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Innovation dynamics and labor force restructuring with asymmetrically developed national innovation systems

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ABSTRACT

The concept of National Innovation System (NIS) has gained a great deal of intellectual and practical attention over the past three decades. We present an endogenous growth model where the NIS of a country determines its accumulation of technological knowledge and the arrival rate of innovations depends on the distance from the technological frontier to the current technological development level (TDL) of the country. We show how, even *within an ideal common market environment* and despite the compensatory mechanism provided by migration and the advantage of backwardness enjoyed by the laggard countries, differences in TDLs among countries foster the economic stagnation of technological laggards. That is, the structural consequences derived from technological underdevelopment are persistent and not simply due to the depreciation of human capital, but to the absence of innovation incentives that follows. Numerical simulations and an empirical analysis are performed to illustrate the main results and relate them to the current European common market setting and the innovation policies of its members.

1. Introduction

1.1. Motivation and intuition

The economic literature has progressively recognized the fact that the assimilation of the most advanced technological capital by less developed countries constitutes a growth mechanism requiring important amounts of both physical and human capital investment (Aghion & Howitt, 1999, 2005; Howitt & Mayer-Foulkes, 2005; Sharif, 2006; Acemoglu, 2008; Borsi & Metiu, 2015). Consequently, quality and level of education asymmetry, as well as, institutional and trade frictions constitute the main divergent forces highlighted in the literature.

The importance of education in terms of human capital formation and accumulation, together with the institutional infrastructure of a country and its governance, have been empirically identified as determinants of innovation-induced growth by Varsakelis (2006), Giménez and Sanaú (2007), Fagerberg, Verspagen, and Caniels (1997), Chen, Hu, and Yang (2011) and Veugelers and Schweiger (2015). Moreover, the cumulative nature of technology is a widely recognized fact (Mukoyama, 2003), and the costs of learning a technology are known to be considerable (Engel & Kleine, 2015; Jovanovic, 1997). Thus, in an ideal common market setting without educational, institutional or trade barriers, all economic fluctuations should be caused by differences in technological development and assimilation levels among countries.

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Consider, for example, a world economy composed by two types of countries each of which is defined by its National Innovation System (NIS). Assume that both countries produce the same good (s), technological innovations are transferred immediately and with negligible cost between them, and no trade, educational, institutional or demand frictions exist between the countries. All labor is skilled and allowed to move freely according to the wage received based on its marginal productivity. Countries only differ in their technological development level (TDL), which, at the same time, determines their ability to assimilate the knowledge implicit in any newly developed technology and generate further innovations (Ballot & Taymaz, 1997; Castellacci & Natera, 2015). Thus, countries will be distributed in two different groups, one composed by technological leaders and the other one by laggards.

The above description corresponds to a textbook European common market subject exclusively to differences in TDLs across its members. We analyze the consequences derived from the corresponding technological adjustment process in terms of optimal labor allocation, migration patterns and technological evolution. We will identify the level of technological development of a country with that of its technological base. As illustrated by Furman, Porter, and Stern (2002) and Castellacci and Natera (2013), the technological base [infrastructure] of a given country limits its ability to innovate and learn through assimilation if it does not develop simultaneously to the level of technological knowledge acquired by the workers. That is, human capital is redundant if it is not complemented by an adequate technological infrastructure. The lower the level of development of the technological infrastructure, the lower the factor productivity obtained from any new technology and the probability of generating innovations (Silva & Teixeira, 2011; Teixeira, Silva, & Mamede, 2014).

As a consequence, the optimal allocation of labor across countries and their corresponding economic evolution would be directly determined by the level of development of their respective technological bases. However, despite the importance that innovation and the diffusion of technology have had for the European growth process through the 1980s, laggard countries failed to take advantage of the more advanced technology available due to a lack of their own R&D capabilities (Fagerberg et al., 1997).

In this regard, the pervasive effects inherent in an underdeveloped NIS become evident when considering several indicators within the technology and innovation-related pillars composing the global competitiveness index (World Economic Forum, 2013). Table 1 presents the indicators selected from these technology-related pillars for the countries under analysis in the paper. The data represent the position of the corresponding country from a total of 148 composing the global competitiveness ranking.

As illustrated in Table 1, the main constraints suffered by technological laggards (Greece, Italy, Portugal and Spain) are not the lack of skilled human capital or a limited access to the latest technologies available. Though slightly behind in both indicators, their situation is not considerably worse than that of the technological leaders (Denmark, Finland, Germany and Sweden). Indeed, as our empirical analysis will show, laggard countries are able to increase the resources dedicated to R&D activities when subject to a negative shock to their economies. On the other hand, the structural nature of the constraints suffered by these countries is reflected on:

- Their lack of capacity to innovate and retain talented human capital.
- The inability of their firms to absorb technologies.

1.2. Contribution

Given the intuition provided in the previous section, we build our model on two main features of the European economic system:

- From a formal standpoint, Table 1 together with the literature surveyed imply that:
  - The integration of physical and human capital is required to generate persistent economic growth.
  - The development of the NIS is essential to determine the capacity of a country to assimilate technology and innovate.

- From an empirical standpoint, the following behavior is observed across the European countries analyzed:
  - Technological leaders do not modify the intensity of their R&D when subject to shocks to their real economy.
  - Technological laggards react to shocks to their real economy by modifying the intensity of their R&D. However, these responses lack a persistent effect on their NISs.

Our model accounts for the formal features described above and explains the empirically observed behavior of the countries being analyzed. In particular, we illustrate how, even within a frictionless common market environment where technological innovations become immediately available to all countries, differences in TDLs constrain the incentives and the capacity of the laggards to innovate. Thus, as suggested by the literature on technological catch-up and absorptive capacities, differences in TDLs alone suffice to constrain the convergence process of the laggards (Hanusch & Pyka, 2009; López, Molero, & Santos-Arteaga, 2011; Castellacci & Natera, 2016).

However, the current paper goes beyond the fact that technological underdevelopment depreciates the skilled composition of the labor force and generates unemployment. As stated by the theoretical literature on brain drain and economic development (Bosetti, Cattaneo, & Verdolini, 2015; Docquier & Rapoport, 2012), migration processes reallocate skilled workers among the technologically developed countries allowing for a temporary

Table 1
Several innovation-related indicators composing the global competitiveness index*.

Country	Availability of scientists and engineers	Availability of latest technologies	Firm-level technology absorption	Capacity for innovation	Country capacity to retain talent
Denmark	36	29	20	13	43
Finland	1	1	7	2	2
Germany	17	13	16	3	9
Sweden	10	2	1	7	10
Greece	5	67	88	117	86
Italy	29	69	112	31	117
Portugal	16	15	29	42	111
Spain	11	33	49	57	108

**Note*: Data retrieved from the *The Global Competitiveness Report 2013-2014: Full Data Edition.* Refer to World Economic Forum (2013) for additional information regarding these variables. The indicators have been taken from the 7th (Labor market efficiency), 9th (Technological readiness) and 12th (Innovation) pillars.

relief within the laggard ones. We illustrate how, despite this compensatory mechanism and the advantage of backwardness enjoyed by the laggards, their incentives to innovate may also stagnate unless exogenous structural incentives are provided.

The structural consequences derived from technological underdevelopment are therefore persistent and due not only to the depreciation of skilled unemployed human capital through time, but also to the long-run innovation disincentives that follow, which oppose the advantage of backwardness defined by Gerschenkron (1952). That is, the incentives generated by the economic system may be insufficient for the laggards to recover technologically and converge. Thus, the design of science and innovation policy mixes should not only address the current brain drain taking place among technological laggards (Heitor, Horta, & Mendonça, 2014), but also try to prevent their long-run economic stagnation (Borrás & Edquist, 2013).

1.3. On innovation and employment

Innovation is quite a difficult concept to grasp and measure (Vivarelli, 2014b). Standard indicators such as research and development (R&D) and patents are not always fully available and are often inadequate to capture technological progress. In particular, small and medium enterprises generally perform innovation activities by acquiring capital and implementing its inherent technology into their production processes. Such an innovation strategy is referred to as embodied technological change. Empirical studies of the European Community have shown that R&D expenditures usually relate to product innovation, while innovative investments are associated with process innovation (Antonucci & Pianta, 2002; Parisi, Schiantarelli, & Sembenelli, 2006).

We consider both these approaches to innovation in our empirical analysis. More precisely, we will use the R&D intensity variables available from Eurostat and the Summary Innovation Index (SII) designed by the European Commission to measure the technological development and innovation capacities of countries. Formally, we introduce a variable, ξ, to simplify and condense the main ideas and concepts determining the TDL and the innovation capacity of a country. This variable will be used to define the total factor productivity (process) and the probability of introducing an innovation (product), which together determine the number of skilled workers that can be employed by the country. At the same time, introducing an innovation to the market will lead to both an increase in total factor productivity and an improvement in the technological base of the country.

The effect of innovation on employment has been empirically shown to depend on whether the innovation introduced is in a product or in a process. See Vivarelli (2013) for a review of the literature on this topic. Harrison, Jaumandreu, Mairesse, and Peters (2014) used firm level data from Germany, France, UK, and Spain over the period 1998–2000 to illustrate the importance that the interaction between product and process innovation and the demand for products has for employment creation. They observed that process innovation causes a displacement of employment, while product innovation tends to generate employment. Bogliacino, Lucchese, & Pianta (2013) reached a similar conclusion analyzing European business services over the period 1996–2007. However, they also noticed that the demand for new and old products can mitigate the negative displacement effect. Van Roy, Vertesy, & Vivarelli (2015). measured the labor-friendly nature of innovation within a set of 20.000 European patenting firms over the period 2003–2012. They observed that the positive impact of innovation is significant for firms in the high-tech manufacturing sector but not for firms in the low-tech manufacturing and service sectors.

The efficiency of the compensation mechanism for the initial labor-saving impact of (process) innovation depends on the institutional environment of the country and on the sector specific values of parameters such as demand elasticity, degree of competition, capital-labor substitution, demand expectations, and so on (Pianta, 2005; Vivarelli, 2014b). We assume that all countries are identical in this respect, all endowed with an infinitely elastic demand and the same institutional environment.

Our assumptions impose a positive relationship between innovation and employment, with a more developed technological base allowing a country to attract and employ a higher number of (skilled) workers. This leads to a self-reinforcing pattern in the behavior of countries, since a larger number of highly productive workers generates a higher amount of output and yields a higher innovation probability. In this regard, the growth mechanism considered in this paper differs from the standard one employed by growth theorists, which relies on capital accumulation as the mechanism leading to productivity growth and economic development (Greenwood, Hercowitz, & Krusell, 1997; Wilson, 2009). In our setting, knowledge will be assumed to be embodied in the technological base of a country and accumulate as its NIS develops.

Finally, we also assume that the efficient implementation of the available technology requires suitable skills among the labor force, i.e. skilled-biased technological change. Consequently, the lack of skilled labor limits the adoption and diffusion of new technology, defining a human resource constraint that restricts the production of a country and its capacity to innovate (Amendola & Gaffard, 1988; Murphy & Topel, 2016; Pargianas, 2016). Note, that at the same time, we do not consider the budgetary burdens derived from a relative increment in the number of unskilled or unemployed workers within the laggard countries.

The paper proceeds as follows. Section 2 introduces the model and derives analytically the optimal behavior of countries. Section 3 analyzes numerically the main consequences of the model for convergence via wage differentials. Section 4 verifies empirically the formal results obtained in the previous sections. Section 5 studies the resulting policy implications and the consequences for the Europe 2020 strategy. Section 6 presents the main conclusions derived from the paper. Formal proofs are relegated to the appendix.

2. The basic model

2.1. Assumptions

Consider, without loss of generality, a common market area consisting of two countries and one industrial sector (NIS) per country composed by a finite number of M firms operating within it. We assume that the goods produced in each country are identical, that is, both countries have a unique overlapping sector. The main results obtained hold if a continuum of industrial sectors is considered. In this case, differences between countries would be based on the relative development of their NISs (Lundvall, 2007; Hardeman, Frenken, Nomaler, & Ter Wal, 2015). Similarly, if a larger number of countries is assumed to compose the common market area, they could be classified in different convergence groups according to their TDLs, an exercise already validated empirically by Filippetti and Archibugi (2011) for the Euro-27 group. In addition, identical unitary prices are assumed in both countries for the most technologically advanced good being produced. The exchange rate is fixed within the area and is assumed to be equal to one.

