong rise of Japan during the 20^{th} century or, more recently, the cases of Korea, Taiwan, Singapore or Brazil show how little we know about the role of supporting institutions in economic development. In this respect, Mazzoleni and Nelson (2007) have argued that, in order to catch up in the 21^{st} century, developing nations may need to adapt certain institutions - domestic university systems and public research institutions - to generate more strength in the relevant fields of science and technology[1] . If this is so, for emergent nations to catch up will require a proper understanding of the subtle mechanisms of institutional change (Cimoli et al., 2006).

In this work, we take on the aforementioned challenges by proposing a co-evolution model of institutions and technology that should be able to shed new light on the sources of industrial leadership in high-tech industries. Furthermore, our proposed model assumes a major role for institutions in economic growth, and it fits with the conception of development as a catch-up problem.

In our model, heterogeneous for-profit firms, with distinct national identities, co-evolve with their respective national university systems. Firms compete on a worldwide level in a science-based industry, and they drive technological change and industry growth. Since we will assume that firms fund capacity growth out of current profits, whether they grow

[1] Reasons for this adaptations include the stricter legal conditions established by the WTO, the increased protection of intellectual property rights in the TRIPS agreement, and the powerful contemporary expansion in many fields of application-oriented sciences.

or fall into decline depends on their profitability. Likewise, we consider that firms carry out R&D to come up with new processes that increase productivity at the firm level.

The key input for firms to carry out R&D are scientists, who are trained in national university systems. We characterize these institutions in such a way that they show different degrees of institutional responsiveness to the industry needs in different nations. In the most complex version of the model, we consider that scientists may migrate to foreign industries, depending on wage differentials and on other non-monetary considerations. We also assume (implicitly) the role of other supporting institutions (public agencies and labs, government programs or international associations) which underlie each nation's absorptive capacity of foreign technology.

The dynamics of industrial leadership and industry growth in the model arise from the combination of technological, institutional and market factors. Technological and strategic factors include the firms' technological capabilities (which underlie the productivity of R&D), the firms' differential willingness to carry out R&D, and the type of returns to scale that may exist within our modeled industry. Market factors include the size and initial distribution of market demand, and the different prices at which firms from distinct nations can obtain essential inputs for production. The rhythm at which firms invest in capacity growth or the initial distribution of scientific salaries among nations may also be considered as market factors. Finally, the institutional factors include the uneven responsiveness of domestic university systems, the degree of international mobility of scientists, and the effectiveness with which national institutions allow for the assimilation of foreign technology.

Our model fits in with the literature on evolutionary modeling[2] , but it includes signif-

[2] See Silverberg and Verspagen (2005) for a detailed survey of this literature.

icant methodological and theoretical innovations. Regarding theory, our model responds to recent claims by Nelson (2005) and Verspagen (2005) who have pointed out that formal evolutionary theorizing could enter into rapidly decreasing returns if it does not incorporate mechanisms of co-evolution between institutions and technology into a new generation of models. Malerba (2006) also points out the analysis of co-evolution processes as being a pending research path at the theoretical frontier of evolutionary economics. We try to move forward in this direction by considering, in our model, elements such as the higher or lower flexibility with which university budgets and training priorities adapt to industry needs, the determinants of the international mobility of highly-skilled labor, and the existence of institutions that support the absorptive capacity of nations.

Regarding methodology, we agree with Silverberg and Soete (1994) or Silverberg and Verspagen (2005) in that evolutionary theorists face the methodological challenge of developing more practically relevant models. As Verspagen (2005) claims, formal evolutionary theory rarely generates precise results, mostly as a consequence of the nature of available models, which involve very complex interactions generating rather unpredictable (and obscure) dynamics. One way to overcome this limitation would be to build up a new class of models on the basis of "relatively simple, evolutionary microeconomic foundations to generate a broader range of phenomena in the evolutionary interpretation of technology and growth, rather than increasing the sophistication of the microfoundations" (Verspagen, 2005, p. 501). In our model, we delineate a minimal set of assumptions that, without evading the inherent complexity of economic change, attempts to offer precise results via the combined use of analytical tools, and the econometric analysis of simulation results. More precisely, we explore the model in different settings, with increasing complexity, so that we can obtain local analytical results by using Taylor polynomial approximations.

Later, we check the global validity of these results through simulations, and go into specific questions in greater depth via an econometric analysis.

Furthermore, despite the abstract and clearly theoretical character of our model, we believe that it shows plausible properties which fit (in a qualitative and stylized way) well-known facts that have been observed in the evolution of high-tech industries and other processes of economic change. Thus, we can mention the following stylized facts (see Mowery and Nelson, 1999; Murmann, 2003):

1. The evolution of science-based industries shows the emergence of strong leadership positions, which may be altered by surprising leadership shifts.
2. The market shares and the proportion of scientists working in each national industry display strongly-related dynamic patterns.
3. There is sustained growth in the levels of production and productivity in the distinct national industries and at the worldwide level.
4. The growth rates of output and productivity in distinct national industries are different.
5. The unit price of the final product falls as technology progresses and production rises.
6. There is a relationship between the rate of investment and the firms' profit rate.

Apart from reproducing these generally-accepted facts, our model also offers new results. As a brief anticipation of some of our results, we can mention the following findings:

1. The technological capabilities of firms, cheap access to essential production inputs, and institutional responsiveness are the factors most favoring industrial leadership

and industry growth.

2. The international diffusion of knowledge and technology increases the productivity of R&D while also reinforcing the role of cheap access to essential inputs for production (such as energy and raw materials) as a source of leadership. Obviously, this result leads to interesting reflections on economic development and, specifically, on the future of the BRICs (Brazil, Russia, India and China).

3. The R&D to sales ratio plays an ambiguous role as a source of leadership. Thus, maintaining a high R&D to sales ratio is not always the most efficient strategic behavior.

4. It is possible that industrial leadership may be achieved by a national firm which is not especially strong in any of the mentioned leadership factors but which enjoys a sufficiently favorable combination of said factors.

5. The model shows that, in order to maintain a position in the global market, a minimum (variable) stock of scientists is necessary. This result should make us reflect on the key role of university systems for nations seeking to catch up.

6. Finally, the mobility of scientists strengthens the technological capacity of the receiving nation and its possibilities of leadership. Mobility makes leadership changes more probable.

The rest of the paper is organized as follows: we present the co-evolution model in Section 2. We show how the model can be explored in different settings moving, with increasing complexity, from a single industry version to a multi-industry version. In Sections 3 and 4, we carry out the dynamic analysis of the model without international mobility of scientists. We explore the role of different factors in industrial leadership, and the existence, rhythm and possible multiplicity of industrial leadership shifts. In Section 3 we analyze the model using formal methods, before devoting Section 4 to exploring the model through simulations. Section 5 is devoted to the analysis of the model with international mobility of scientists. Finally, we state our conclusions.

2 The Model

Given the inherent complexity of each and every evolutionary framework, it is only possible to progress theoretically and methodologically at the same time if we greatly simplify previously-studied aspects. We are aware of the simplifications in our model and, hence, when necessary, we refer to previous contributions where a more extensive treatment of certain questions can be found.

Let us begin our model by assuming the existence of n $(i = 1, ..., n)$ firms, each one with a different national identity, which compete on a worldwide level within a science-based industry. Since we assume (for simplicity) the existence of only one firm in each national industry, we can refer to these firms indistinctly as the *national firm* i, or the *national industry* i[3] . For clarity, we present our assumptions within three subsections: production, growth and demand; innovation; and institutions.

[3] Fatas-Villafranca et al. (2008) study the dynamics of industrial leadership in a model with distinct firms within each national industry. However, the complexity of this model impedes the consideration of certain aspects which we now study: the international diffusion of technology, the international mobility of scientists or the application of analytical methods.

On the other hand, note that we use the concept "national firm" to point out that different firms/industries have features responding to a specific national identity. Therefore, "national firm" does not mean "state firm" in our model.

2.1 Production, growth & demand

Equations (1) and (2), below, formalize the assumptions underlying production and capacity growth for each national firm:

$$q_i(t) = A_i(t)k_i^b(t), \quad b > 0 \tag{1}$$

In equation (1), we assume full capacity use ($k_i(t)$ denotes firm i's capacity at any time), different returns to scale depending on the value of parameter b, and a changing level of technology $A_i(t)$ at the firm level.

Equation (2) states that firms devote a constant proportion θ of their current profits to support capacity growth[4] .

$$\dot{k}_i = \theta \left(p(t) - c_i(t)\right) q_i(t), \quad \theta \in (0,1) \tag{2}$$

The variable $p(t)$ denotes the price the homogenous product is sold at in the worldwide market, while $c_i(t)$ is firm i's unit cost. It must be pointed out that we are assuming that there is no depreciation of capital and that this does not have significant effects on our results.

In equation (3) below, we assume that the global market clears at any time as in the Nelson and Winter (1982) models of Schumpeterian competition.

$$p(t) = \frac{\delta}{q(t)} \quad \text{with} \quad q(t) = \sum_j q_j(t), \quad \delta > 0 \tag{3}$$

Thus, everything that is produced is sold at a price given by equation (3). Parameter δ captures the size of the potential market on a global level[5] .

[4] The determinants of firms' growth is a very controversial and interesting research topic. It is an open issue from an empirical and theoretical perspective (see Bottazzi and Secchi, 2006). Since we cannot deal with this question in the present paper, we refer to previous contributions by Nelson and Winter (1982) or Metcalfe (1999) to justify our assumption.

[5] Let us note that, as the global output grows driven by the dynamics of investment and technological change, equation (3) determines that the unit price declines. This property fits a very well-known fact, characteristic of many science-based industries.