There are initially $n \in \aleph$ workers per firm in each country. The labor force is composed exclusively by skilled workers, who are used in manufacturing and innovation activities. That is, the initial endowments of human capital are identical in both countries. A differentiated distributive approach distinguishing between *unskilled* manufacturing and *skilled* innovative labor is presented in López et al. (2011). We are however interested here in the divergent effects derived from the continuously evolving technological race that takes place between countries through time absent labor allocation considerations. Thus, human capital formation processes are not accounted for and identical education systems are assumed in both countries, a far from mild assumption when the European market area is considered (European Commission, 2013). It should be noted that relaxing this assumption would worsen the innovation capabilities of the laggards.

If labor is used in manufacturing activities, the quantity of manufactured output produced is limited by the relative TDL of the country. This variable reflects the distance existing between two countries within a particular technological paradigm and it is described as follows: $\xi = \lambda^r/\lambda^*$, where λ^* accounts for the level of development of the technological base necessary to generate the latest productivity improving innovation (i.e. the technological frontier), while λ^r stands for the level of development achieved by the technological base of the country. At the same time, when labor is used in innovative activities it increases the probability of innovating and achieving a higher TDL, i.e. of improving the technological base of the country. The innovation probability of a country as well as the productivity of its labor will both be determined by ξ, a fundamental point to which we will return in the next section.

We assume time to be continuous and measured by discrete innovations. That is, one unit of time corresponds to the time interval required for the next innovation to appear. If, in particular, two innovations take place simultaneously, continuity allows separating them in two different units of time (Aghion & Howitt, 1992).

At a given point in time, one of the firms within a given country develops and introduces an innovation in the market while the remaining ones behave as manufacturers. We will refer to the former one as the *innovator firm* (IF) and to the latter ones as the *manufacturing firms* (MFs). The country whose industry accounts for the latest innovation will be called *innovator country*. Differently from the theoretical literature on quality ladders (Grossman & Helpman, 1991), we assume that *all firms in both countries* have immediate access to the most advanced production technology.

A common development strategy is assumed to be followed by the whole [common] market area so that no patent or technological monopoly constitutes an impediment for convergence between countries. Thus, innovations give the innovator a factor productivity advantage over the rest of the firms in both countries. As a result, all firms will charge the same quality adjusted price for the most technologically advanced good being produced. We assume that innovation incentives are provided by infinitely elastic demand functions absorbing the whole production of the good per period of time in each country. This assumption, together with the fixed unitary exchange rate and the identical quality adjusted prices, prevent both countries from trading in goods.

It should be emphasized that relaxing any of the assumptions described above would have an immediate effect on the innovation incentives of the laggard countries, yielding a downward shift of their corresponding equilibrium wage functions. This would restrain the prompt response of laggards to decrements in the relative development of their NIS and increase the lower limit level of ξ at which the stagnant trap starts.

The production function of a MF located in a technological laggard country is given by

$$Y_{sm} = \xi A^{1-\alpha} K^{\alpha} n^{1-\alpha}, \tag{1}$$

where K refers to the physical capital used in production while A corresponds to the productivity of the technology, which will be assumed identical to the productivity frontier $\overline{A^*}$ at all points in time for both countries. Note that the most productive technology can only be exploited up to the limit imposed by the TDL of the country. That is, all firms in both countries are able to produce the most technologically advanced good and have access to the same frontier technology, but their total factor productivity differs depending on the value of ξ achieved by the country where they are located.

The production function of an IF in its industrial sector is given by

$$Y_{sn} = \Gamma^2 A^{1-\alpha} K^{\alpha} n^{1-\alpha} \tag{2}$$

where $\Gamma > 1$, and $\xi = 1$. Developing a leading technological innovation allows the IF to increment its productivity over that of the previous industry leader by a factor of Γ. That is, total factor productivity grows at a constant rate of $(\Gamma - 1)$ per unit of time. Also, being a technological leader implies that the value of ξ within the corresponding industrial sector must be equal to one.

In order to account for geographical knowledge and technology spillovers, we will assume that the production function of the MFs located within the innovator country is given by

$$Y_{sm} = \gamma A^{1-\alpha} K^{\alpha} n^{1-\alpha}, \qquad 1 < \gamma < \Gamma \tag{3}$$

MFs located in the innovator country benefit from being geographically close to the IF, which allows for direct information spillovers that increase their factor productivity (Cohen & Levinthal, 1989; Singh, 2007; Livanis & Lamin, 2016). This location advantage constitutes the only friction in favor of the innovator country explicitly introduced within the current environment.

All workers receive the same wage within a country, w^m in technological laggards and w^n in the innovator country, independently of their activity. Since the price of the most technologically developed good being produced is identical in both countries, all wages will be directly comparable in real terms. That is, divergences in real wages will be caused by productivity frictions derived from differences in ξ values between countries. We omit the effects that monetary policies designed to distort prices may have on the wage distribution between countries. Governments are therefore limited in their ability to use these instruments and compete exclusively in terms of TDLs.

2.2. Optimizing countries

Countries face the intertemporal problem of maximizing the expected flow of profits obtained from their firms while being limited by their TDL. The expected profit function corresponding to a technological laggard country is given by

$$\Pi(t) = E \int_t^{+\infty} e^{-\rho[\tau - t]} \pi(n|\xi) d\tau, \tag{4}$$

where

$$\pi(n|\xi) = \xi A^{1-\alpha} K^{\alpha} n^{1-\alpha} - w^m n, \tag{5}$$

ρ represents the rate of time preference for any given firm, assumed identical both among firms and between countries, and w^m stands for the wage paid to the skilled labor.

Note that the definition of $\pi(n|\cdot)$ provides a simplified version of the proportional composition of the industrial sectors under consideration and will be also used for the profit function of the innovator country. That is, the factor productivity of the industrial sector of the innovator country is given by $1/M)\Gamma + M - 1)/M)\gamma$, which should lead to the following expression for its profit function:

$$\pi(n|\gamma) = \left(\frac{\Gamma}{M} + \frac{M-1}{M}\gamma\right)A^{1-\alpha}K^{\alpha}n^{1-\alpha} - w^{m}n. \tag{6}$$

This equation describes a unique IF whose productivity (Γ) is higher than the productivity (γ) of the remaining $M-1$ MFs within the country. However, to simplify this equation we define the profit function of the innovator country as follows

$$\pi(n|\gamma) = \gamma A^{1-\alpha}K^{\alpha}n^{1-\alpha} - w^{m}n. \tag{6'}$$

A similar simplification is imposed when defining the stochastic evolution of the TDL of countries. Innovations within the industrial sectors of a country are governed by a Poisson process whose arrival rates are respectively defined by $\theta_{(\gamma,n)} = \gamma n$ and $\theta_{(\xi,n)} = \left(\overline{\xi} + (1-\overline{\xi})\xi\right)n$. That is, the technological distance between countries and the number of skilled workers affect their innovation probabilities. Note that we have endowed laggards with a basic TDL, $\overline{\xi}$, on which their current ξ can build to prevent complete stagnation at low levels of development. The importance of $\overline{\xi}$ as a mechanism of direct technology transfer will be highlighted in the numerical simulations. As illustrated in the following section, these functional forms decrease the converging capabilities of technological laggards. Note that the workers located in the innovator country have access to a more developed technological infrastructure than those located within the laggard country. As a result, knowledge and human capital accumulate and spread faster in the innovator country, leading to a higher innovation probability. See Gupta and Chakraborty (2006) for a related formal setting.

The stochastic evolution of the TDL achieved by a country per innovation unit of time is determined by its current value and the Poisson process defining the innovation arrival rate. The increase in the TDL of *a laggard country if an innovation takes place among any of its firms* equals

$$d\xi^{m} = \left(\frac{\Gamma^{2}}{M} - \frac{\xi}{M} + \frac{M-1}{M}\gamma - \frac{M-1}{M}\xi\right)dz_{\xi}, \tag{7}$$

with the arrival rate of the corresponding Poisson process z_{ξ} determined by $\theta_{(\xi,n)}$.

Similarly, the increase in the TDL of *an innovator country if an innovation takes place among any of its firms* equals

$$d\xi^{n} = \left(\frac{\Gamma^{2}}{M} - \frac{\Gamma}{M}\right)dz_{\xi}. \tag{8}$$

The technological growth function defined within the laggard industry consists of an increase from an initial ξ productivity level in all M firms to a resulting Γ^2 level in one of the firms and a level of γ in all the $M-1$ remaining ones. In the same way, an innovator country would obtain an increment in the productivity of one of its firms from a level of Γ to a level of Γ^2, with all of its $M-1$ remaining firms stabilized at γ.

Eqs. (5)–(8) and the Poisson arrival rates illustrate how the model allows for the index variable ξ to account for all the technological differences existing between countries. That is, we are implicitly assuming that an innovation develops the technological infrastructure of its corresponding industrial sector but that such an advantage does not necessarily generalize to the whole country. In this regard, Eqs. (7) and (8) could be redefined in terms of industrial sectors, instead of firms within a sector, to highlight this restriction. Such a constraint emphasizes the importance that *the whole* technological infrastructure of a country (i.e. its NIS) has for its economic development (Furman et al., 2002; Bartels, Voss, Lederer, & Bachtrog, 2012).

Indeed, a country may master technologically a particular sector but lack the required infrastructure at the country level to evolve technologically and grow, a case represented by Cuba and its highly sophisticated biotechnological sector (Thorsteinsdóttir, Sáenz, Quach, Daar, & Singer, 2004; Nature, 2009). Similarly, individual firms within laggard countries may master innovation in their corresponding sectors while the country remains technologically underdeveloped (Forbes & Wield, 2008). In other words, increasing the number of sectors considered would not modify the main results obtained.

Furthermore, the skilled labor force must interact with the technological infrastructure of the country to generate economic growth. That is, countries can be endowed with a highly qualified labor force but lack the infrastructure to develop technologically and generate innovations. Two significant examples where the lack of coordination between human capital and their corresponding infrastructures has constrained economic growth are those of India and Russia. The former has a large (publicly funded) technological infrastructure and a considerable education base, but is constrained by a fragmented innovation environment exacerbated by bureaucratic inefficiencies (Abhyankar, 2014; Herstatt, Tiwari, Ernst, & Buse, 2008). The latter is characterized by the very high quality of its research but is limited in the absorption capacity of innovations and the generation of significant technology-based economic growth (Williams, 2011).

Due to the comparative nature of this study, we consider the innovator country as the reference point to which laggard countries must converge. Thus, we simplify the equations defining the stochastic evolution of ξ as we did with the profit function of the innovator country. That is, we treat the evolution of each sector as that of a unique firm. Note that this modification leaves the main results qualitatively unaffected while simplifying the presentation considerably.

The stochastic differential equation defining the evolution of ξ within the laggard country reads as follows:

$$d\xi^{m} = \left[\frac{\pi(n|\xi)}{\pi(n|\gamma)}\right]dt + \left(\Gamma^{2} - \xi\right)dz_{\xi}, \tag{9}$$

while that defining the evolution of ξ within the innovator country is given by

$$d\xi^{n} = [1]dt + \left(\Gamma^{2} - 1\right)dz_{\xi}. \tag{10}$$

All profits have been assumed to be invested by each country in the improvement of their relative TDLs, with the laggard country being able to invest a smaller amount than the innovator one *ceteris paribus*. Note the larger improvement in TDL derived from an innovation by the laggards relative to that of the leader/innovator. That is, it is possible for the laggards to catch-up with the innovator though the probability of doing so is determined by $\theta_{(\xi,n)}$.

The model has been designed to represent different countries within a common market area that share sufficient similarities to allow for relatively frictionless migration flows between them. Thus, even though n is initially identical in each country, relative changes would take place if a laggard country cannot provide the wage incentives required to maintain its skilled labor force. The absence of trade between countries implies that the migration patterns act as a compensatory force to equate their w levels.

2.2.1. Optimality

The continuous flow of technology has a direct effect on the optimal behavior of countries, which must maximize all the output obtained from their skilled labor given their relative TDL and the probability that any of their firms develops the next innovation.

The Bellman equation defining the intertemporal optimization problem of a laggard country is given by[1]

$$\rho V^m(\xi) = \max_n \left[\pi(n|\xi) + V_\xi(\xi)\left[\frac{\pi(n|\xi)}{\pi(n|\gamma)}\right] + \theta_{(\xi,n)}[V(\Gamma^2) - V(\xi)]\right], \tag{11}$$

while that of the innovator country is

$$\rho V^n(\xi) = \max_n \left[\pi(n|\gamma) + V_\xi(\xi) + \theta_{(\gamma,n)}[V(\Gamma^2) - V(1)]\right]. \tag{12}$$

Both equations allow for a direct comparison between the outputs generated through manufacturing and innovation activities, respectively. Manufacturing increases the current profits of countries (i.e. $\pi(n|\xi)$ for laggard countries and $\pi(n|\gamma)$ for innovator ones), and leads to a deterministic increase in ξ, whose marginal value is denoted by $V_\xi(\xi)$. Clearly, the marginal value effect of manufacturing on ξ must account for the corresponding profits obtained and invested by the firms of the innovator country.

At the same time, the expected output derived from introducing an innovation is computed multiplying the arrival rate defined by the corresponding Poisson process, $\theta_{(\xi,n)}$ and $\theta_{(\gamma,n)}$, by the respective value increase determined by the changes in ξ, $[V(\Gamma^2) - V(\xi)]$ and $[V(\Gamma^2) - V(1)]$. Countries must therefore find a balance between their (short run) manufacturing incentives and their (long run) expected innovation profits. See Arcalean et al. (2012) for a related trade-off setting. After some algebra, we obtain the following first order condition for laggard countries

$$w_*^m = \frac{(\bar{\xi} + (1-\bar{\xi})\xi)[V(\Gamma^2) - V(\xi)]}{\left(1 + \frac{V_\xi(\xi)}{\pi(n|\gamma)}\right)}, \tag{13}$$

and the corresponding one for the innovator country

$$w_*^n = \gamma[V(\Gamma^2) - V(1)], \tag{14}$$

with

$$w_*^m = w^m - (1-\alpha)\xi A^{1-\alpha}K^\alpha n^{-\alpha}, \qquad w_*^n = w^n - (1-\alpha)\gamma A^{1-\alpha}K^\alpha n^{-\alpha}. \tag{15}$$

The first order conditions are expressed as equilibrium equations describing the wage differentials between countries. The optimal wage paid to skilled workers, w_*^i, with $i = m, n$, is therefore determined by the value gain differentials $[V(\Gamma^2) - V(\cdot)]$ existing between both countries and the marginal value change generated by technological development in laggard countries, $V_\xi(\xi)$. In other words, the first order conditions provide a rule relating the optimal allocation of skilled labor between countries to the relative values of ξ (and γ).

Absent cultural differences-based frictions, which is a far from innocuous assumption to be made regarding the European Union and its member states (De Simone & Manchin, 2012), migration patterns can be assumed to follow real wage differentials between countries. That is, workers may be assumed to maximize their total consumption, c, given the unique set of unitary prices and a budget constrain such that $c \le w$, where w stands for the wage received by the worker. In this case, optimal wage dynamics depend on the relative differences existing between $[V(\Gamma^2) - V(1)]$ and $[V(\Gamma^2) - V(\xi)]/(1 + V_\xi(\xi)/\pi(n|\gamma))$. In particular, the model will give place to convergent dynamical patterns if

$$V(\Gamma^2) - V(1) < \left[(\frac{\bar{\xi} + (1-\bar{\xi})\xi)}{\gamma}\right]\frac{[V(\Gamma^2) - V(\xi)]}{\left(1 + \frac{V_\xi(\xi)}{\pi(n|\gamma)}\right)}, \tag{16}$$

while divergent dynamical patterns may be generated reversing the above inequality.

Divergences are also exacerbated if the technological distance between countries leads the wage paid to skilled workers within the innovator country to be higher than the one paid by the laggards. That is, if technological laggards were forced to hire a lower number of workers in order to increase their relative productivity and, therefore, their wages, then the corresponding innovation probability $\theta_{(\xi,n)}$ would also decrease. The numerical section shows that as the degree of concavity defining the value function increases, the set of ξ values leading to the technological stagnation of the laggards tends to widen.

3. Results

3.1. Basic intuition

The implications of the relative TDL for the wage differentials and optimal distribution of labor between the innovator and the laggard are determined by the first order conditions defined by Eqs. (13) and (14). In other words, the technological evolution of laggard countries will be determined by the value function form defining the right hand sides of both these equilibrium equations.

In our model, wage differentials can be used by laggard countries to attract skilled labor in order to compensate for their lower TDL. At the same time, the number of skilled workers determines the investment in R&D activities through the innovation probability. Thus, the compensation mechanism implemented by the government via higher wages does not only aim at attracting skilled labor but also indicates an increase of the investment in R&D activities (and technological infrastructure). Our model can be generalized to account explicitly for this difference, at the cost of incrementing the number of equilibrium equations and increasing the complexity of the resulting mathematical structure. However, the main results would not be qualitatively modified and the intuition derived from such a model can also be described using the simpler one presented in the current paper.

Note that, in order for the system to be in equilibrium, wages in both countries must be identical, that is, $w^n = w^m$. The resulting equilibrium dynamics are easily understood after observing that whenever $w_*^n \ge w_*^m$, then $w^n > w^m$ *ceteris paribus*, generating a divergent pattern. Assume, for example, that $w_*^n = w_*^m$. Then, in order to pay its workers the same wage as the innovator country, i.e. for w^m to be equal to w^n, the laggard country must unilaterally decrease the number of skilled workers hired, n_m. By doing so, both its innovation probability, $\theta_{(\xi,n)}$, and output level decrease relative to those of the innovator country. A similar but milder process, due to the fact that $\gamma > \xi$, applies to the n_n workers of the innovator country when $w_*^n < w_*^m$. Note, however, that this latter advantage in wages does not guarantee the technological convergence of the laggard, since this country remains constrained by a ξ value that decreases progressively as the technological gap between countries widens through time.

3.2. Numerical simulations

Eqs. (13) and (14) can be interpreted as the wage incentives available from the respective countries so that they may grow through technological innovations. If, on the right hand side, the numerator is larger than the denominator, then the wages offered

[1] Refer to the Appendix A section at the end of the paper for the derivation of both these Bellman equations.

by the corresponding country increase due to the relatively high expected rewards obtained from an innovation. If the numerator is smaller than the denominator, then the incentives to grow technologically decrease as the resulting catching up process does not provide a sufficient motivation in terms of innovation rewards.

Consider the case of a laggard country whose TDL falls below that of the current innovator. The existing technological gap implies that $[V(\Gamma^2) - V(\xi)] > [V(\Gamma^2) - V(1)]$, a value difference providing convergence incentives due to the advantage of backwardness exhibited by the laggard country. Indeed, the numerators on the right hand sides of Eqs. (13) and (14) represent the *expected* [via marginal probability increments] gain from using an additional unit of skilled labor in innovative activities. If, at the same time, the denominator of w_*^m decreases when ξ does, an increasing amount of labor resources could be absorbed by the laggard country due to the resulting relative increment in its wage level.

Note that $V_\xi(\xi)/\pi(n|\gamma)$ represents the productivity effects that result from manufacturing labor activities. As the reference profit value of the innovator country $\pi(n|\gamma)$ increases, so does the reward derived from increasing the productivity of manufacturing, which leads to higher wages being offered by the laggard. If $V_\xi(\xi)$ increases, then the gain in manufacturing productivity becomes relatively large compared to $\pi(n|\gamma)$. Thus, whenever $V_\xi(\xi)/\pi(n|\gamma)$ increases (decreases) laggard wages decrease (increase), as relatively low (high) reference profits are attainable through large (small) productivity increments.

Therefore, the dynamic evolution of the system depends on the value function form assumed in Eqs. (13) and (14). We concentrate on the concave value function scenario, which seems the most plausible one given the current situation of the technological laggards within the European economic area in terms of NIS (Di Caprio, Santos Arteaga, & Tavana, 2015; Filippetti & Archibugi, 2011). A concave value function leads laggard countries to stagnation if $V_\xi(\xi)$ exhibits a sufficiently large increase when ξ approaches zero. As a consequence, countries with relatively low ξ values would hire an increasingly lower proportion of skilled labor.

The numerical wage function simulated to represent the convergence (and divergence) intervals defined by Equation (16) assumes $V(\Gamma^2) - V(1) = 1$, $\gamma = 1.1$ and $\pi(n|\gamma) = 20$. Note that $[V(\Gamma^2) - V(\xi)] = 1$ whenever $\xi = 1$. Thus, the different patterns obtained from varying the concavity of the value functions can be compared among themselves and relative to $V(\Gamma^2) - V(1) = 1$ as ξ decreases. It should be emphasized that, while conditioning quantitatively the results obtained, the numerical values chosen do not affect the qualitative intuition derived from the model.

Fig. 1 shows that decrements in the reference profit value obtainable by the laggards may lead to reversals in the dynamical patterns exhibited by wages. The simulated profit functions have been obtained changing the denominator of w_*^m in Eq. (13) from $1 + V_\xi(\xi)/20$ to $1 + V_\xi(\xi)/10$, with $V(\xi) = \xi^{1-\alpha}/1-\alpha)$, $\alpha = 2$ and $\bar{\xi} = 0.5$.

The upper and lower areas defined with respect to $[V(\Gamma^2) - V(1)] = 1$ within Figs. 1–3 represent the corresponding convergent and divergent equilibrium sections described above. Moreover, the simulations introduced in Figs. 2 and 3 illustrate how as the degree of concavity of the laggard value function increases (i.e. as the marginal productivity gain derived from ξ increases) the interval of ξ values leading to their technological stagnation tends to widen.

In Fig. 2 we compare w_*^m in Equation (13) with $[V(\Gamma^2) - V(1)] = 1$ when $V(\xi) = \xi^{\frac{1}{2}}$, $V(\xi) = \xi^{\frac{1}{4}}$, $V(\xi) = \ln\xi$, and $V(\xi) = \frac{\xi^{1-\alpha}}{1-\alpha}$ with $\alpha = 2$. The curvature, i.e. the coefficient of relative risk aversion, of these value functions is equal to 0.5, 0.75, 1 and 2, respectively. Note the lack of capacity of the laggards to converge when $\bar{\xi} = 0.5$ and $V(\xi) = \xi^{\frac{1}{2}}$ or $V(\xi) = \xi^{\frac{1}{4}}$. That is, the innovation probability of the laggards when these value functions are considered does not suffice to generate convergence for any value of ξ. Thus, in Fig. 3 we

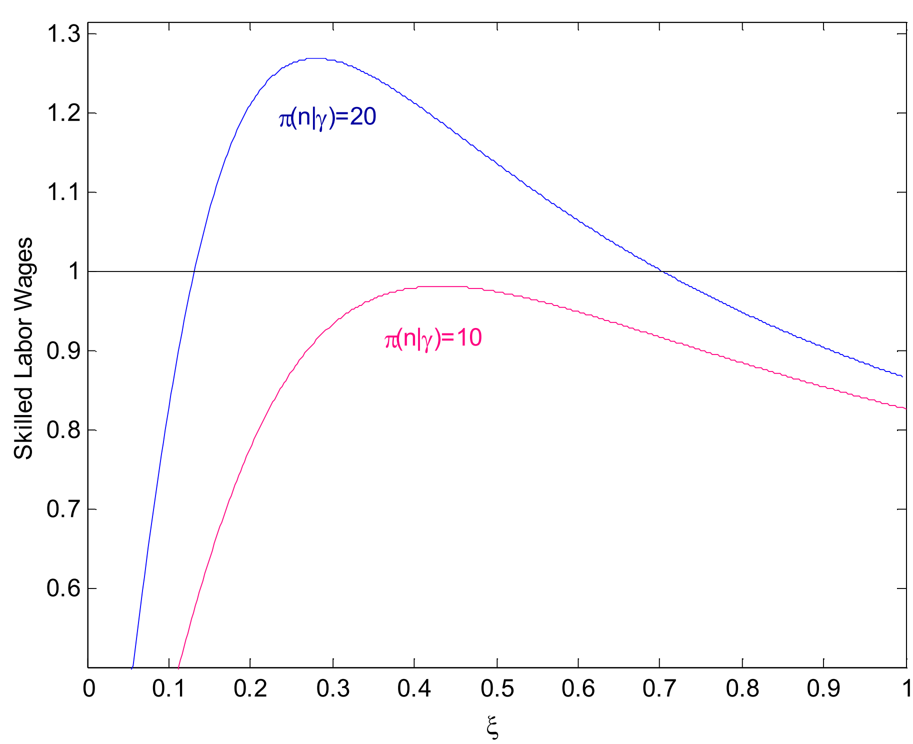


Fig. 1. Decreasing the reference innovator profits ($\bar{\xi} = 0.5$).