2.2 Innovation & technological change

Since we are interested in analyzing industrial leadership in industries where science-based technological change is a key competitive weapon, we will assume that firms carry out industrial R&D and that they fund these activities by devoting a constant proportion of their sales (r_i) at any time to R&D[6] . We formalize this assumption in equation (4).

$$\gamma_i(t) = r_i p(t) q_i(t), \quad \text{with} \quad r_i \in (0,1) \tag{4}$$

Concerning R&D activities in the model, let us say, on the one hand, that "scientists" are the fundamental input to carry out these activities. Therefore, firms devote their R&D budgets ($\gamma_i(t)$) to hiring scientists at a price given by the national salary $w_i(t)$ of scientists in each nation. On the other hand, let us suppose that R&D scientists within each firm improve their firm's technology by coming up with new processes of production (or process improvements). In equation (5) we state that the rate of technological change at the firm level is a function of the number of "scientists" working for the firm ($h_i(t)$), and of the productivity of R&D activities[7] :

$$\frac{\dot{A_i}}{A_i} = \chi_i(t) h_i(t) = \left[\alpha_i + \beta_i \left(\frac{A^*(t) - A_i(t)}{A^*(t)}\right)\right] \frac{\gamma_i(t)}{w_i(t)} \tag{5}$$

with $0 \leq \alpha_i, 1 > \beta_i$ and $A^*(t) = Max\{A_1(t), ..., A_n(t)\}$.

The productivity of R&D $\left(\chi_i(t) = \alpha_i + \beta_i \left(\frac{A^*(t)-A_i(t)}{A^*(t)}\right)\right)$ is determined not only by the technological capabilities of national firms (given by α_i), but also by positive externalities derived from the international diffusion of knowledge and technology (given by

[6] See Winter (2005) or Coad and Rao (2007) for the origins, extensions and implications of this assumption. Empirical evidence on the R&D to sales ratio as an operating routine can be found in, for example, Albaladejo and Romijn (2000).

[7] This assumption is habitual, both in evolutionary models (Fatas-Villafranca et al., 2008) as well as in mainstream approaches (Romer, 1990). The classic article by Nelson (1982) - on R&D efficiency - provides an excellent framework to appreciate the meaning of equation (5).

$\beta_i\left(\frac{A^*(t)-A_i(t)}{A^*(t)}\right)$). The ratio $\frac{A^*(t)-A_i(t)}{A^*(t)}$ captures the technological gap separating the i-national industry from the leading technology at any time, while β_i captures the role of certain national supporting institutions which favor the assimilation of foreign technology.

Given the previous assumptions, it is clear that the firms in our model bear both production costs and R&D costs. Regarding production costs, let us assume that capital in the model plays its role as the numeraire. Nevertheless, as in Nelson and Winter (1982), we assume that the cost and requirements per unit of capital of the essential inputs for production (ρ_i) are different for each national industry. Thus, it is clear that the firm's total costs will be given by $\rho_i k_i(t) + \gamma_i(t)$. Therefore, each firm's unit cost at t will be given by the equation (6):

$$c_i(t) = \frac{\rho_i}{A_i(t)k_i^{b-1}(t)} + r_i p(t) \tag{6}$$

2.3 Institutions: National university systems

We will assume that scientists are trained within their respective national university systems and that the number of new scientists depends on the amount of resources that each uni-system devotes to research and training in key scientific disciplines for the industry. We capture this assumption in equation (7):

$$y_i(t) = \frac{u_i(t)}{\eta}, \quad \text{for simplicity} \quad \eta = 1 \rightarrow y_i(t) = u_i(t) \tag{7}$$

we denote by $u_i(t)$ the total amount of resources that nation i devotes to university research and training in the key disciplines, and by $y_i(t)$ the number of new scientists that finish their training (in these key disciplines) within the i-university system at t. Clearly, $\frac{1}{\eta}$ somehow represents the "productivity" of the university systems in the training of new scientists but, for the sake of formal simplicity, we assume that it is common to all nations and equal to one.

In equation (8) we propose that the amount of resources $u_i(t)$ that each nation devotes to research and training in key disciplines for the industry is related to the industry's size through the parameter λ_i. This parameter measures the responsiveness of nation i´s university system to the scientific and training needs of its national industry. Then, if we capture the size of each national industry at any time by its overall volume of sales, the flow of new scientists will be

$$y_i(t) = u_i(t) = \lambda_i p(t) q_i(t), \quad 0 < \lambda_i < 1 \tag{8}$$

The distribution of parameters $\{\lambda_i\}$, $i = 1, ..., n$ captures the disparity that exists among different nations regarding institutional responsiveness to industry needs.

Finally, let us consider the functioning of the market for scientists. In the general version of the model (Section 5), we will assume that a proportion σ, $(0 \leq \sigma \leq 1)$, of the scientists finishing their training in each nation at any time directly decide to stay in their country and join their national industry. The remaining proportion $(1 - \sigma)$ consider the possibility of emigrating and developing their career in another nation; we will refer to this part $(1 - \sigma)y_i(t)$ of the total amount $y_i(t)$ of new scientists as the "mobile" scientists.[8] As Johnson and Regets (1998) show, the motivations for scientists to develop their career in one national industry or another include both wage differentials and non-monetary considerations (specially considerations related to their ability to work effectively in their chosen field; see Güth (2007)). Although we will formalize this statement in Section 5, in the other sections we will explore the dynamics of our model under conditions of an absence of international mobility of scientists for clarity[9] , that is $\sigma = 1$. Thus, if we

[8] For the sake of formal tractability, we assume that international mobility only affects those scientists that finish their training at a given time t. That is, only those scientists starting out consider the possibility of emigrating.

[9] For a long time, nations relied on people trained "at home" to cover their needs for highly-skilled labor (except for the case of top scientists and engineers; see Nelson, 1992). However, this situation has experienced significant changes recently (see Regets, 2007).

assume that the adjustment of the national salary of scientists assures market clearing, then equation (9) will allow us to determine the dynamics of the stock of scientists in each nation:

$$y_i(t) = \dot{h}_i \tag{9}$$

2.4 Dynamical equations of the model

In order to deduce the fundamental equations that drive the model dynamics, we begin by obtaining $\dot{w}_i$ from (9). Firstly, considering that $h_i(t) = \frac{\gamma_i(t)}{w_i(t)}$ we can obtain that:

$$\frac{\dot{w}_i}{w_i} = \frac{\dot{\gamma}_i}{\gamma_i} - \frac{y_i(t)}{h_i(t)}$$

Let us now consider the worldwide market share of each national firm/industry which is given by $s_i(t) = \frac{q_i(t)}{q(t)}$. Then, taking equations (3), (4) and (8) into account, it is straightforward that:

$$\frac{\dot{w}_i}{w_i} = \frac{\dot{s}_i}{s_i} - \frac{\lambda_i w_i(t)}{r_i} \tag{10}$$

Let us now obtain the market shares dynamics. From equations (1), (2), (4), (5) and (6) it is clear that:

$$\frac{\dot{k}_i}{k_i} = \theta\left[\frac{\delta\left(1-r_i\right)s_i(t)}{k_i(t)} - \rho_i\right] \tag{11}$$

$$\frac{\dot{A}_i}{A_i} = \frac{\delta\left[\alpha_i + \beta_i\frac{(A^*(t)-A_i(t))}{A^*(t)}\right] r_i s_i(t)}{w_i(t)} \tag{12}$$

$$\frac{\dot{q}_i}{q_i} = \frac{\dot{A}_i}{A_i} + b\frac{\dot{k}_i}{k_i} = \delta s_i(t)\left[\frac{\left[\alpha_i + \beta_i\frac{(A^*(t)-A_i(t))}{A^*(t)}\right] r_i}{w_i(t)} + \frac{b\theta(1-r_i)}{k_i(t)}\right] - b\theta\rho_i \tag{13}$$

And then, considering equation (13) and the simple relationships $\frac{\dot{s}_i}{s_i} = \frac{\dot{q}_i}{q_i} - \frac{\dot{q}}{q}$ and

$\frac{\dot{q}}{q} = \sum_j s_j(t) \frac{\dot{q}_j}{q_j}$ we obtain the following expression:

$$\frac{\dot{s}_i}{s_i} = b\theta\left(\overline{\rho} - \rho_i\right) + \delta \left[\begin{array}{c} s_i(t)\left(\frac{\left(\alpha_i + \beta_i \frac{(A^*(t) - A_i(t))}{A^*(t)}\right) r_i}{w_i(t)} + \frac{b\theta(1-r_i)}{k_i(t)} \right) - \\ \sum_j s_j^2(t) \left(\frac{\left(\alpha_j + \beta_j \frac{(A^*(t) - A_j(t))}{A^*(t)}\right) r_j}{w_j(t)} + \frac{b\theta(1-r_j)}{k_j(t)} \right) \end{array} \right] \quad (14)$$

with

$$\overline{\rho} = \sum_j s_j(t)\rho_j$$

Equations (10), (11), (12) and (14) characterize the model dynamics. Equation (14) synthesizes the dynamics of market shares, while equations (10), (11) and (12) drive, respectively, the dynamics of the scientific salaries, the growth of capacity and technological change[10] .

Equation (14) can be also written as:

$$\frac{\dot{s}_i}{s_i} = \left(\hat{A}_i - \overline{\hat{A}}\right) + b\left(\widehat{k}_i - \overline{\widehat{k}}\right) = \left(\hat{A}_i - \overline{\hat{A}}\right) + b\theta\left(\pi_i - \overline{\pi}\right), \quad (15)$$

with

$$\overline{\hat{A}} = \sum_j s_j \hat{A}_j, \overline{\widehat{k}} = \sum_j s_j \widehat{k}_j, \hat{A}_i = \frac{\dot{A}_i}{A_i}, \widehat{k}_i = \frac{\dot{k}_i}{k_i}, \pi_i(t) = \frac{\delta(1-r_i)s_i(t)}{k_i(t)} - \rho_i, \overline{\pi} = \sum_j s_j(t)\pi_j(t)$$

Equation (15) shows how the competitive process underlying the dynamics of market shares is governed by the differences which exist between national rates of technological progress and capital growth, and their respective average rates (worldwide) of variation. For simplicity, we refer to $\left(\hat{A}_i - \overline{\hat{A}}\right)$ and $\left(\widehat{k}_i - \overline{\widehat{k}}\right)$ as the *technological* component and the *expansive* component of the competitive process, respectively.