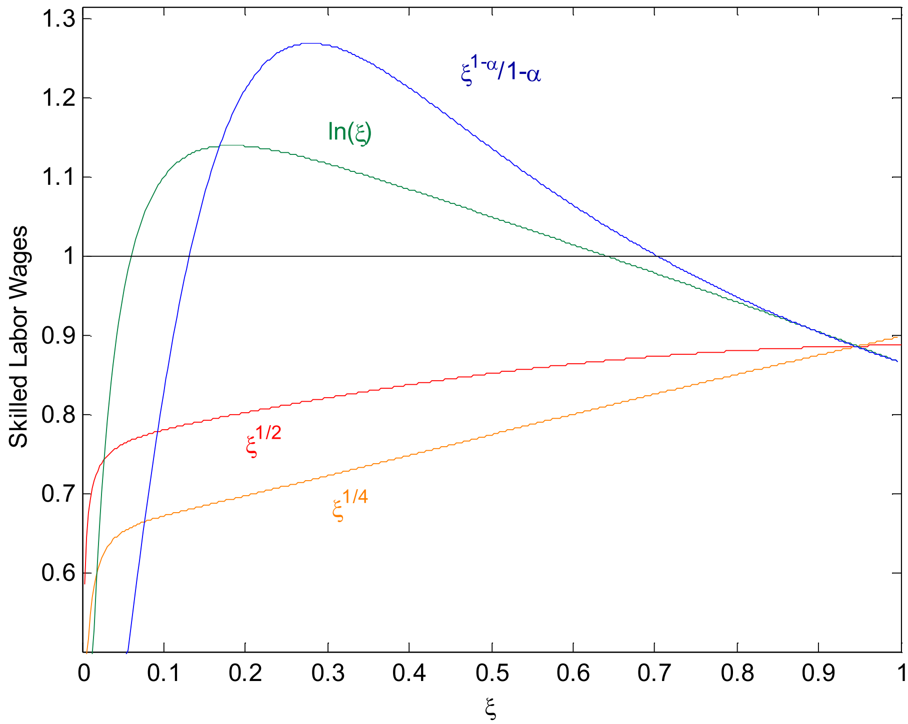


Fig. 2. Wage function differentials and stagnant intervals ($\bar{\xi} = 0.5$) Stagnant interval for $\ln(\xi)$: [0.0.065] $\cup$[0.640, 1], and for $\xi^{1-\alpha}/1-\alpha$): [0.0.130] $\cup$ [0.7030, 1].

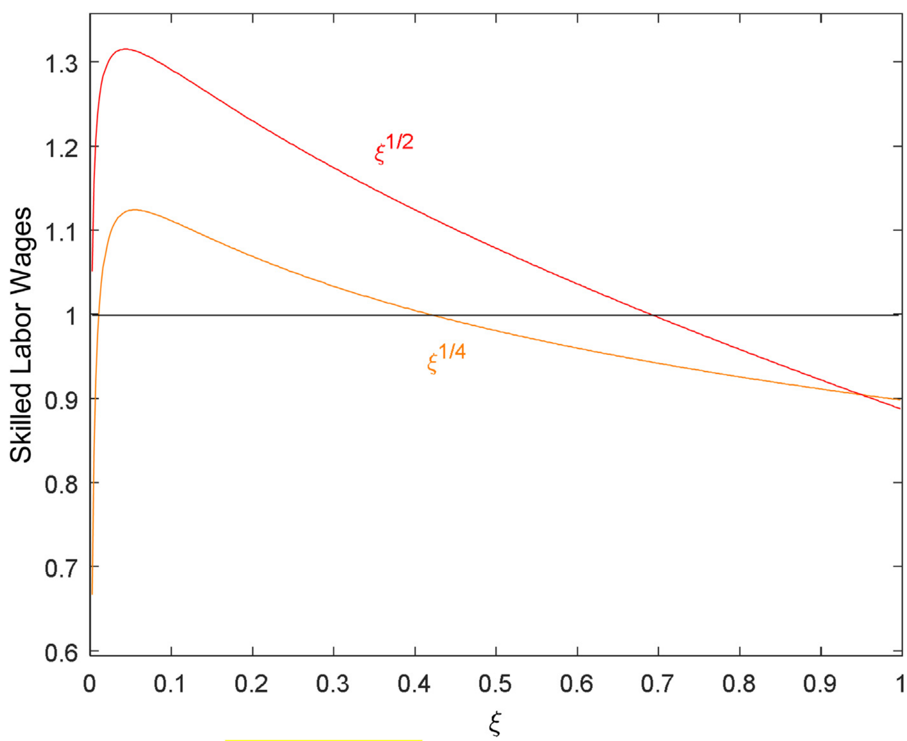


Fig. 3. Increments in concavity value and the widening of stagnant intervals ($\bar{\xi} = 0.9$).

increase the basic endowment of technological development of the laggards to $\bar{\xi} = 0.9$. The resulting increment in the probability of innovation suffices to foster the convergence capacity of the laggards, which is lower for the more concave value function.

Figs. 4 and 5 compare the effects that different value functions have on the width of the stagnant intervals. More precisely, these figures illustrate how the innovation incentives derived from the increments in technological development value differentials are compensated by the marginal productivity effects resulting from the curvature of the value function. Note, in particular, the larger innovation value increments defined by the isoelastic function relative to the natural logarithm one in Fig. 4, where the value

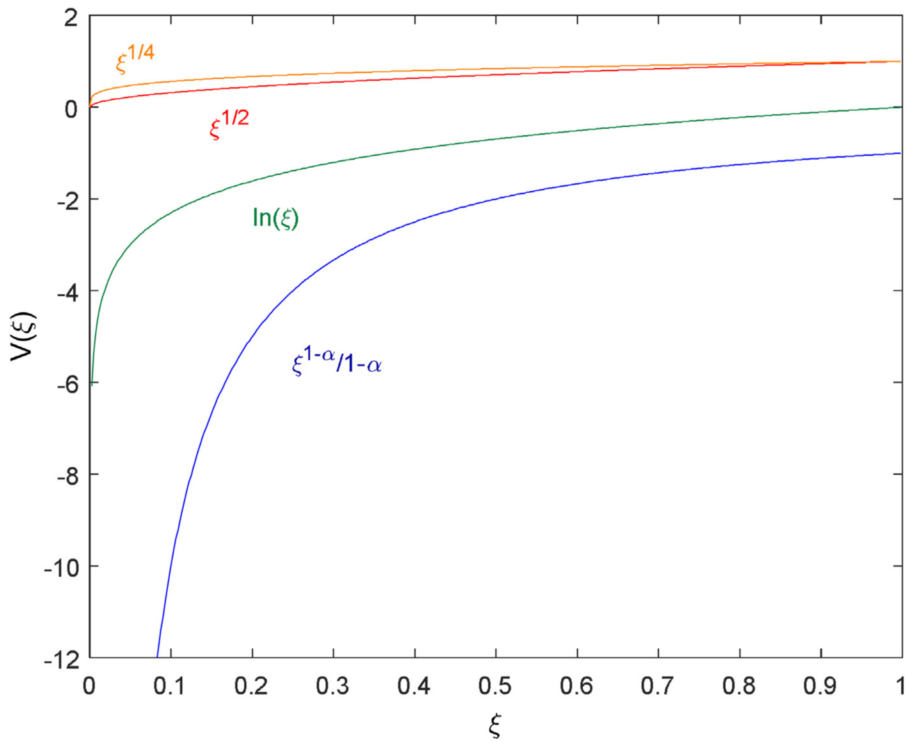


Fig. 4. Value functions defined within the domain [0; 1].

functions $V(\xi) = \xi^{\frac{1}{2}}$, $V(\xi) = \xi^{\frac{1}{4}}$, $V(\xi) = \ln\xi$, and $V(\xi) = \xi^{1-\alpha}/(1-\alpha)$ are represented on the domain [0,1].

However, when determining the laggard wages defined in Figs. 2 and 3, these increments in the value gain derived from an innovation are weighted downwards by the effect of the marginal increment in the productivity of manufacturing. Fig. 5 illustrates both effects at work for the isoelastic value function. In the same way, Figs. 3 and 4 show that the lower technological value gains achieved for $\xi \in [0; 1]$ together with a higher curvature of the value function lead to a larger stagnant interval when $V(\xi)$ shifts from $\xi^{\frac{1}{2}}$ to $\xi^{\frac{1}{4}}$.

Clearly, any increment in the technological value gains achieved by the innovator country would widen the stagnant interval faced by the laggards.

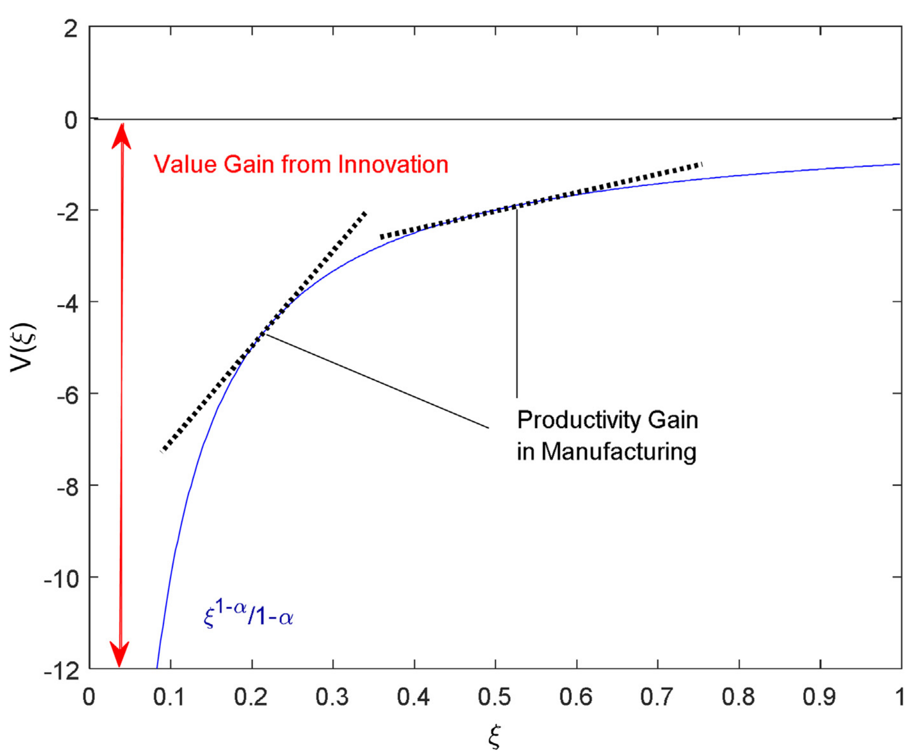


Fig. 5. Value gain from innovation vs. productivity gain in manufacturing.

Migration flows equate wage levels between countries and stabilize the system as further innovations are developed. As illustrated in Figs. 1–3, when ξ approaches zero, n_m decreases in the laggard, whose innovation probability, $\theta_{(\xi,n)}$, falls as the innovator country widens the technological gap. Absent migration, laggards would be able to keep a constant n_m value while paying a decreasing wage to their workers as the divergent process takes place. However, keeping a constant amount of skilled labor does not necessarily prevent stagnation since the innovator country, which has an identical labor endowment, maintains a consistently higher innovation probability through time.

4. Empirical analysis

4.1. Descriptive statistics

The main structural properties defining the European common market framework are reflected in our model. To validate this claim, we analyze the behavior of the variables presented in Table 2, which will be used to determine the differences between the laggards and the leaders in terms of their economic performance and TDLs. We build a panel of data using the Eurostat series of these variables over the 2000–2013 period. The data retrieved from Eurostat for the whole set of countries under analysis is summarized in the online appendix.

The variables presented in Table 2 have been selected to verify the main dynamical patterns that result from the theoretical model introduced in the previous sections. ΔGDP, ΔAVGDP and Prod describe the evolution of the manufacturing (production) process within the economic system. These variables are mainly determined by the TDL of the corresponding NISs (Lundvall, 2007) and reflect the structural capacity of countries to generate the output required to foster economic growth. Note, that while ΔGDP constitutes a proxy for the evolution of the national economic conditions, ΔAVGDP provides a measure of dispersion describing the convergent or divergent process taking place among the selected countries.

The second set of variables, Emig and LF, reflects the population adjustment process taking place through migratory flows. Given the evolution of these variables, we can observe how the labor market assimilates and adjusts to the real shocks affecting the economic system. However, as illustrated in our model, these flows are only part of the adjustment process. The structural adjustment process takes mainly place through the interaction of the skilled labor force and the technological base of the country, whose level of development determines the innovation capacity of the country. This latter trend is captured by the last four variables, i.e. the number of workers dedicated to R&D activities, their proportion of the labor force, the expenditure on R&D activities and the summary innovation index.

Given the results derived from our model and the dynamic trends observed in Figs. 10 and 11 for both the European leader and laggard countries, we will assume that emigration flows are mainly determined by the economic conditions of the sending country (Gropas & Triandafyllidou, 2014). That is, when subject to real economic shocks such as the crisis of 2008, technologically developed countries endowed with a superior NIS do not experience an increasing flow of emigrants, while technological laggards do.

Some technical remarks regarding the choice of the total number of emigrants as the variable measuring the emigration process follow. Note that we have not considered the standard labor force age group (15–64) within the total number of emigrants since the corresponding data matrix has multiple values omitted for the countries under analysis. A similar observation applies to immigration data. In particular, there are substantial lacunae in the data when trying to identify either the immigrants within the 15–64 age group or those who are citizens from other European countries (refer to the Eurostat matrix [migr_imm1ctz]). Given this latter constraint and the fact that immigrants arrive from multiple sending countries and are not always migrating for purely economic reasons (Morano-Foadi & Malena, 2012), we have decided to concentrate on emigration flows. Furthermore, in our model immigrants constitute the complement of emigrants, i.e. the workers leaving from a country are those received by the other country.

The average values of the main indicators over the period 2000–2013 are described in Table 3, where the moderate innovators [laggards] and the innovation leaders are represented in red and

Table 2
Variables analyzed in the model.

Variable Name	Description [Eurostat data matrix code] (2000-2013 period except when indicated)
GDP	Real Gross Domestic Product per capita.
ΔGDP	Percentage change of GDP over previous time period [nama_aux_gph]
ΔAVGDP	$\left(GDP_j - \frac{\sum_{i=1}^{8} GDP_i}{8}\right) / \frac{\sum_{i=1}^{8} GDP_i}{8}, j = 1, \ldots, 8$ $\mathbf{\Delta AVGDP} = \frac{\text{Real GDP per capita in country} j - \text{Average Real GDP per capita in all eight countries}}{\text{Average Real GDP per capita in all eight countries}}$ The index j refers to the country being considered. [computed from variables in nama_aux_gph]
Prod	Labour productivity per hour worked: real output (deflated GDP measured in chain-linked volumes, reference year 2005) per unit of labour input (measured by the total number of hours worked) [tsdec310]
Emig	Total number of emigrants per year [migr_emi1ctz]
LF	Labor force (active population): sum of employed and unemployed persons [lfsi_act_a]
Emig/LF	Total number of emigrants per year as a percentage of the labor force [computed from variables in migr_emi1ctz and lfsi_act_a]
#R&D	Total R&D personnel in all sectors of performance [rd_p_persocc]
#R&D/LF	Total R&D personnel in all sectors as a percentage of the labor force [computed from variables in rd_p_persocc and lfsi_act_a]
$R&D	Total intramural R&D expenditure in all sectors of performance: Euro per inhabitant [rd_e_gerdtot]
SII	Summary Innovation Index (2006–2013 period)

Table 3
Average values of the main indicators over the period 2000–2013.

Country	GDP	Δ GDP	Δ AVGDP	LF	Emig.	Emig/LF	Prod.	# R&D	# R&D/LF	$ R&D	SII
Denmark	37643	0,39	46,61	2899,3	42,990	1,483	50,8	48,962	1,687	1075,6	0,687
Finland	29900	1,33	16,29	2645,9	12,937	0,489	38,2	55,624	2,103	1119,4	0,671
Germany	28107	1,24	9,39	40794,4	511,241	1,259	40,6	516,809	1,266	764,8	0,672
Sweden	33071	1,71	28,61	4800,3	41,880	0,869	42,1	76,935	1,589	1282,4	0,748
Greece	16838	0,71	-34,26	4885,5	80,494	1,633	20,0	35,332	0,723	114,1	0,378
Italy	24029	-0,24	-6,32	24404,5	75,004	0,306	32,2	197,405	0,807	293,4	0,417
Portugal	14664	0,14	-42,85	5466,6	22,171	0,408	16,0	35,682	0,653	171,3	0,390
Spain	20564	0,62	-19,92	21416,9	254,437	1,111	28,9	181,757	0,840	250,0	0,399

black characters, respectively.[2] The differences between technological leaders and laggards are evident when considering the main structural variables. Note, for example, how annual GDP variations differ substantially from the average growth dispersion illustrated by the variable ΔAVGDP. Among the technological leaders, this difference is particularly relevant for Denmark, whose increment in GDP relative to the average level is not reflected in ΔGDP. Given our formal results, we could state that the substantial differences in labour productivity between both groups of countries together with the lower intensity of R&D activities and investment among the laggards lead to the lower development of their NISs reflected by the respective SII values.

The evolution of Germany and Spain deserves particular attention, since it reflects the different trends followed by leaders and laggards within the European area and provides intuition for the statistical analysis performed in the next section. The values of the main structural indicators for both countries over the entire time period considered are presented in Tables 4 and 5, respectively.

Figs. 6 and 7 describe the evolution of the main structural variables of both countries. The behavior of ΔGDP illustrates how Germany grows at a higher rate than Spain since 2006, with the difference between both countries decreasing in the latter years. However, the dispersion exhibited by ΔAVGDP indicates a divergent process, particularly since the beginning of the 2008 crisis. The absence of a convergent trend is also illustrated by the productivity of both countries, which has increased over the years by five percentage points, while keeping a constant distance of ten points between them. The lower capacity of the laggards to react to structural shocks will also arise in the statistical correlation analysis, with laggards being affected by shocks to GDP growth while leaders react to average growth dispersion differentials.

The emigration flows present an even more drastic picture consisting of a steady substantial growth in Spain since 2005 and a considerable decrease in Germany after the crisis. The convergence between both countries in terms of R&D personnel as a percentage of the labor force also slows down in 2008 and reverses its trend afterwards. Overall, Figs. 6 and 7 show that the crisis accentuates the structural weaknesses of the laggard relative to the leader, leading to the subsequent emigration process and to a lower dedication of skilled labor to R&D activities.

4.2. Correlation analysis

The analysis of the correlation between the structural variables considered validates the main results obtained from the formal model. We first compute the correlation between variables for all countries. Then, a second analysis differentiating between technological leaders and laggards is performed. As intuition suggests, the results will differ considerably between both types of countries, while following from those presented in Figs. 1–5.

Table 6 presents the correlations obtained when both leaders and laggards are included in the analysis. The absence of a relationship between the main structural variables and the annual growth of GDP may seem a bit surprising. However, a considerable positive relation is obtained when the dispersion based on the average GDP of all countries is considered. An increment in the dispersion between both groups of countries reflects the divergent process taking place among the countries that compose them.

Note how emigration relates positively to the productivity of the labor force and to the average growth dispersion among countries, indicating an increment in the number of emigrants together with an increase in labor productivity as the GDP of a country grows with respect to the average. We elaborate further on this relation through this section, differentiating in terms of the TDL of countries.

In summary, the structural variables are highly correlated among themselves and relate positively to increments in GDP dispersion and productivity, both of which are accompanied by an increase in the size of the emigrant population. This description matches better the behavior of the technologically developed countries in our model than that of the laggards (see Figs. 2 and 3). The intuition justifying this claim is reinforced by the absence of a relation between negative shocks to the economic system and the incentives of countries to adjusts (i.e. increase) the resources dedicated to their innovation systems. Recovering from the shock does not only allow the country to regain its previous production capacity, but also to expand it, thereby increasing the value gain derived from an innovation.

That is, given the results of our model, laggards should dedicate a larger proportion of their resources to develop their NISs both as the technological distance with respect to the leaders widens (i.e. as ξ decreases) and as the value gain derived from an innovation increases for any given ξ (i.e. as w_*^m shifts upwards). A persistent negative shock to the real economy should therefore be compensated by an increase in the resources allocated to R&D activities, though this response does not necessarily lead to the development of the NIS of the laggards.

In order to provide additional intuition, we have illustrated the relation between ΔGDP and emigration flows (Emig/LF) for all countries in Fig. 8(a), where a clear pattern cannot be seen to emerge. However, when considering only the technological laggards in Fig. 8(b), negative shocks to the economy are met with increments in the emigration flow. At the same time, the positive relation between ΔAVGDP and emigration flows for all countries is illustrated in Fig. 9(a) and reinforced in Fig. 9(b), which describes the stronger relation arising when the technological leaders are considered.

Therefore, we perform a statistical correlation analysis for each group of countries separately. Consider first the technological leaders.

The results displayed in Table 7 illustrate the absence of a significant relation between the structural variables and the

[2] This classification follows from the Innovation Union Scoreboard provided by the European Commission, which is available at http://ec.europa.eu/growth/industry/innovation/facts-figures/scoreboards/index_en.htm?nl_id=1041.

Table 4
Values of the main indicators for Germany over the period 2000–2013.

Indicator	Germany													
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ΔGDP	2,9	1,3	−0,2	−0,4	1,2	0,7	3,8	3,4	1,3	−4,9	4,2	3,3	0,5	0,2
ΔAVGDP	10,099	9,578	8,516	7,233	5,824	4,956	5,461	6,618	8,368	9,519	11,977	14,833	17,282	11,205
Emig/LF	1,703	1,530	1,571	1,576	1,745	1,538	1,548	1,536	1,776	0,689	0,607	0,605	0,580	0,622
Prod	37,3	38,2	38,7	39,1	39,4	39,9	41,3	42	42	40,9	41,7	42,4	42,6	42,8
#R&D/LF	1,225	1,213	1,210	1,189	1,178	1,163	1,182	1,221	1,260	1,287	1,320	1,396	1,430	1,447
$R&D	616,1	632,2	647,3	660,8	666	675,6	713	746,9	809,2	817,2	855,1	923,5	966,6	977,4
SII							0,646	0,65	0,655	0,667	0,689	0,685	0,69	0,69

Table 5
Values of the main indicators for Spain over the period 2000–2013.

Indicator	Spain													
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ΔGDP	4,2	2,5	1,2	1,4	1,6	1,9	2,5	1,6	−0,7	−4,5	−0,5	−0,1	−1,7	−0,7
ΔAVGDP	−19,623	−18,847	−18,409	−18,260	−18,657	−18,367	−19,021	−19,853	−19,741	−18,744	−20,731	−21,148	−21,553	−25,986
Emig/LF			0,193	0,326	0,270	0,322	0,653	1,013	1,250	1,634	1,726	1,745	1,905	2,295
Prod	27,3	27,3	27,4	27,6	27,7	27,9	28,1	28,5	28,7	29,4	30	30,4	31,5	32,1
#R&D/LF	0,685	0,697	0,708	0,767	0,795	0,827	0,868	0,897	0,935	0,949	0,950	0,918	0,891	0,877
$R&D	142,8	153,8	175,3	196,4	210,3	235,5	268,5	297,9	321,9	315,4	313,8	303,9	286	278,5
SII							0,375	0,396	0,398	0,403	0,399	0,402	0,411	0,408

Fig. 6. ΔGDP and ΔAVGDP for Germany (DE) and Spain (SP) over the period 2000–2013.

annual GDP growth among technological leaders. However, the structural variables and the emigration flows relate significantly to the average GDP dispersion variable. In other words, ΔAVGDP describes the structural-based growth of these countries. Note how emigration correlates positively with productivity and the relative growth of the economy. In this regard, the increment in productivity may be due to the increase in emigration or to the high TDL of the countries.