[10] According to equations (12) and (13), the growth rates of productivity and output will generally differ among the distinct national industries. This is a very well-known fact in industrial dynamics.

3 The Model's Dynamics

In Sections 3 and 4 we will analyze our model dynamics with the aim of clarifying the role of different sources of leadership and the conditions for industrial leadership shifts. In this section, we will carry out the analytical study of the equations defining the dynamics and, afterwards, in Section 4, we will complete the analysis with simulations.

From now on, we use the term *sources of industrial leadership* to refer to those technological, institutional or market factors that may allow one national firm/industry to gain and maintain (at least temporarily) the highest share in the global market. On the other hand, we denote by *industrial leadership shifts* those situations in which one firm overtakes the previous leader in terms of market share. Likewise, we will say that one firm/industry has consolidated its leadership in the market when, from an instant of time t^* onwards, it maintains its market share sufficiently close to 1.

3.1 One particular case: the model for one isolated industry

As a first approximation to our model dynamics, let us assume that there is one national industry that has no relationships with other nations and that it has a volume of sales $pq_i = s_i\delta$. Let us also assume that there is a technological frontier A^* which is greater than the technological level $A_i(t)$ of nation i. We will consider this frontier to be constant for simplicity. Taking on these simple conjectures, if we assume the rest of conditions which define the model, the dynamics of national industry i will be given by the following equations.

$$\frac{\dot{w_i}}{w_i} = -\frac{\lambda_i w_i(t)}{r_i}$$
$$\frac{\dot{k_i}}{k_i} = \theta\left[\frac{\delta s_i\,(1-r_i)}{k_i(t)} - \rho_i\right] = \theta\pi_i(t) \tag{16}$$
$$\frac{\dot{A_i}}{A_i} = \frac{\delta s_i r_i}{w_i(t)}\left[\alpha_i + \beta_i \frac{A^* - A_i(t)}{A^*}\right]$$

The model (16) can be solved analytically[11] . The path for the productive capacity is

$$k_i(t) = -(k_i^e - k_i(0))e^{-\rho_i\theta t} + k_i^e \tag{17}$$

with $k_i^e = \frac{\delta s_i(1-r_i)}{\rho_i}$ being the steady solution. Hence, if we suppose that the profits for this industry are initially positive, which is the same as assuming $k_i(0) < k_i^e$, any solution path $k_i(t)$ converges to k_i^e in a strictly growing form.

The time evolution of the national salary of scientists $w_i(t)$ is driven by

$$w_i(t) = w_i(0)\frac{1}{1 + w_i(0)\frac{\lambda_i}{r_i}t} \tag{18}$$

We will obtain the evolution of $A_i(t)$ in two cases. In the first case we will assume $\beta_i = 0$; that is to say, there is no international diffusion of knowledge. In the second case, we assume $\beta_i \neq 0$. The technological level in the first case is

$$A_i^{\beta_i=0}(t) = A_i(0)e^{\frac{\delta s_i r_i \alpha_i}{w_i(0)}t + \frac{1}{2}\delta s_i \alpha_i \lambda_i t^2} \tag{19}$$

and its trajectory can be seen in Figure 1. This figure and all those in this work respond to the standard scenario in Table 1; in each figure we only indicate those values which differ from this scenario.

[11] The second equation in (16) is a linear differential equation with constant coefficients with the solution (17). From the first equation of (16), with $w_i(t) = \frac{1}{z(t)}$, we can obtain (18). Once we know $w_i(t)$, if $\beta_i = 0$, the third equation of (16) can be solved as an exact differential equation obtaining (19). Finally, if $\beta_i > 0$, the previous equation is of the separate variables type, with the solution being (20).

When we assume that $\beta_i > 0$, the solution for an initial value $A_i(0)$ is:

$$A_i^{\beta_i \neq 0}(t) = \frac{\frac{A_i(0)}{\alpha_i+\beta_i-\beta_i\frac{A_i(0)}{A^*}}(\alpha_i+\beta_i)e^{\frac{\delta s_i r_i(\alpha_i+\beta_i)}{w_i(0)}t+\frac{1}{2}\delta s_i(\alpha_i+\beta_i)\lambda_i t^2}}{1+\frac{A_i(0)}{\alpha_i+\beta_i-\beta_i\frac{A_i(0)}{A^*}}\frac{\beta_i}{A^*}e^{\frac{\delta s_i r_i(\alpha_i+\beta_i)}{w_i(0)}t+\frac{1}{2}\delta s_i(\alpha_i+\beta_i)\lambda_i t^2}} \quad (20)$$

We can see that if $\beta_i > 0$, there is a limit to technology growth at a level $L = \lim A_i^{\beta_i \neq 0}(t) = \frac{A^*(\alpha_i+\beta_i)}{\beta_i}$. This solution has been obtained with the condition of a constant value for A^* and it is only relevant while $A_i^{\beta_i \neq 0}(t) < A^*$. This must be borne in mind while representing the trajectory in Figure 1.

FIGURE 1

With the aid of the previous expressions, specifically (16), (17), (18), (19) and (20), we can synthesize the main properties of the dynamics of one isolated national industry. According to (17), the capital stock $k_i(t)$ grows constantly, tending to its steady level. It does this at a faster rate when the propensity to invest, θ, is greater. Furthermore, from the second equation of (16), we can interpret the process of capital accumulation as the result of the dynamics of the profit rate[12] . Likewise, let us notice that the productivity of capital $f_i(t) = \frac{q_i(t)}{k_i(t)} = A_i(t)k_i(t)^{b-1}$, increases with technological progress and it can increase, decrease or remain constant as capital accumulates, depending on the type of returns to scale in the industry ($b > 1, =, < 1$).

On the other hand, according to (16), the salary of scientists $w_i(t)$ decreases more quickly, the lower the R&D to sales ratio (r_i) in the industry and the higher the responsiveness (λ_i) of the national university system.

The evolution of the technology level is different depending whether the international diffusion of knowledge takes place (see Figure 1). If it does occur, technological progress

[12] The existence of a relationship between the rate of investment and the profit rate is a well-known fact in economic growth.

is faster but its evolution is more complex. If there is no diffusion, (19) shows that $A_i(t)$ grows exponentially, increasing more quickly, the lower $w_i(0)$ is, and the higher the size of the market δs_i, the productivity of R&D α_i, the R&D to sales ratio r_i and the institutional responsiveness λ_i are.

Regarding industry growth, since $q_i(t) = A_i(t)k_i(t)^b$, it is clear that the immediate sources of growth are $A_i(t)$ and $k_i(t)$. Therefore, the propensity to invest θ, the size of the domestic market δs_i, the low relative price of human capital, the R&D productivity α_i and the responsiveness λ_i of the uni-system will be growth engines, while the cost of production inputs ρ_i will have a negative effect. Moreover, there is a contradictory influence of the R&D to sales ratio r_i. This factor favors growth due to its positive effect on technology, but it weakens growth because of its negative effects on the profit rate (and, then, on capacity growth). As we will see, this contradictory effect also exists in an open global market.

3.2 Two national industries competing on a worldwide level

The presence of various national industries is necessary for competition to exist. The simplest case is the one with two industries. The equations (10), (11), (12) and (14), which characterize the dynamics of the general model, become specific in this case for national industry 1 in

$$\begin{aligned}
\frac{\dot{w}_1}{w_1} &= \frac{\dot{s}_1}{s_1} - \frac{\lambda_1 w_1(t)}{r_1} \\
\frac{\dot{k}_1}{k_1} &= \theta \left[\frac{\delta (1 - r_1) s_1(t)}{k_1(t)} - \rho_1 \right] \\
\frac{\dot{A}_1}{A_1} &= \frac{\delta r_1 s_1(t)}{w_1(t)} \left[\alpha_1 + \beta_1 \frac{A^*(t) - A_1(t)}{A^*(t)} \right] \\
\frac{\dot{s}_1}{s_1} &= (1 - s_1(t)) \left[\hat{A}_1 - \hat{A}_2 + b \left(\widehat{k}_1 - \widehat{k}_2 \right) \right]
\end{aligned} \tag{21}$$

Firstly, let us consider the case without international diffusion of knowledge, $\beta_1 = 0$.

We will study the local evolution of market shares starting from the Taylor polynomial approximation of $s_1(t)$, which is[13] :

$$\begin{aligned} s_1(t) &= s_1(0) + \dot{s}_1(0)t + \frac{1}{2}\ddot{s}_1(0)t^2 + .. \qquad (22) \\ &= s_1(0) + s_1(0)(1-s_1(0))\left[\frac{\dot{A}_1(0)}{A_1(0)} - \frac{\dot{A}_2(0)}{A_2(0)} + b\left(\frac{\dot{k}_1(0)}{k_1(0)} - \frac{\dot{k}_2(0)}{k_2(0)}\right)\right] t \\ &\quad + \frac{1}{2}\dot{s}_1(0)(1-2s_1(0))\left[\frac{\dot{A}_1(0)}{A_1(0)} - \frac{\dot{A}_2(0)}{A_2(0)} + b\left(\frac{\dot{k}_1(0)}{k_1(0)} - \frac{\dot{k}_2(0)}{k_2(0)}\right)\right] t^2 \\ &\quad + \frac{1}{2}s_1(0)(1-s_1(0))\left[\delta\alpha_1\lambda_1 s_1(0) - \delta\alpha_2\lambda_2 s_2(0)\right] t^2 \\ &\quad + \frac{1}{2}\dot{s}_1(0)s_1(0)(1-s_1(0))b\left[\left[\frac{\dot{k}_1(0)}{k_1(0)} + \theta\rho_1\right]\frac{1}{s_1(0)} + \left[\frac{\dot{k}_2(0)}{k_2(0)} + \theta\rho_2\right]\frac{1}{s_2(0)}\right] t^2 \\ &\quad - \frac{1}{2}s_1(0)(1-s_1(0))b\left[\frac{\dot{k}_1(0)}{k_1(0)}\left[\frac{\dot{k}_1(0)}{k_1(0)} + \theta\rho_1\right] - \frac{\dot{k}_2(0)}{k_2(0)}\left[\frac{\dot{k}_2(0)}{k_2(0)} + \theta\rho_2\right]\right] t^2 + .. \end{aligned}$$

The expression of $\dot{s}_1(0)$ in (22) shows what the main factors favoring the growth of the market share for national industry 1 are. Industry 2 will experience similar factors and, as these favor the competitive advantage of 2, they will be negative for 1. If we observe

$$\frac{\dot{A}_1(0)}{A_1(0)} + b\frac{\dot{k}_1(0)}{k_1(0)} = \delta s_1(0)\left(\frac{r_1\alpha_1}{w_1(0)} + b\theta\frac{1-r_1}{k_1(0)}\right) - b\theta\rho_1$$

we can state that the initial value of the market share $s_1(0)$, the productivity of R&D, and low salaries are all favorable factors for the growth of industry 1. On the contrary, the cost of production inputs ρ_1 is a negative factor for the industry, and the R&D to sales ratio r_1 has a contradictory influence. The role of these and other factors can be better appreciated if the above-mentioned expression is rewritten in the following way:

$$\frac{\dot{A}_1(0)}{A_1(0)} + b\frac{\dot{k}_1(0)}{k_1(0)} = \alpha_1 h_1(0) + b\theta[p(0)(1-r_1)\frac{q_1(0)}{k_1(0)} - \rho_1]$$

The higher the number of scientists ($h_1(0)$) and their productivity in the national industry (α_1), and the higher the productivity of capital ($\frac{q_1(0)}{k_1(0)}$), the greater industry 1's

[13] This Taylor expansion, expressed as a function of the initial values and parameters, is available upon request.

competitive advantage and its rate of industry growth will be. The negative effect of ρ_1 on the profit rate is clear, while the contradictory effect of the R&D to sales ratio (r_1) consists of, on the one hand, favoring a higher number of scientists in the industry and, on the other hand, implying a smaller profit rate. All the common parameters - that is, the potential market size δ, the returns to scale factor b and the propensity to invest $\theta-$ favor industrial growth and, as we will see in the simulations, they all also accelerate the process of market competition.

Apart from the above-mentioned factors, there are other sources which are seemingly less significant for industrial leadership. One way to see them is to observe $\ddot{s}_1(0)$ in (22) (coefficient of t^2) assuming $\dot{s}_1(0) = 0$; with this hypothesis, the sign of $\ddot{s}_1(0)$ coincides with that of

$$\delta\alpha_1\lambda_1 s_1(0) - \delta\alpha_2\lambda_2 s_2(0) - b\left[\frac{\dot{k}_1(0)}{k_1(0)}\left(\frac{\dot{k}_1(0)}{k_1(0)} + \theta\rho_1\right) - \frac{\dot{k}_2(0)}{k_2(0)}\left(\frac{\dot{k}_2(0)}{k_2(0)} + \theta\rho_2\right)\right]$$

We can clearly see that the responsiveness λ_1 of the university system is a favorable factor for market share growth which has not appeared previously. Since $\frac{\dot{h}_i}{h_i} = \frac{\lambda_i}{r_i} w_i(t)$, the responsiveness of national uni-systems is essential for the growth of the number of skilled national scientists. This result reveals that the lack of responsiveness by uni-systems may block the competitive advantage of national industries in certain conditions.

Given the difficulty in obtaining global close-form market shares solutions, we will rely on (22) to find conditions that ensure that $s_1(t)$ grows around $t = 0$. The most immediate sufficient condition is $\dot{s}_1(0) > 0$, which becomes:

$$\frac{\delta s_1(0) r_1 \alpha_1}{w_1(0)} + b\left(\frac{\delta s_1(0)\,(1 - r_1)}{k_1(0)} - \rho_1\right)\theta > \frac{\delta s_2(0) r_2 \alpha_2}{w_2(0)} + b\left(\frac{\delta s_2(0)\,(1 - r_2)}{k_2(0)} - \rho_2\right)\theta \quad (23)$$

However, with international diffusion of technology ($\beta_i > 0$) neither (22) nor (23) are valid. If we suppose that the technological frontier is $A^*(t) = A_2(t)$, the new Taylor expansion for $s_1(t)$, which can be obtained from (21), will be:

$$\begin{aligned} s_1(t) &= s_1(0) + \dot{s}_1(0)t + .. \\ &= s_1(0) + s_1(0)(1 - s_1(0)) \left[\begin{array}{c} \frac{\delta r_1 \alpha_1 s_1(0)}{w_1(0)} + \frac{\delta r_1 s_1(0)}{w_1(0)} \left(\beta_1 - \beta_1 \frac{A_1(0)}{A^*(0)} \right) - \frac{\delta r_2 \alpha_2 s_2(0)}{w_2(0)} \\ + b\theta \left(\frac{\delta(1-r_1) s_1(0)}{k_1(0)} - \rho_1 - \frac{\delta(1-r_2) s_2(0)}{k_2(0)} + \rho_2 \right) \end{array} \right] t + .. \end{aligned} \tag{24}$$

Once again, the condition $\dot{s}_1(0) > 0$ is sufficient for the growth of s_1, and in this case it becomes:

$$\begin{array}{c} \frac{\delta r_1 s_1(0) \alpha_1}{w_1(0)} + \frac{\delta r_1 s_1(0)}{w_1(0)} \left(\beta_1 - \beta_1 \frac{A_1(0)}{A^*(0)} \right) + b\theta \left(\frac{\delta s_1(0)(1-r_1)}{k_1(0)} - \rho_1 \right) > \\ \frac{\delta s_2(0) r_2 \alpha_2}{w_2(0)} + b\theta \left(\frac{\delta s_2(0)(1-r_2)}{k_2(0)} - \rho_2 \right) \end{array} \tag{25}$$

If we compare (23) and (25), we observe that both expressions differ in

$$\frac{\delta r_1 s_1(0)}{w_1(0)} \left(\beta_1 - \beta_1 \frac{A_1(0)}{A^*(0)} \right),$$

which captures the effect of international diffusion. As a consequence, if the parameters and the initial conditions $k_i(0)$, $w_i(0)$ were identical in both industries, the share of industry 1 could grow and, consequently, industry 2's market share would fall, despite starting out as leader. This shows that international diffusion is a powerful mechanism that may erode the advantage of the leader.

Finally, to sum up, the above-mentioned arguments allow us to offer some general conclusions:

1. If there is no international diffusion of technology, the stabilization of market shares for the case in which both industries remain in the market is not to be expected. This stabilization requires, among other things, that $\dot{s}_1(t) = 0$ and $\ddot{s}_1(t) = 0$ are fulfilled from a given t and this is unlikely. It is to be expected that the industry that enjoys a clear advantage, either through innovation (higher α_i, λ_i or r_i) or through capacity expansion (lower ρ_i or r_i), will consolidate its leadership. See Figure 2a, where industry 2 enjoys a higher productivity of R&D.

2. If there is international diffusion of knowledge and technology, there will be a wide range of parametric values allowing the "non-leader" to increase its market share. It can also impede the leader industry from cementing its leadership. These situations are favored by values of the returns-to-scale parameter lower than 1 ($b < 1$) because the lower b is, the higher the weight of growth via innovation compared to that via capacity expansion. This type of situation is also produced if the propensity to invest (θ) is too low. See Figure 2b.

3. Whether there is international diffusion of technology or not, in both cases we can find surprising industrial leadership shifts. Thus, in Figure 2c, with technology diffusion, we show how the emerging national industry (industry 1), with an initial market share of 0.11, manages to take over the market from the initial market leader (industry 2 with an initial share of 0.89). The sources underlying this surprising leadership shift are, on the one hand, the cheap access to production inputs (ρ_i) for industry 1, and, on the other hand, the higher responsiveness (λ_i) of industry 1's university system. These kinds of surprising leadership shifts are relatively frequent in real high-tech industries (see Mowery and Nelson, 1999).

FIGURE 2

3.3 The model with n national industries in global competition

The model with n firms/industries generalizes what we have seen for the case of 2 national industries. The equations (10), (11), (12) and (14) characterize the dynamics of the general model. When there is no international diffusion $\beta_i = 0$, the development of Taylor similar to (22) is:

$$
\begin{aligned}
s_1(t) \;=\;& s_1(0) + s_1(0)\left[\frac{\dot{A}_1(0)}{A_1(0)} - \sum_j s_j(0)\frac{\dot{A}_j(0)}{A_j(0)} + b\left(\frac{\dot{k}_1(0)}{k_1(0)} - \sum_j s_j(0)\frac{\dot{k}_j(0)}{k_j(0)}\right)\right] t \qquad (26) \\
& + \frac{1}{2}\dot{s}_1(0)\left[\frac{\dot{A}_1(0)}{A_1(0)} - \sum_j s_j(0)\frac{\dot{A}_j(0)}{A_j(0)} + b\left(\frac{\dot{k}_1(0)}{k_1(0)} - \sum_j s_j(0)\frac{\dot{k}_j(0)}{k_j(0)}\right)\right] t^2 \\
& + \frac{1}{2}s_1(0)\left[\begin{array}{c} \delta\alpha_1\lambda_1 s_1(0) - \sum_j s_j(0)\delta\alpha_j\lambda_j s_j(0) \\ -\sum_j s_j(0)\frac{\dot{A}_j(0)}{A_j(0)}\left[\frac{\dot{A}_j(0)}{A_j(0)} - \sum_r s_r(0)\frac{\dot{A}_r(0)}{A_r(0)} + b\left(\frac{\dot{k}_j(0)}{k_j(0)} - \sum_r s_r(0)\frac{\dot{k}_r(0)}{k_r(0)}\right)\right] \end{array}\right] t^2 \\
& + \frac{1}{2}s_1(0)b\left[\overbrace{\left[\frac{\dot{k}_1(0)}{k_1(0)}\right]}^{\circ} - \overbrace{\left[\sum_j s_j(0)\frac{\dot{k}_j(0)}{k_j(0)}\right]}^{\circ}\right] t^2 + \ldots
\end{aligned}
$$