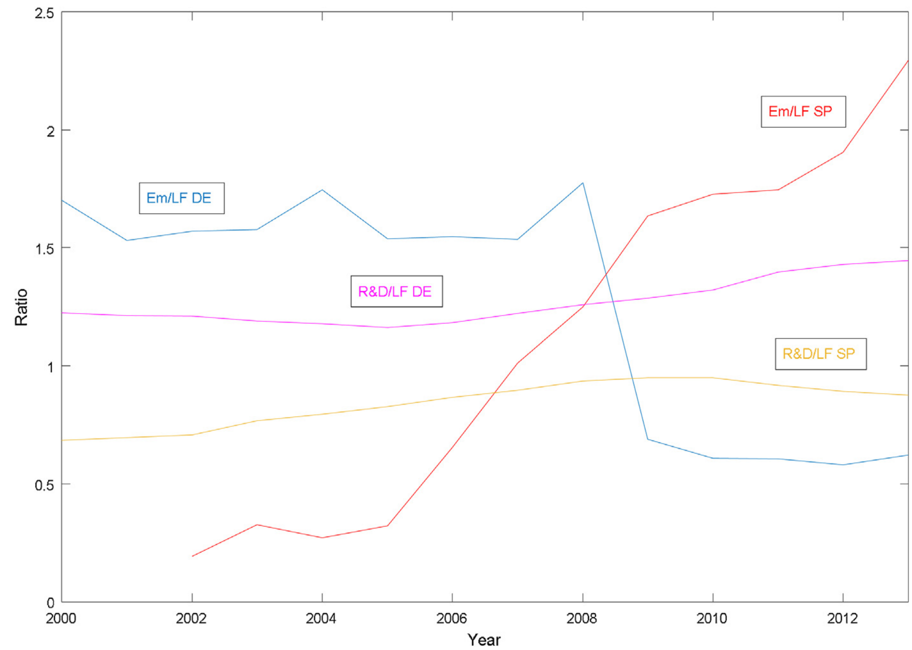


Fig. 7. Em/LF and R&D/LF for Germany (DE) and Spain (SP) over the period 2000–2013.

At the same time, the resources devoted to innovation activities, i.e. the proportion of R&D personnel in the labor force and the expenditure in R&D activities, decrease as emigration increases. This is the type of behavior described in our model for countries with a high ξ and whose value functions do not provide a substantial incentive for the development of innovations (see Figs. 2 and 3). Technologically developed countries have the capacity to innovate but the expected value gain is not as substantial as it would be for a laggard, whose main constraint is given by its limited capacity to innovate in terms of innovation probability. Thus, leaders may experience an increase in emigration and a decrease in the resources dedicated to R&D activities while growing due to their developed NISs.

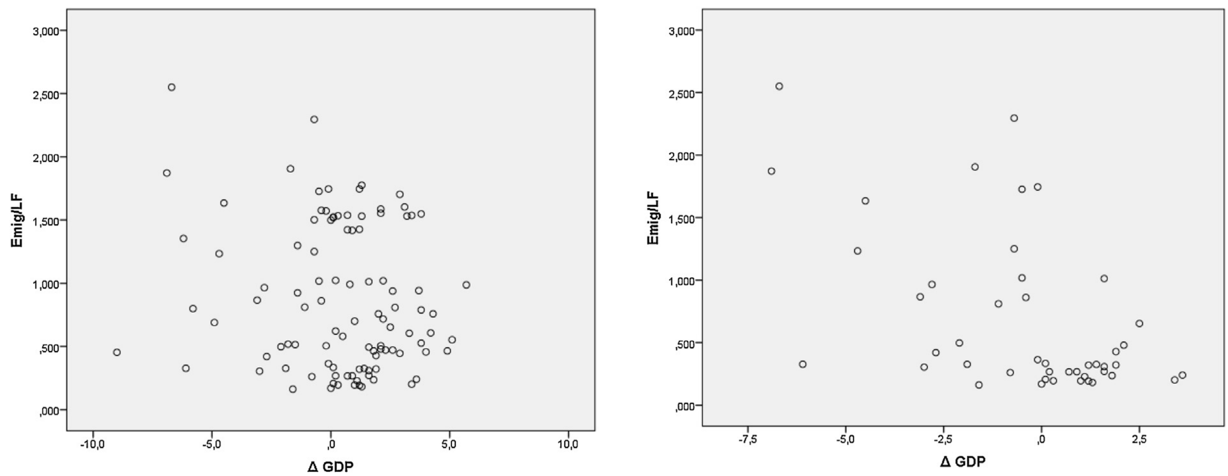
Consider now the technological laggards described in Table 8. As in the case of the leaders, ΔAVGDP describes the structural-based growth of the country. However, laggard countries also react to shocks to ΔGDP. In this case, negative real shocks are met with increments in the resources dedicated to R&D activities and an increase in the emigration flow. That is, the economic system of the laggards is more sensitive to shocks to the real economy, with the labor market and the R&D intensity reacting to smooth them. This adjustment mechanism, consisting of an increment in the resources devoted to R&D activities in order to compensate – to some extent – for the divergent effects of a negative GDP shock, can be observed for the lower levels of ξ in Figs. 2 and 3. That is, as the potential gains derived from an innovation increase [via a decrease in ξ or a direct increase in the value gain from innovating], so do the incentives of the laggards to increment their R&D activities.

As already stated, the equilibrium wages have two related interpretations in our model. One as incentives to prevent skilled emigration and the other as investment in innovation-related resources through the skilled labor employed by the country. Thus,

Table 6
Correlation values between the main indicators for all countries.

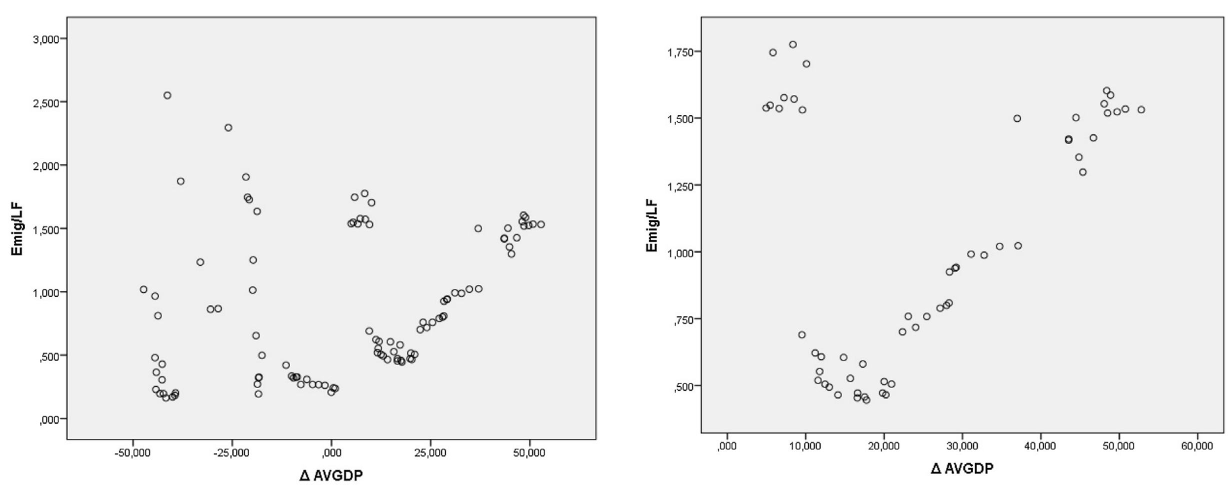
Indicator		Δ GDP	Δ AVGDP	Emig/LF	Prod.	# R&D/LF	$ R&D	SII
Δ GDP	Pearson Correlation	1	,116	-,166	,066	,053	,074	,212
	Sig. (2-tailed)		,226	,097	,492	,595	,447	,095
	N	111	111	101	111	103	107	63
Δ AVGDP	Pearson Correlation	,116	1	**,289***	**,970****	**,780****	**,872****	**,908****
	Sig. (2-tailed)	,226		,003	,000	,000	,000	,000
	N	111	111	101	111	103	107	63
Emig/LF	Pearson Correlation	−,166	**,289***	1	**,341****	,138	,152	-,013
	Sig. (2-tailed)	,097	,003		,000	,177	,131	,917
	N	101	101	102	102	97	100	62
Prod.	Pearson Correlation	,066	**,970****	**,341****	1	**,754****	**,850****	**,877****
	Sig. (2-tailed)	,492	,000	,000		,000	,000	,000
	N	111	111	102	112	104	108	64
# R&D/LF	Pearson Correlation	,053	**,780****	,138	**,754****	1	**,915****	**,866****
	Sig. (2-tailed)	,595	,000	,177	,000		,000	,000
	N	103	103	97	104	104	104	61
$ R&D	Pearson Correlation	,074	**,872****	,152	**,850****	**,915****	1	**,965****
	Sig. (2-tailed)	,447	,000	,131	,000	,000		,000
	N	107	107	100	108	104	108	64
SII	Pearson Correlation	,212	**,908****	−,013	**,877****	**,866****	**,965****	1
	Sig. (2-tailed)	,095	,000	,917	,000	,000	,000	
	N	63	63	62	64	61	64	64

* Correlation is significant at the 0.01 level (2-tailed).



(a) All countries **(b) Technological laggards**

Fig. 8. Scatterplot illustrating the relation between ΔGDP and Emig/LF.



(a) All countries **(b) Technological leaders**

Fig. 9. Scatterplot illustrating the relation between ΔAVGDP and Emig/LF.

by increasing the wage paid above the one of the leaders, the laggards aim both at preventing migration and increasing their innovation probability through n_m. As shown by the correlations, despite the efforts of the laggards to prevent the differences between NISs from widening, emigrant flows would result from negative shocks to the real economy. However, despite the considerable brain drain process described in the literature (Gropas and Triandafyllidou, 2014), either a majority of the emigrants leaving the laggard countries could be considered to be unskilled ones or the labor force is sufficiently skilled to compensate for the brain drain process. Thus, increments in the emigration flow respond to changes in GDP in the same manner the country attempts to compensate for the decrease in GDP by increasing its R&D resources.

Finally, note how the development of the NIS (SII) among technological laggards relates significantly to ΔAVGDP, productivity, and the intensity of R&D activities, but not to emigration. That is, the development of the NIS of a country requires considerable structural investments in R&D activities, with emigration acting as a compensatory mechanism relating to real but not to structural shocks to the economy. Once established, as in the case of the technological leaders, the NIS evolves together with ΔAVGDP and the funds allocated to R&D activities.

5. Policy implications

5.1. Structural constraints at work

The model introduced in the paper has formally proven that technological underdevelopment may pervade within technological laggards in [long-term] structural terms despite the compensatory migration effect at work. This is the type of dynamic scenario described by the Eurostat and Innovation Union Scoreboard-based Figs. 10 and 11.

These figures illustrate the different trajectories followed by the moderate innovators [laggards], including Spain (SP), Greece (GR), Italy (IT) and Portugal (PT), and the innovation leaders, consisting of Germany (DE), Denmark (DK), Finland (FI) and Sweden (SE). Fig. 10 illustrates the total number of long-term emigrants as a percentage of the labor force (Em/LF) for all the countries during

Table 7
Correlation values between the main indicators for the technological leaders.

Indicator		Δ GDP	Δ AVGDP	Emig/LF	Prod.	# R&D/LF	$ R&D	SII
Δ GDP	Pearson Correlation	1	−,090	−,035	−,149	−,060	−,180	,016
	Sig. (2-tailed)		,508	,795	,272	,669	,192	,931
	N	56	56	56	56	54	54	32
Δ AVGDP	Pearson Correlation	-,090	1	**,361****	**,846****	,106	**,390****	**,376***
	Sig. (2-tailed)	,508		,006	,000	,446	,004	,034
	N	56	56	56	56	54	54	32
Emig/LF	Pearson Correlation	−,035	**,361****	1	**,570****	−**,607****	−**,397****	,012
	Sig. (2-tailed)	,795	,006		,000	,000	,003	,946
	N	56	56	56	56	54	54	32
Prod.	Pearson Correlation	−,149	**,846****	**,570****	1	−,076	**,298***	,183
	Sig. (2-tailed)	,272	,000	,000		,587	,029	,317
	N	56	56	56	56	54	54	32
# R&D/LF	Pearson Correlation	−,060	,106	−**,607****	-,076	1	**,597****	−,098
	Sig. (2-tailed)	,669	,446	,000	,587		,000	,594
	N	54	54	54	54	54	54	32
$ R&D	Pearson Correlation	−,180	**,390****	−**,397****	**,298***	**,597****	1	**,615****
	Sig. (2-tailed)	,192	,004	,003	,029	,000		,000
	N	54	54	54	54	54	54	32
SII	Pearson Correlation	,016	**,376***	,012	,183	−,098	**,615****	1
	Sig. (2-tailed)	,931	,034	,946	,317	,594	,000	
	N	32	32	32	32	32	32	32

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 8
Correlation values between the main indicators for the technological laggards.

Indicator		Δ GDP	Δ AVGDP	Emig/LF	Prod.	# R&D/LF	$ R&D	SII
Δ GDP	Pearson Correlation	1	,020	−**,538****	−,096	−**,379****	−**,284***	−,293
	Sig. (2-tailed)		,885	,000	,486	,007	,039	,109
	N	55	55	45	55	49	53	31
Δ AVGDP	Pearson Correlation	,020	1	−,188	**,941****	**,300***	**,598****	**,365***
	Sig. (2-tailed)	,885		,217	,000	,036	,000	,043
	N	55	55	45	55	49	53	31
Emig/LF	Pearson Correlation	−**,538****	−,188	1	,027	**,430****	,009	-,030
	Sig. (2-tailed)	,000	,217		,859	,004	,953	,877
	N	45	45	46	46	43	46	30
Prod.	Pearson Correlation	−,096	**,941****	,027	1	**,515****	**,738****	**,457****
	Sig. (2-tailed)	,486	,000	,859		,000	,000	,009
	N	55	55	46	56	50	54	32
# R&D/LF	Pearson Correlation	−**,379****	**,300***	**,430****	**,515****	1	**,788****	**,861****
	Sig. (2-tailed)	,007	,036	,004	,000		,000	,000
	N	49	49	43	50	50	50	29
$ R&D	Pearson Correlation	−**,284***	**,598****	,009	**,738****	**,788****	1	**,676****
	Sig. (2-tailed)	,039	,000	,953	,000	,000		,000
	N	53	53	46	54	50	54	32
SII	Pearson Correlation	−,293	**,365***	−,030	**,457****	**,861****	**,676****	1
	Sig. (2-tailed)	,109	,043	,877	,009	,000	,000	
	N	31	31	30	32	29	32	32

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

approximately the last fifteen years. Fig. 11 provides the SII, which has been used as a proxy for the quality and strength of the NIS of each country. Note that, in the current paper, we have represented this concept using the variable ξ.

Consider the trends observed in the emigration patterns within both sets of countries. The increment in [long-term] emigration observed among the laggards, particularly Greece and Spain in the years immediately following the 2008 crisis, contrasts with the containment observed among the technological leaders, with Denmark and Finland experiencing decrements in their corresponding number of emigrants. However, the main decrease in the emigration flow is the one experienced by Germany, which, due to its considerable size in economic and population terms, remains as the main European technological reference country.

At the same time, the data illustrates how this compensatory migration mechanism lacks a structural counterpart in the development of the NISs of the laggards, which remain consistently below the European average, while countries like Denmark and Germany have consistently developed them after 2008. In other words, the European economy does not converge in structural technological terms. We could complement Figs. 10 and 11 by illustrating the net financial assets of the corresponding group of countries, with the government debt of all technological laggards accounting for more than 100% of their GDPs. Despite the expected increment in the innovative activity of the laggards, due to their advantage of backwardness and the inflow of foreign funds, we observe a progressive stagnation in the development of their NISs relative to those of the technological leaders.

Thus, in addition to the synergies lost due to the modification of the labor force (Herrmann and Peine, 2011), the reallocation of labor through migration hides a perverse structural problem in the laggard countries. As Table 1 illustrated in the introduction,

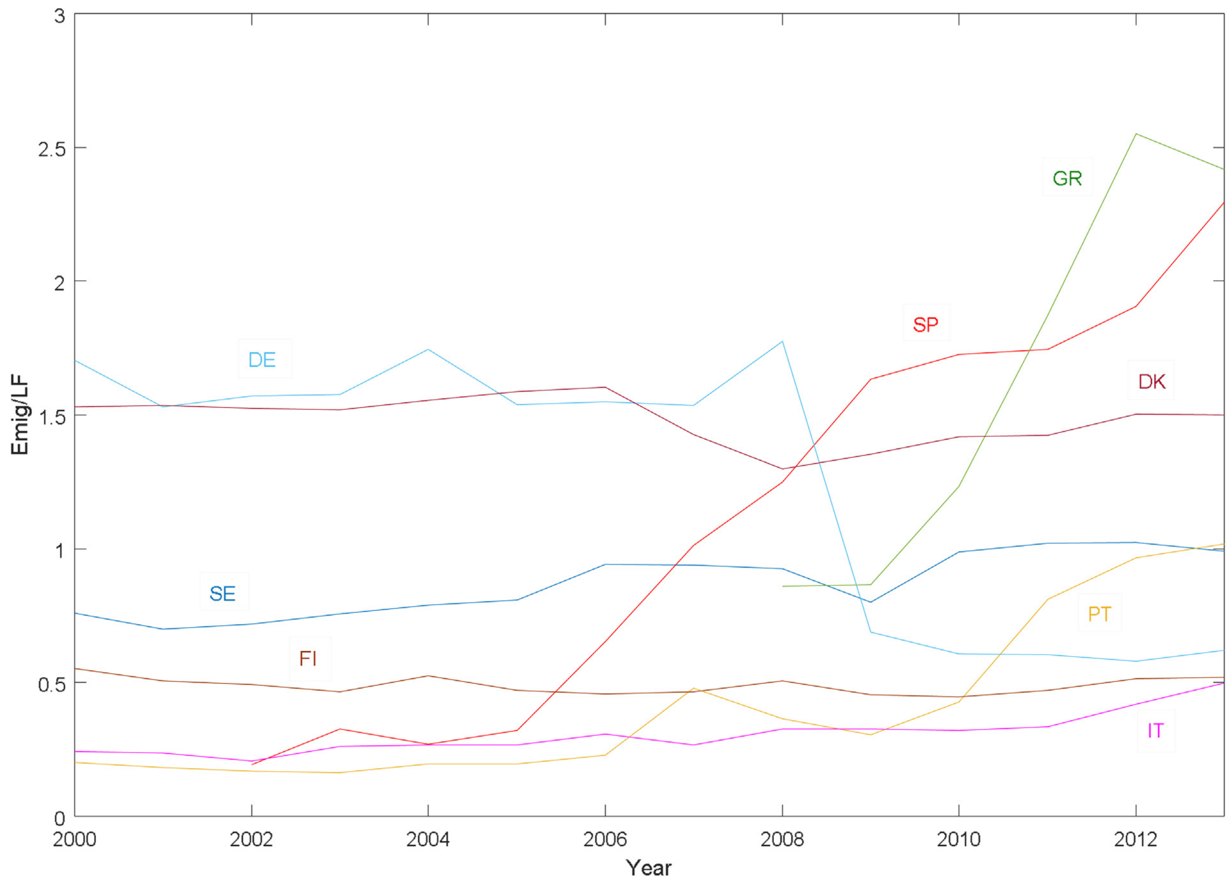


Fig. 10. Total number of long-term emigrants as a percentage of the labor force*.
**Note*: Refer to http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=migr_emi1ctz&lang=en for additional information about this variable.

laggard countries endowed with a considerable amount of human capital (in terms of available scientists and engineers) and reasonable access to the latest technologies available, lack the capacity to absorb technology and innovate, resulting in the loss of human capital as a consequence of their structural (technological) underdevelopment.

5.2. Consequences for the Europe 2020 strategy

The Europe 2020 strategy was adopted by the European Council in 2010 and represents the agenda of the European Union regarding economic growth and employment during 2010–2020. It concentrates on sustainable and inclusive growth to overcome the structural weaknesses of the European economy and improve its competitiveness and productivity (European Commission, 2015). The 2020 headline targets are monitored by Eurostat using nine indicators, whose current position (in green) in relation to the 2020 key targets (in red) is presented in Fig. 12.

Fig. 12 illustrates how the developments achieved fall short in the indicators that can be considered to follow directly from the structural conditions of the country: R&D expenditure and intensity [target: 3% of GDP to be invested in the research and development (R&D) sector] and employment absorption by the productive system [target: 75% of the population aged 20–64 years to be employed]. Note, that this is the case despite the attainments obtained in the human capital indicators, i.e. the increment in tertiary education and the reduction in early leaves from education and training. That is, the structural problems prevail despite the availability of skilled labor, with migration acting as a dispersion mechanism.

5.2.1. Structural policies

Our theoretical model has been designed to emphasize the interaction required between human and physical capital to generate economic growth. The model has illustrated how the resources dedicated to R&D activities may decrease among leaders, while laggards react to negative shocks to their systems to prevent the potential stagnation of their economies. However, these latter countries lack the technological infrastructure required to innovate and generate economic growth. Due to this fact, a direct transfer of technology across countries would be insufficient to foster the required response. That is, the infrastructure required by the laggards to develop their innovation systems should be the result of cooperation at the European level.

The European Commission has already considered the development of industrial clusters aimed at enhancing cooperation among firms and improving the technological infrastructure of the laggards. This policy objective was highlighted in the years previous to the crisis of 2008. From a structural perspective, our results indicate that such a cooperation strategy was the correct one. However, as the data illustrates, countries have discontinued its application to focus on the immediate consequences derived from the crisis.

Assume that the different Innobarometers issued by the European Commission reflect the main policy objectives of the European Union through the years. The following policy recommendations can be suggested based on our results:

- Cluster design and development: The 2006 Innobarometer (European Commission, 2006) emphasized the fundamental role of a common European approach in the development of

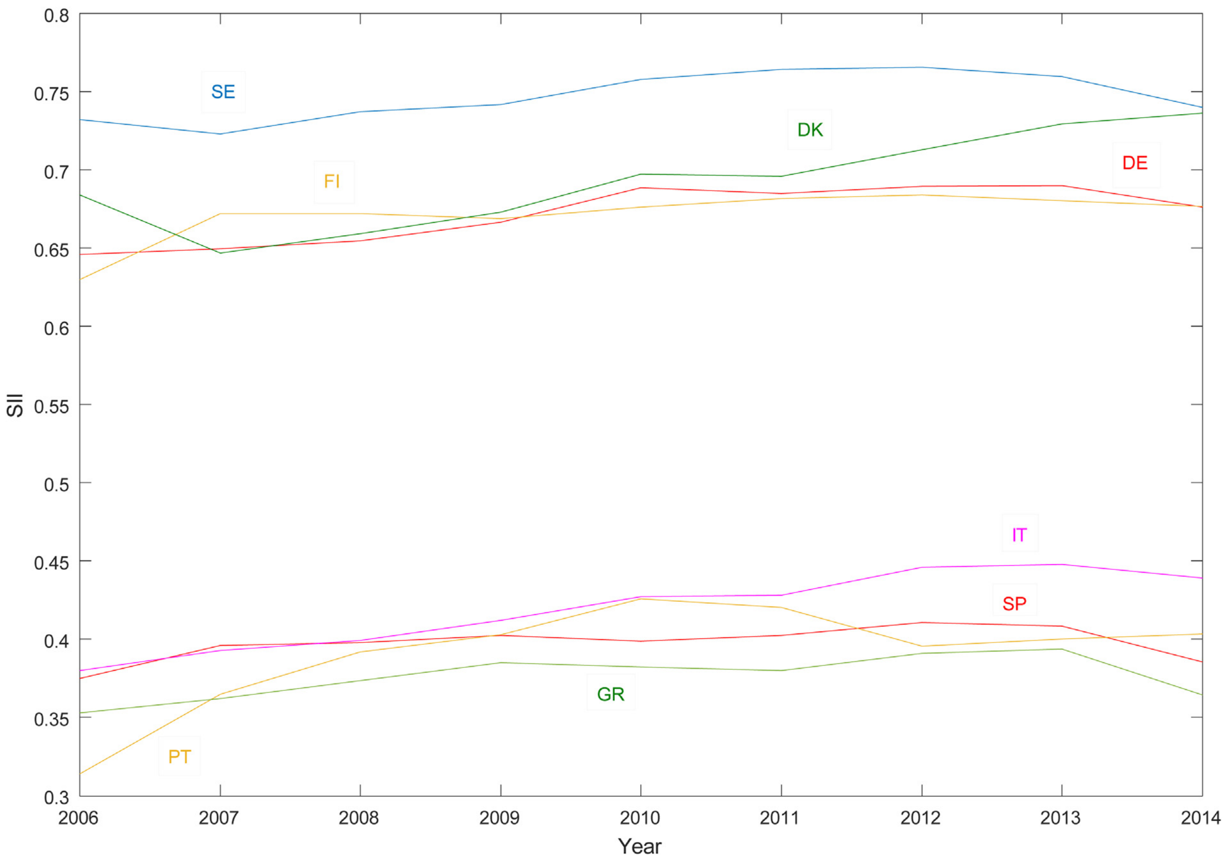


Fig. 11. SII [summary innovation index]*.
*Note: The SII [summary innovation index] variable is calculated by the Innovation Union Scoreboard.
The calculation of and additional intuition regarding the SII variable can be found at http://ec.europa.eu/growth/industry/innovation/facts-figures/scoreboards/index_en.htm?nl_id=1041.

cooperative clusters used to transfer knowledge and improve the technological infrastructure of laggard countries. In this regard, Malik and Cunningham (2006) highlighted the lack of cohesion among European countries in technological and innovation policy terms - a trend that is being partially corrected in the latter years (Izsak et al., 2015).