The coefficient of t in (26) again shows that, the greater the following expression, the more national industry 1 will grow:

$$
\frac{\dot{A}_1(0)}{A_1(0)} + b\frac{\dot{k}_1(0)}{k_1(0)} = \frac{\delta\alpha_1 r_1 s_1(0)}{w_1(0)} + b\theta\left[\frac{\delta\left(1-r_1\right)s_1(0)}{k_1(0)} - \rho_1\right]
$$

This also allows us to generalize what we have already seen in the case of two national industries with respect to the factors underlying the sources of leadership. Moreover, as in the case of 2 industries, we can use (26) to obtain sufficient conditions for the growth of $s_1(t)$. The requirement $\dot{s}_1(0) > 0$ leads to the condition

$$
\begin{gathered}
\frac{\delta\alpha_1 r_1 s_1(0)}{w_1(0)} + b\theta\left[\frac{\delta(1-r_1)s_1(0)}{k_1(0)} - \rho_1\right] > \\
\sum_j s_j(0)\frac{\delta\alpha_j r_j s_j(0)}{w_j(0)} + \sum_j s_j(0)b\theta\left[\frac{\delta(1-r_j)s_j(0)}{k_j(0)} - \rho_j\right]
\end{gathered}
$$

And if we compare two industries, we can assure that $s_1(t)$ grows (and it does so relatively more than the industry $i's$ market share) if

$$
\frac{\delta s_1(0) r_1\alpha_1}{w_1(0)} + b\left[\frac{\delta s_1(0)\left(1-r_1\right)}{k_1(0)} - \rho_1\right]\theta > \frac{\delta s_i(0) r_i\alpha_i}{w_i(0)} + b\left[\frac{\delta s_i(0)\left(1-r_i\right)}{k_i(0)} - \rho_i\right]\theta \qquad (27)
$$

Furthermore, if we assume that there is international diffusion and that the leading national industry is n, the technological frontier will be $A^*(t) = A_n(t)$. The Taylor expansion of $s_1(t)$, similar to (26) will be:

$$\begin{aligned} s_1(t) &= s_1(0) + \dot{s}_1(0)t + .. \qquad (28) \\ &= s_1(0) + s_1(0) \left[\begin{array}{c} \frac{\delta\alpha_1 r_1 s_1(0)}{w_1(0)} + \frac{\delta r_1 s_1(0)}{w_1(0)} \left(\beta_1 - \beta_1 \frac{A_1(0)}{A_n(0)}\right) \\ -\sum_j s_j(0) \left[\frac{\delta\alpha_j r_j s_j(0)}{w_j(0)} + \frac{\delta r_j s_j(0)}{w_j(0)} \left(\beta_j - \beta_j \frac{A_j(0)}{A_n(0)}\right)\right] \\ +b\left(\theta\left[\frac{\delta(1-r_1)s_1(0)}{k_1(0)} - \rho_1\right] - \sum_j s_j(0)\theta\left[\frac{\delta(1-r_j)s_j(0)}{k_j(0)} - \rho_j\right]\right) \end{array} \right] t + .. \end{aligned}$$

which shows that a sufficient condition for $s_1(t)$ to grow in a neighborhood of $t = 0$ is:

$$\begin{aligned} \frac{\dot{A}_1(0)}{A_1(0)} + b\frac{\dot{k}_1(0)}{k_1(0)} &> \sum_j s_j \frac{\dot{A}_j(0)}{A_j(0)} + b\sum_j s_j \frac{\dot{k}_j(0)}{k_j(0)} \qquad (29) \\ &\Longleftrightarrow \frac{\delta\alpha_1 r_1 s_1(0)}{w_1(0)} + \frac{\delta r_1 s_1(0)}{w_1(0)}\left(\beta_1 - \beta_1 \frac{A_1(0)}{A_n(0)}\right) \\ &\quad +b\theta\left[\frac{\delta(1-r_1)s_1(0)}{k_1(0)} - \rho_1\right] \\ &> \sum_j s_j(0) \left[\begin{array}{c} \frac{\delta\alpha_j r_j s_j(0)}{w_j(0)} + \frac{\delta r_j s_j(0)}{w_j(0)}\left(\beta_j - \beta_j \frac{A_j(0)}{A_n(0)}\right) \\ +b\theta\left[\frac{\delta(1-r_j)s_j(0)}{k_j(0)} - \rho_j\right] \end{array} \right] \end{aligned}$$

If we only consider the relative growth of industry 1 with respect to the leader, the condition will be

$$\begin{aligned} &\frac{\delta r_1 s_1(0)\alpha_1}{w_1(0)} + \frac{\delta r_1 s_1(0)}{w_1(0)}\left(\beta_1 - \beta_1\frac{A_1(0)}{A^*(0)}\right) + b\theta\left(\frac{\delta s_1(0)(1-r_1)}{k_1(0)} - \rho_1\right) \qquad (30) \\ &> \frac{\delta s_n(0) r_n \alpha_n}{w_n(0)} + b\theta\left(\frac{\delta s_n(0)(1-r_n)}{k_n(0)} - \rho_n\right) \end{aligned}$$

If we compare (27) and (30), we can see the essential difference in:

$$\frac{\delta r_1 s_1(0)}{w_1(0)}\left(\beta_1 - \beta_1\frac{A_1(0)}{A^*(0)}\right),$$

which captures the effect of the international diffusion of knowledge.

A careful look at these sufficient conditions, and given the similarity with how we obtained them for the case of two nations, allows us to affirm the same three general conclusions that we stated for the case of two industries. Hence, the general validity of those conclusions is confirmed.

Finally, let us show to what extent certain institutional factors may matter for industrial leadership in high-tech industries. We will pay attention to the requirements of scientists in the model. Let us note that we can restate equation (15) as:

$$\frac{\dot{s}_i}{s_i} = \left(\chi_i(t)h_i(t) - \overline{\widehat{A}}\right) + b\theta\left(\pi_i(t) - \overline{\pi}\right)$$

Then, the following sufficient condition for national industry i not to lose its share in the global market can be obtained:

$$\dot{s}_i \geq 0 \Leftrightarrow h_i(t) \geq \frac{\overline{\widehat{A}} + b\theta\left(\overline{\pi} - \pi_i(t)\right)}{\chi_i(t)}.$$

Note that $\frac{\overline{\widehat{A}}+b\theta(\overline{\pi}-\pi_i(t))}{\chi_i(t)}$ represents a minimal (variable) threshold for the number of scientists. The faster the rate ($\overline{\widehat{A}}$) of technical change in the sector and the lower the productivity of $R\&D$, the greater this threshold will be. If we relate this result to the arguments put forward by Mazzoleni and Nelson (2007), and we remember that $\dot{h}_i = \lambda_i \delta s_i(t)$ (with $\delta s_i(t)$ being normally lower in developing nations), we can appreciate to what extent responsive university systems (with high values of λ_i) are a fundamental factor for emergent industries seeking to catch-up. To illustrate this result, we show in Figure 2d how the proportions of scientists evolve during the surprising leadership shift depicted in Figure 2c. As we can see by comparing both Figures, the market shares, and the proportions of scientists working in each nation show strongly-related dynamics during the process.

4 Simulations

4.1 The Sources of industrial leadership

To complete the analysis of the previous Section, we will carry out simulations for three national industries ($n = 3$) which allow a certain generalization of the results obtained for the sources of leadership. The consideration of more industries, $n = 4, 5, ..$, would doubtlessly be interesting but, at the same time, would make the analysis more difficult and less clear. The simulation with three industries is already very complex and shows all the relevant cases. Hence, simulations with more than three industries would not offer a qualitative leap, although more industries would mean more shifts. The drivers of the leadership shifts are the same and the general conclusions obtained with the model for $n = 2$ are still correct.

To be specific, we will analyze, for the case of three industries, the role played by $\lambda_i, \beta_i, \alpha_i, r_i$ and ρ_i, and by the common parameters θ, b and δ. Firstly, we will analyze the isolated influence of each factor. Secondly, we will explore some of their interactions. Finally, we will measure the weight of each source of leadership.

To isolate the effect of one factor (one parameter), we will consider that all other parameters have the same value for each national industry, except the factor we wish to study, which verifies that:

$$x_1 = x_2(1 - a_x) < x_2 < x_3 = x_2(1 + a_x),$$

where x represents the factor we study ($x = \lambda_i, \alpha_i, r_i$ or ρ_i) and a_x the degree of heterogeneity.

We will run the simulations departing from the standard scenario - see Table 1. The values of the initial conditions and parameters in this setting are chosen because they represent plausible conditions. Thus, we assume that all firms start out from a positive profit situation; R&D costs are significantly lower than production costs; parameters λ_i, r_i are taken such that the growth rate of the national stock of scientists ($\frac{\lambda_i w_i(t)}{r_i}$) is plausible; and, finally, in accordance with previous contributions (Nelson and Winter, 1982 or Kwasnicki and Kwasnicka, 1992), we have chosen plausible values for $r_i, \theta, \delta, k_i(0)$ and $A_i(0)$.

TABLE 1

4.1.1 Analyzing the influence of each factor without international diffusion

Firstly, we analyze the isolated effect of each factor assuming that there is no diffusion ($\beta_i = 0$). The most relevant conclusion is that the industry with a higher λ_i, α_i or lower ρ_i will become leader. These results do not depend on the degrees of heterogeneity (a_λ, a_α or a_ρ); if we set these parameters at higher values, then the leadership is consolidated more quickly. This reinforces our local results in Section 3, generalizing them for the complete dynamic process. Moreover, as was to be expected from the local analysis, increasing parameters θ, b, and δ, accelerates the rise to industrial leadership. An example of university systems as a source of leadership can be seen in Figure 3a, where the leadership shift is produced because nation 2's uni-system is more responsive than the uni-system of the initial leader (national industry 1). Nevertheless, we have chosen the example to show also how industry 3 (the one enjoying the most responsive uni-system) fails to reach leadership because it departs from an initial market share which turns out to be too small. This result anticipates that the interactions between different factors as determinants of leadership matter, as we will explain later in more detail.

FIGURE 3

The contradictory effect of r_i, which we have seen analytically, is also maintained in the simulations. It is not clear that investing more in R&D is always a source of leadership. It strongly depends on the salary of national scientists. The simulations show that for low initial values of the salary, the R&D to sales ratio is a source of leadership (see Figure 4a); while for sufficiently high salary values the industry with the lowest r_i becomes the leader

(Figure 4b).

FIGURE 4

4.1.2 Analyzing the influence of each factor with international diffusion

The aforementioned results can vary strongly if we suppose that there is international diffusion of technology. The simulations show that if the international diffusion is sufficiently intense, there are qualitative changes in the market shares dynamics, as we have already seen in Section 3. In these situations, the industries following the leader may assimilate technical advantages via the technological component in equation (15). This allows them to delay or even impede the leader's consolidation of their position, leading to situations of market sharing between various national industries. The simulations also show that the influence of international diffusion is greater, the lower the returns to scale and the propensity to invest in the global sector. In Figure 3b we show how the time evolution already presented in Figure 3a changes when there is international diffusion and lower returns to scale. In this case, the emerging industry (industry 3), which was sinking at the start in Figure 3a, ends up taking over the market, although sharing it with the challenging industry (industry 2).

4.2 Estimating the relative influence of different sources of industrial leadership

Once the effects have been analyzed one by one, it is useful to estimate how these factors contribute to industrial leadership when they act together. We will see this econometrically by estimating the weight of each source of leadership, starting out from data obtained from simulations of the model. The departure point is given by the following specified relation:

$$t^*((1+a_\alpha)\alpha)^{\phi_\alpha}((1+a_\rho)\rho)^{\phi_\rho}((1+a_\lambda)\lambda)^{\phi_\lambda}((1+a_r)r)^{\phi r}=C,$$

where the weight of each source of leadership will be given by the estimation of the corresponding exponent. The convenience of using the specified relation is supported by our econometric results.

The results of the fits are reported in Table 2 which includes the parameter estimates, their $t-$values and R^2. We have carried out eight different estimations by applying the non-linear least-squares method. As can be seen in Table 2, we have considered $\beta_i = 0$ in two of the fits, and $\beta_i \neq 0$ in the rest of them. To capture the effects of the returns to scale we have considered $b = 1.1$ in four fits, and $b = 0.8$ in the others.

For every possible combination (β_i, b) in Table 2 we run the model 57 times to obtain different values of t^* - the instant of time in which we consider the leader's market share to be sufficiently close to 1. In each run, we start out from the parametric values of industry 2 in the standard scenario (Table 1), and we systematically change one or several parametric values for industries 1 and 3. To be specific, we consider variations of a_x between 0.01 and 0.09.

TABLE 2

We can clearly see in our table that the specified relation is very explicative, since the R^2 values are higher than 0.76 in all cases and, in general, much higher, sometimes approaching the value of 1. This gives us the confidence to believe that our conclusions are solid ones. Regarding the weight of the sources, we can see in Table 2 that ρ and α are the ones with a greater value (higher ϕ_ρ, ϕ_α) and are always higher than the weights of λ and r. In the case of ϕ_λ and ϕ_r we always get $\phi_\lambda > \phi_r$ (except for $\beta_i = 0.01$, $b = 1.1$ when they are almost equal). Comparing the order of the weights ϕ_ρ, ϕ_α we observe that it is not always the same. It strongly depends on the existence of international diffusion of knowledge and, if diffusion is sufficiently low, it is conditioned by the type of returns to scale. To sum up, in normal situations with international diffusion, we may find either the order $\phi_\rho > \phi_\alpha > \phi_\lambda > \phi_r$, or $\phi_\alpha > \phi_\rho > \phi_\lambda > \phi_r$ when diffusion is not intense and there are decreasing returns.

These results were to be expected from our previous conclusions since α and ρ had a very strong influence on the consolidation of leadership. The former parameter influences leadership via the technological component in equation (15), and the latter via the expansive component. As we have also mentioned, the parameter which measures the responsiveness of the university system (λ) does not exercise a direct influence on market share dynamics (it appears in the second term of the Taylor expansion). Therefore, it is not unusual that its estimated influence on leadership is lower than that of parameters such as α or ρ, which have a direct influence. However, we must not forget the conclusions of Section 3 regarding the role of university systems.

It also makes sense that the estimated weight of the R&D to sales ratio r be even lower, given that this factor has a positive effect on the technological component, but a negative one on the expansive component.

The change in order between ϕ_ρ and ϕ_α when there is international diffusion is due to the fact that, if the diffusion of technology is sufficiently intense, then the technological component in equation (15) becomes less influential as a source of leadership, and the key source of leadership turns out to be the price of essential inputs for production (ρ via the capacity expansion component in equation (15)).

4.3 Industrial leadership shifts

In this section we briefly try to complement the preceding simulations by looking at the possibility of leadership shifts in the market. We have already commented on this possibility in preceding sections - see Figures 2c, 3a and 3b. If there is no international diffusion of knowledge ($\beta_i = 0$), the results of our simulations are clear. Any industry may become leader, whether it be the industry with an advantage over the others granted by one of its leadership sources, or an industry which has not been favored by any of the sources. The simulations show that the joint effects of market, technological and institutional factors can lead to a surprising leadership if they are suitably combined in a given national industry. Moreover, if there is technology diffusion ($\beta_i > 0$), we can find situations in which consolidated leadership is not achieved by any of the industries. These situations are favored by decreasing returns to scale ($b < 1$) and by low propensities to invest (low θ). Figure 5a and Figure 5b illustrate this possibility without and with international diffusion of technology.

FIGURE 5

5 International mobility of scientists

We now consider a more general version of our model taking into account the international mobility of scientists. Let us assume, that a proportion σ, $(0 \leq \sigma < 1)$, of the scientists who finalize their training in each nation at any time decides, directly, to remain in their nation and join their national industry. The remaining proportion $(1-\sigma)$ consider the possibility of emigrating and developing their career in another nation. Thus, the number of new scientists that directly join their national industry is $\sigma y_i(t)$, and the overall (worldwide) number of mobile scientists at any time will be $(1-\sigma)\sum_j y_j(t)$.

Now, if we denote by $\upsilon_i(t)$, $(0 \leq \upsilon_i(t) \leq 1, \sum_j \upsilon_j(t) = 1)$, the proportion of the overall number of mobile scientists which decide to join the national industry i at t, it is clear that the condition of market clearing for the market of scientists in nation i will be:

$$\sigma y_i(t) + (1-\sigma)\upsilon_i(t)\sum_j y_j(t) = \dot{h}_i \tag{31}$$

Obviously, this equation generalizes equation (9). Therefore, we can obtain from (31) the generalized dynamics of the salary of scientists which substitute equation (10):

$$\frac{\dot{w}_i}{w_i} = \frac{\dot{s}_i}{s_i} - \frac{w_i(t)}{r_i}\left[\sigma\lambda_i + (1-\sigma)\frac{\upsilon_i(t)}{s_i(t)}\sum_j s_j(t)\lambda_j\right] \quad (32)$$

In order to formalize the dynamics driving the evolution of $\{\upsilon_i(t)\}_{i=1}^n$, we consider that scientists decide to develop their career in one national industry or another depending both on the wage differentials and on other non-monetary considerations. Among the latter, the possibilities perceived by scientists with regards to their ability to work effectively in their chosen field are fundamental (Güth, 2007; Regets, 2007). In our model, the greater or lesser effectiveness of the scientists' work is determined by the different productivity of R&D ($\chi_i(t)$) in the distinct national industries. Thus, if we denote by ε, $(0 < \varepsilon < 1)$ the relative sensitivity of scientists to non-monetary considerations, we can state that the evolution of $\{\upsilon_i(t)\}_{i=1}^n$ is given by the following replicator dynamics system:

$$\frac{\dot{\upsilon}_i}{\upsilon_i} = (1-\varepsilon)\left(w_i(t) - \overline{w}_\upsilon\right) + \varepsilon\left(\chi_i(t) - \overline{\chi}_\upsilon\right) \quad (33)$$

with $\overline{w}_\upsilon = \sum_j \upsilon_j(t)w_j(t)$ and $\overline{\chi}_\upsilon = \sum_j \upsilon_j(t)\chi_j(t)$.

Clearly, the model's dynamics for the case with international mobility of scientists are determined by equations (11), (12), (14), (32) and (33). We shall see (via simulations) some of the properties of this version of the model.

FIGURE 6

The simulations show that, in general, all the results obtained in the version without mobility regarding factors of growth and their relevance are maintained even when there is mobility. The same can be said regarding the existence of surprising leadership shifts. However, based upon the numerous simulations carried out (some of which are shown in

Figure 6), we can also point out that the international mobility of scientists favors the appearance and disappearance of leadership shifts. If a national industry is not a leader but it does attract scientists trained in this discipline, this competitive advantage can help it to achieve the leadership. As well as this, mobility can generate successive leadership shifts between different industries. In Figure 6b, we can see how leadership shifts between industries are carried out without any of the industries actually leaving the market (the situation represented is the same as in Figure 3b, but assuming that any scientist is willing to develop their career in a different nation from the one they studied or trained in, $\sigma = 0$).

In the same way, if we observe Figure 6a, we can confirm that the leadership shift seen in Figure 3a disappears. In this case, the scientists' mobility ($\sigma = 0.6$) means that the initial leader (industry 1) attracts scientists in such a way that the competitive advantages of the other two industries are not sufficient to seize the leadership. It has been shown that if the mobility is low ($\sigma = 0.8$) the leadership shift of Figure 3a re-appears.

Finally, we point out that other simulations for different ε have shown that the greater or lesser weight of monetary factors is very significant in questions of mobility. This, doubtlessly requires a deeper future study. This analysis will have to include a more complex definition of the salary evolution of scientists, also taking on board other factors such as legal labor conditions, freedom for investigation, and social recognition, among others.

6 Conclusions

Our aim in this work has been to propose a suitable model for the dynamic analysis of industrial leadership and industry growth in science-based industries. We have posed a model which, apart from moving in this direction, incorporates a richer body of institutions than are dealt with at present and fits with the conception of development as a catch-up problem. We have analyzed different versions of the model, with increasing complexity, by using formal methods and simulations.

The study of the model for the case of one isolated industry (as a first approximation to the general dynamics) reveals that only the second of the two immediate sources of growth in the model - capital accumulation and technological change – maintains its potential in the long term. The first source is strongly linked to θ (propensity to invest) and ρ_i (cost of production inputs), while the second one can be identified with α_i (technological capabilities), β_i (absorptive capacity), λ_i (responsiveness of uni-systems) and r_i (R&D to sales ratio).

This version of the model (one isolated nation) clearly shows the positive role of lower values of ρ_i and higher values of α_i and λ_i. Furthermore it shows the ambiguous role of r_i as a source of leadership. Thus, we have demonstrated that maintaining a high R&D to sales ratio is not always the most efficient strategic behavior. It will depend on the productivity of R&D, on the national salary of skilled labor, on the productivity of capital and on the existence of scale economies. This model also shows the crucial roles of the training in university systems and the absorptive capacity of nations for the rhythm of technological change. Moreover, if the national industry's absorptive capacity is sufficiently high, the international diffusion of leading technology will significantly accelerate industry growth.

The analysis of more complex versions of the model (2 or more national industries in global competition) confirms all the results obtained for the simplest case, and reveals new properties of the model. In these models we have used the Taylor polynomial approximation for the time-evolution of market shares to obtain (local) analytical results and simulations to assure the validity of these results at a global level.

The simulations allow us to apply econometric techniques to evaluate the relative and direct influence of different leadership sources (ρ_i, α_i, λ_i and r_i), setting out from a plausible standard scenario. The coefficients of direct impact we have obtained point to the production cost per unit of capital and the productivity of R&D as being those factors with the highest impact, followed by the responsiveness of uni-systems. They are the engines of growth and the factors which facilitate the rise to leadership and its consolidation. Once again, the international diffusion of knowledge conditions the nature of the results. More precisely, if the absorptive capacity of all the national industries is such that there is international diffusion of leading technology, the role of cheap access to essential production inputs as a source of leadership is intensified. This result seems to indicate that, if the technology is diffused internationally with facility, other factors (such as the privileged access to certain raw materials, energy, etc.) take on a crucial role.

Likewise, we have seen that, in certain cases, the rise to industrial leadership is not achieved by those competitors with a clear advantage in one (or several) sources of leadership, but rather by those who enjoy a sufficiently good combination of distinct factors. This result may explain the frequent existence of surprising leadership shifts in science-based industries.

Moreover, the international diffusion of knowledge and leading technology makes it difficult for one single industry to consolidate its market leadership and favors catching-up and the appearance of surprising leadership shifts. We have shown that, for non-leading industries, maintaining a position in the global market may be difficult (or even impossible) if the international diffusion of knowledge does not reach a certain intensity. These effects are even more relevant, the lower the returns to scale in the industry and the initial leader's propensity to invest. Given that the international diffusion of technology only takes place if the national industries have sufficient absorptive capacity, these results highlight the role of certain supporting institutions (public research institutions, international collaborations, etc.) for developing industries seeking to catch up.

We have also shown (in subsection 3.3) that there is a minimum (variable) stock of scientists that any industry requires so as not to lose market share in the global market. This necessary minimum stock will be greater, the higher the rhythm of technological progress in the sector and the lower the productivity of R&D. If we apply this result to the present reality of high-tech industries, we see that the acceleration of the rate of technological change, and the tightening of the copy conditions as a consequence of the TRIPS agreement, suggest the increase in the minimum stock of scientists needed by any industry trying to, at least, maintain its position. This seems to strengthen the role of national uni-systems and public research institutions (being training centers and attractors of highly-skilled labor) as sources of leadership and development engines in science-based industries.

Finally, our brief analysis of the model with international mobility of scientists seems to confirm the previous results. The principal effect of mobility consists of increasing the possibility of leadership shifts as it alters the competitive conditions between distinct national industries. The model with mobility has clearly shown the relevance of this aspect and suggests the need for a deeper future study.

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List of Symbols

q_i	level of production of the *i*-firm/industry.
k_i	capital stock of the *i*-firm/industry.
c_i	firm *i*'s unit cost.
A_i	level of technology of the *i*-firm/industry.
A^*	Technological frontier.
w_i	salary of scientists in nation *i*.
r_i	firm *i*'s R&D to sales ratio.
u_i	university budget devoted to a relevant scientific discipline in nation *i*.
y_i	number of scientists finishing their training at the *i*-national uni-system at any time.
h_i	number of scientists working in the *i*-national industry.
s_i	firm/industry *i*'s global market share.
f_i	firm/industry *i*'s capital productivity.
n	number of firms/national industries.
p	product price.
t	time.
γ_i	firm/industry *i*'s R&D budget.
ρ_i	firm/industry *i*'s production costs per unit of capital.
π_i	firm/industry *i*'s profit rate per unit of capital.
λ_i	national university system *i*'s institutional responsiveness.
α_i	firm/industry *i*'s technological capabilities.
β_i	firm/industry *i*'s absorptive capacity.
χ_i	firm/industry *i*'s productivity of R&D.
v_i	share of new mobile scientists that join the *i*-national industry.

δ size of the global market potential.

b returns to scale parameter.

a_x heterogeneity degree regarding the *x*-factor (simulations).

x factor that we study in each case (simulations).

ϕ_x Weight of the *x*-source of leadership (econometrics).

θ propensity to invest.

ε sensitivity of mobile scientists to non-monetary factors.

σ level of rigidity in the international mobility of scientists.

Table 1. Standard Scenario

Industry	$k_i(0)$	$A_i(0)$	$w_i(0)$	β_i	r_i	α_i	ρ_i	λ_i	General	Value
1	10	1 or 1.1	1	0 or 0.5	0.02	0.05	1.1	0.002	δ	50
2	10	1.1	1	0 or 0.5	0.02	0.05	1.1	0.002	θ	0.2
3	10	1.2 or 1.1	1	0 or 0.5	0.02	0.05	1.1	0.002	b	0.8 or 1.1

Table 2. The relative weight of different sources of leadership

		ϕ_α	ϕ_ρ	ϕ_λ	ϕ_r	R^2
$\beta_i = 0$	$b = 1.1$	3.13902 (10.054)	5.4027 (17.3402)	1.81971 (5.81396)	1.52815 (4.89456)	0.895207
	$b = 0.8$	3.78228 (13.5852)	3.68589 (13.2663)	2.43679 (8.73075)	1.60784 (5.77501)	0.895062
$\beta_i = 0.01$	$b = 1.1$	1.05134 (17.7021)	1.87383 (31.6159)	0.440438 (7.39752)	0.447815 (7.54012)	0.963803
	$b = 0.8$	1.47217 (40.1575)	1.38696 (37.9113)	0.968431 (26.3511)	0.618209 (16.8634)	0.986483
$\beta_i = 0.1$	$b = 1.1$	3.87734 (7.87644)	8.5566 (17.4178)	2.2803 (4.62071)	1.50028 (3.04767)	0.881726
	$b = 0.8$	9.70067 (7.04141)	13.2 (9.60122)	7.46799 (5.40733)	2.54059 (1.84414) (**)	0.763809
$\beta_i = 0.5$	$b = 1.1$	3.49699 (4.8463)	14.4075 (20.0079)	2.10639 (2.9119)	0.48249 (0.668659) (**)	0.892365
	$b = 0.8$	(*)	(*)	(*)	(*)	(*)

(*) Fit not possible since several firms survive.
(**) The value is not significant.

Figure 1: The case of one isolated industry

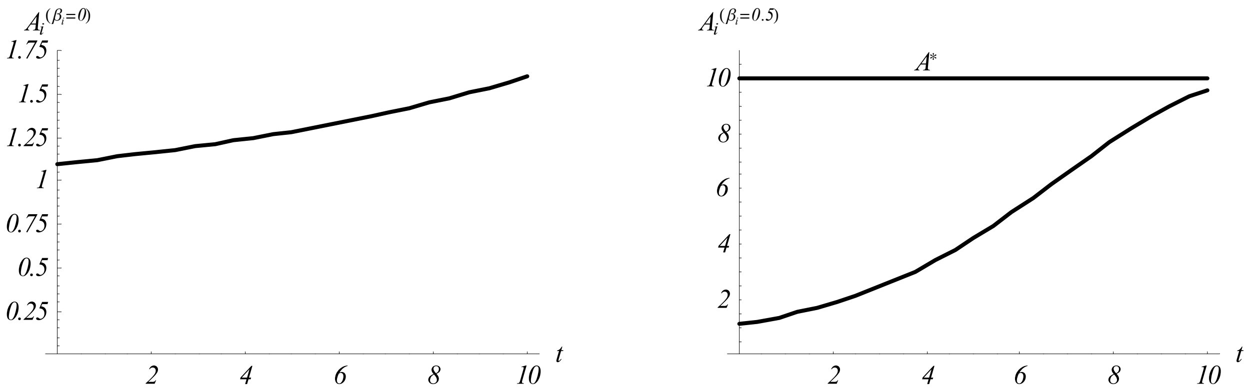
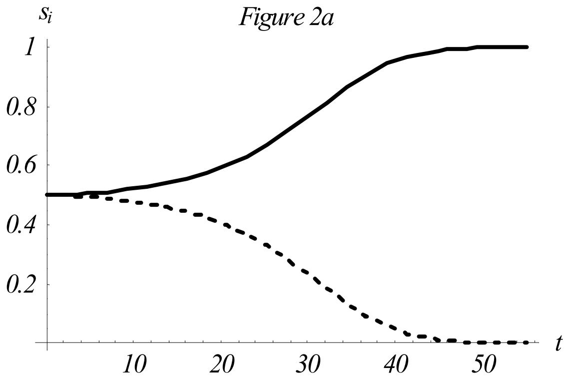
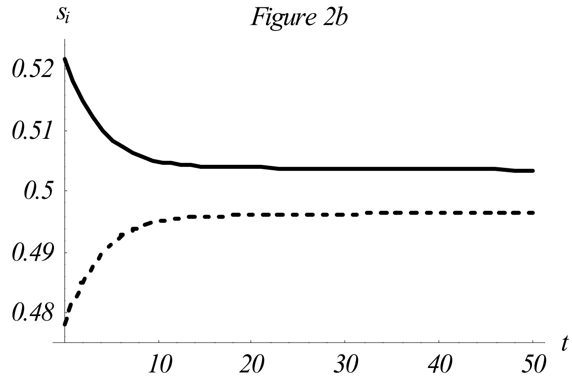


Figure 2: The case of two national industries

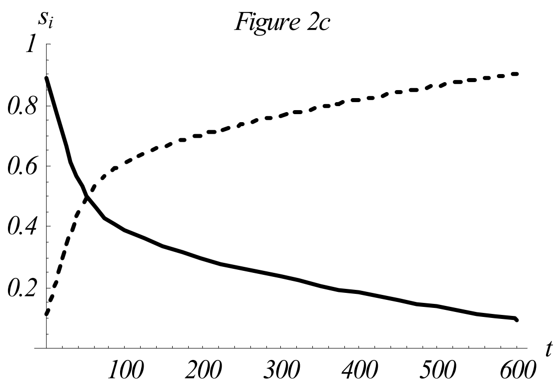
(- - - - firm 1; —— firm 2)

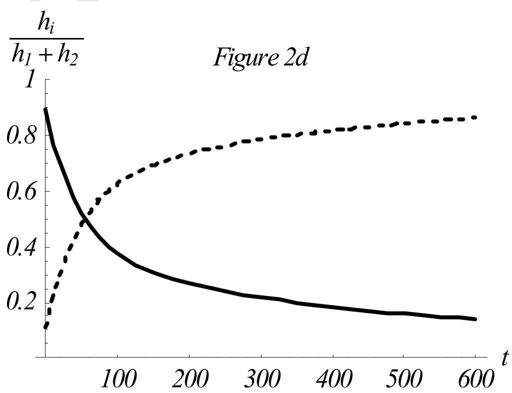


b = 1.1, β_i = 0, α_1 = 0.05 < α_2 = 0.0545



b = 1.1, β_i = 0.5, θ = 0.0006, α_1 = 0.05 < α_2 = 0.0545

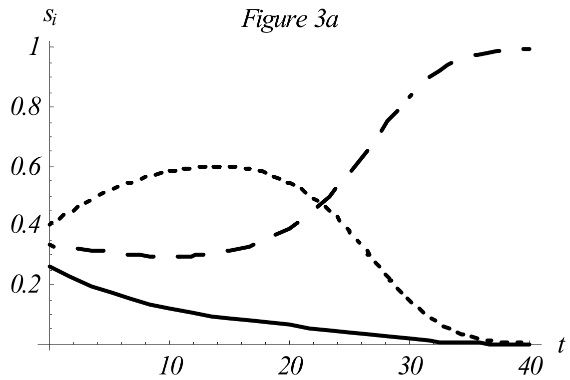




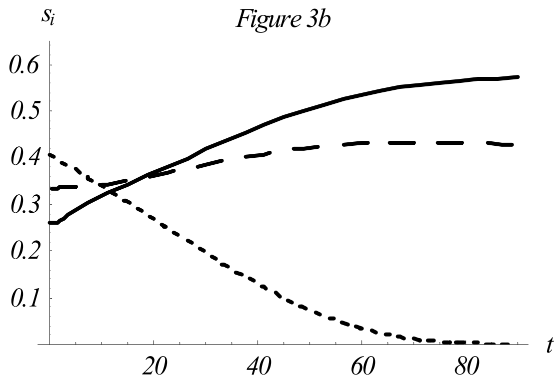
b = 0.8, β_i = 0.8, λ_1 = 0.005 > λ_2 = 0.002, ρ_1 = 1.1 < ρ_2 = 1.2

Figure 3: The case of three national industries

(- - - - - firm 1; — — — firm 2; —— firm 3)



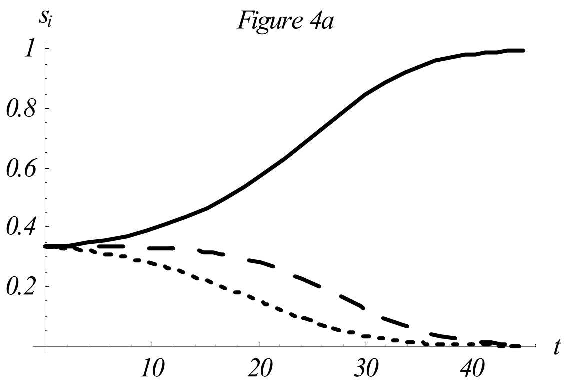
$b = 1.1$, $\beta_i = 0$, $\lambda_1 = 0.001 < \lambda_2 = 0.005 < \lambda_3 = 0.009$



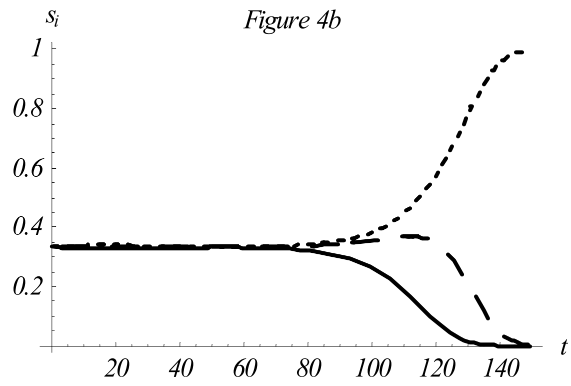
$b = 0.8$, $\beta_i = 0.8$, $\lambda_1 = 0.001 < \lambda_2 = 0.005 < \lambda_3 = 0.009$

Figure 4: The role of the R&D to sales ratio r_i

(- - - - - firm 1; — — — firm 2; —— firm 3)



$b = 1.1$, $\beta_i = 0$, $r_1 = 0.01 < r_2 = 0.02 < r_3 = 0.03$, $w_i(0) = 1$

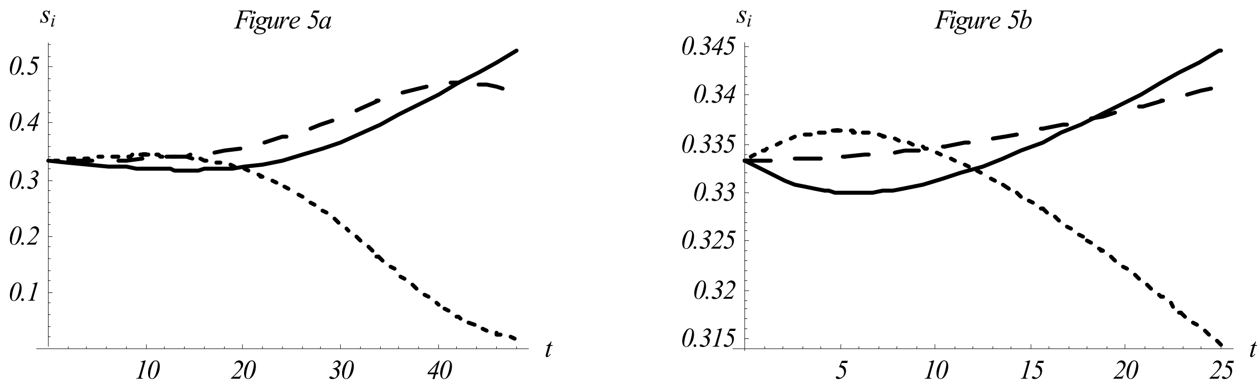


$b = 1.1$, $\beta_i = 0$, $r_1 = 0.01 < r_2 = 0.02 < r_3 = 0.03$, $w_i(0) = 10.75$

Figure 5: Industrial leadership shifts

(- - - - - firm 1; — — — firm 2; —— firm 3)

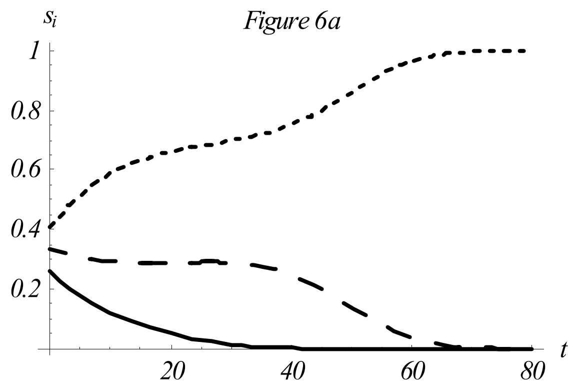
$\lambda_1 = 0.001 < \lambda_2 = 0.002 < \lambda_3 = 0.003$, $\alpha_1 = 0.06 > \alpha_2 = 0.05 > \alpha_3 = 0.04$



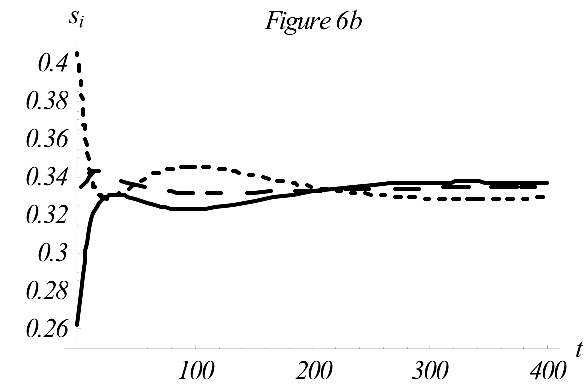
$b = 1.1$, $\beta_i = 0$ $b = 0.8$, $\beta_i = 0.5$

Figure 6: International mobility of scientists

(- - - - - firm 1; — — — firm 2; —— firm 3)



$\sigma = 0.6$, $\varepsilon = 0.5$, $b = 1.1$, $\beta_i = 0$, $\lambda_1 = 0.001 < \lambda_2 = 0.005 < \lambda_3 = 0.009$



$\sigma = 0$, $\varepsilon = 0.5$, $b = 0.8$, $\beta_i = 0.8$, $\lambda_1 = 0.001 < \lambda_2 = 0.005 < \lambda_3 = 0.009$