- Innovation Transfer: The 2007 Innobarometer (European Commission 2007) emphasized the importance for innovation and economic growth of both:

○ knowledge transfer between firms (pg. 29), and
○ a coherent policy to support innovation across firms and countries (pg. 40).

The report also highlighted the heterogeneity and lack of cohesion of the support policies implemented by different countries. The asymmetric effect of the crisis has exacerbated these frictions. In particular, the persistent gap in the SII indicator and the dispersion between both groups of countries described by the ΔAVGDP variable reflect the absence of a coherent innovation policy successfully implemented at the European level.

- Public support is important but cooperation between firms is essential: The 2010, 2012 and 2014 Innobarometers (European Commission, 2010, 2012, 2014b) have focused on the importance of the public sector in supporting innovation. However, public support is insufficient if firms do not define cooperative innovation strategies between them. The struggle to achieve the Europe 2020 structural objectives despite the continuous support displayed at the public level reinforces the importance of this point.

5.2.2. Firm-level policies

The innovation constraint faced by the European laggards is a formal version of what is commonly known as the middle income trap (Vivarelli, 2014a; Ozturk, 2016). The related literature suggests local innovative entrepreneurship as a means to foster innovation and structural change among the laggards, while also considering the role played by the international transference of technology as a complement of domestic innovation (Vivarelli, 2014a).

The main policy recommendations that can be made at the firm level based on the findings of our model follow from Figs. 1–5. As already stated, we have used the migratory flows to modify both the productivity of the manufacturing activities in a country and its capacity to innovate, i.e. the arrival probability of an innovation. That is, emigration has been used to reflect the structural evolution of a country. In this regard, the economic literature has already highlighted the relation between migration and growth, as well as the negative effects resulting from the brain drain experienced by the sending countries, particularly the least developed ones (Docquier, 2013; Docquier, Ozden, & Peri, 2014).

Therefore, the coordination and integration among firms belonging to both types of countries is essential. The employment guidance defined within the Europe 2020 strategy concentrates on investing in skills and the creation of a frictionless and more integrated labor market to try to smooth the existing structural mismatches between labor supply and demand (European Commission, 2014a). A coordinated cooperative strategy

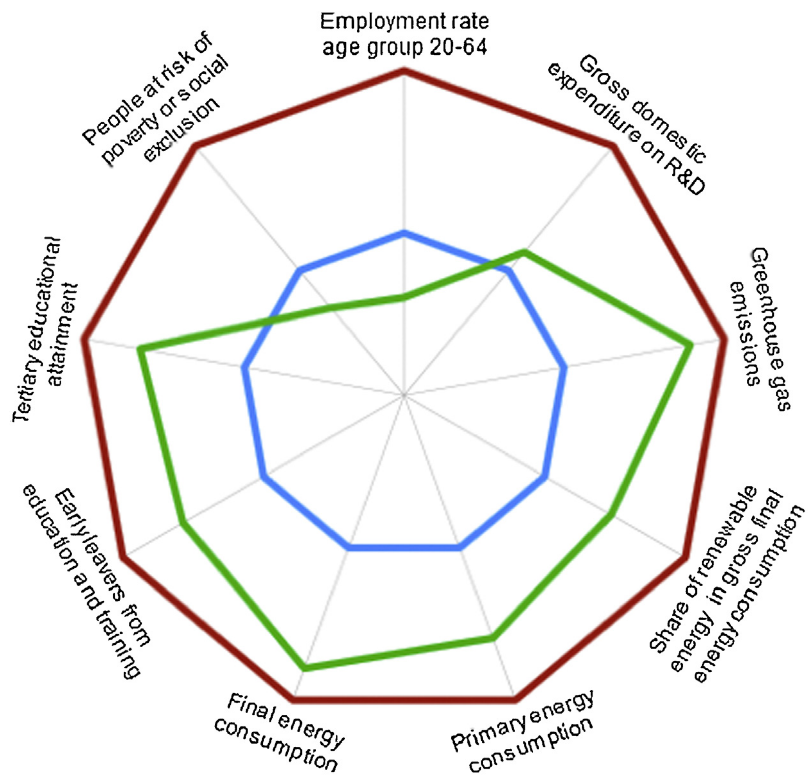


Fig. 12. Situation of the indicators in November 2015 relative to the Europe 2020 targets.
Source: http://ec.europa.eu/eurostat/c/portal/layout?p_l_id=6589552&p_v_l_s_g_id=0.

complementing the research line defined by the European Union framework programme for research and innovation (Horizon 2020) would increase the probability of innovation among the laggard firms and the value of innovation among the leaders. Both types of countries can benefit from a cooperative innovation policy that consists of sharing not only labor but also technology and the resulting value incentives from innovation.

There is plenty of empirical evidence illustrating the innovation benefits that result from sharing knowledge and R&D among highly integrated firms located in countries with similar institutional frameworks and compatible technological bases (Choi & Yeniyurt, 2015; Wu & Wu, 2014; Zheng, Wei, Zhang, & Yang, 2016). Given the fact that cooperating and sharing objectives are mutually beneficial for firms and their respective countries, governments within the European Union should encourage this type of partnership to promote innovation and growth among firms and countries. This policy would allow leaders to compensate for their relatively smaller value gains while laggards would increase their probability of innovation.

6. Conclusion

The formal results that follow from the model introduced in the paper provide a highly intuitive explanation for the technological and migratory patterns currently observed within and between European laggards and innovation leaders. It should be noted that we are aware of the multiple variables affecting and determining the behavior of both these patterns but do not want to impose any exogenous causality between them. Nonetheless, the model allows for a much wider equilibrium perspective than basic causality when analyzing the relation between both patterns in terms of the dynamic evolution of countries.

That is, given the widening differences in technological knowledge assimilation (Alvarez, Di Caprio, & Santos Arteaga, 2016), the existing divergences between laggard and innovator countries in terms of migration may easily be interpreted as the main [and only] compensatory mechanism available. This adjustment mechanism should compensate, to some extent, for the economic and structural asymmetries existing within the heterogeneous set of countries composing the common market [and, except for Denmark and Sweden, currency] area, see Mundell (1961) and the subsequent literature on optimal currency areas and their stability (Fingleton, Garretsen, & Martin, 2015).

Mainly, migration helps correcting asymmetries in unemployment rates across countries, which, in our model translates into the laggards being able to equate wages with the leaders. However, as shown by our model, shifting labor among countries constitutes only a temporal relief for the laggard economies, which remain constrained by their structural deficiencies. At the same time, skilled emigration accentuates the structural deficiencies faced by the laggards, whose absorptive capacities and innovation probabilities are considerably reduced.

It should be emphasized that the results obtained correspond to the most convergence enhancing scenario that may be assumed within the framework of the model. Clearly, developing an innovation does not necessarily guarantee immediate convergence in technological development levels (TDLs). For instance, assuming lower innovation value gains may easily exacerbate the stagnant trap described in the proposed framework. Similar results would follow from relaxing any of the convergence enhancing assumptions imposed through the paper. In the same way, when considering national policy implications, government policies may trigger further divergences among regions if they favor the development of infrastructures within the most developed region. That is, for a given innovation probability, political incentives may be assumed to depend on the size of the value gain differential: if it is large enough and catching up is immediate, resources may be allocated to the laggard region, but if the improvement of the NIS taking place as the result of an innovation is relatively small and catching up follows a cumulative process, then resources would be allocated to develop further the innovative [more developed] regions.

Appendix A. : Bellman equations

A.1. Basic theory

We introduce a set of Poisson processes within the stochastic framework of the model building on Wälde (1999), who adopts the following version of Ito's lemma. Let $\mathbf{z} \equiv (z_1, z_2)^T$ be a vector-valued Poisson process consisting of two independent Poisson processes, z_1 and z_2. Let $f(\mathbf{x}) \equiv (f_1(\mathbf{x}), f_2(\mathbf{x}))^T$, $g(\mathbf{x})$ and $\sigma(\mathbf{x}) \equiv (\sigma_1(\mathbf{x}), \sigma_2(\mathbf{x}))^T$ be continuous real functions of $\mathbf{x} \equiv (x_1, x_2)$. Note that $f_i, g, \sigma_i : \Re^2 \rightarrow \Re$.

Let $\mathbf{x}$ follow $d\mathbf{x} = f(\mathbf{x})dt + \sigma(\mathbf{x})d\mathbf{z}$. Then, the differential $dg(\mathbf{x})$ equals

$$\begin{aligned} dg(\mathbf{x}) = {} & [g_{x_1}(\mathbf{x})f_1(\mathbf{x}) + g_{x_2}(\mathbf{x})f_2(\mathbf{x})]dt \\ & + [g(x_1 + \sigma_1(\mathbf{x}), x_2) - g(\mathbf{x})]dz_1 \\ & + [g(x_1, x_2 + \sigma_2(\mathbf{x})) - g(\mathbf{x})]dz_2.. \end{aligned} \tag{A.1}$$

At the same time, the differential generator *Diff* can be applied to $dg(\mathbf{x})$.

$$\begin{aligned} Diff\ g(\mathbf{x}) = {} & g_{x_1}(\mathbf{x})f_1(\mathbf{x}) + g_{x_2}(\mathbf{x})f_2(\mathbf{x}) \\ & + [g(x_1 + \sigma_1(\mathbf{x}), x_2) - g(\mathbf{x})]a_1 \\ & + [g(x_1, x_2 + \sigma_2(\mathbf{x})) - g(\mathbf{x})]a_2. \end{aligned} \tag{A.2}$$

where $a_i dt, i = 1, 2$, denotes the probability per unit of time that x_i jumps with an amplitude of $\sigma_i(\mathbf{x})$, while $Diff g(\mathbf{x})$ gives the expected change of $g(\mathbf{x})$ per unit of time.

A.2. Laggard countries

Consider the Poisson process triggering the increase in the TDL of an imitator country:

$$d\xi^m = \left(\Gamma^2 - \xi\right)dz_\xi, \tag{A.3}$$

and replace the corresponding variables in Eq. (A.2) according to:

$$\begin{aligned} & \mathbf{x} = \xi, \\ & f_1(\mathbf{x}) = \left[\frac{\pi(n|\xi)}{\pi(n|\gamma)}\right], \\ & f_2(\mathbf{x}) = 0, \\ & g(\mathbf{x}) = V(\mathbf{x}), \\ & \sigma_1(\mathbf{x}) = \left(\Gamma^2 - \xi\right), \\ & a_1 = \theta_{(\xi,n)}, \\ & a_2 = 0, \end{aligned} \tag{A.4}$$

in order to obtain

$$\begin{aligned} E\left(\frac{dV(\xi)}{dt}\right) = {} & V_\xi(\xi)\left[\frac{\pi(n|\xi)}{\pi(n|\gamma)}\right] \\ & + \theta_{(\xi,n)}\left[V\left(\xi + (\Gamma^2 - \xi)\right) - V(\xi)\right]. \end{aligned} \tag{A.5}$$

Finally, include the expected temporal evolution of the value function in the Bellman equation corresponding to this type of problems (refer to any standard optimization text, such as Section 21 in Kamien and Schwartz (1981)) and given by

$$\rho V(\xi) = \max_n\left[\pi(n|\xi) + E\left(\frac{dV(\xi)}{dt}\right)\right], \tag{A.6}$$

to obtain the final Bellman equation optimized by laggard countries based on their respective ξ values:

$$\begin{aligned} \rho V^m(\xi) = \max_n\Bigg[& \pi(n|\xi) + V_\xi(\xi)\left[\frac{\pi(n|\xi)}{\pi(n|\gamma)}\right] \\ & + \theta_{(\xi,n)}\left[V\left(\xi + (\Gamma^2 - \xi)\right) - V(\xi)\right]\Bigg]. \end{aligned} \tag{A.7}$$

A.3. Innovator countries

Consider the Poisson processes triggering the increase in the TDL of an innovator country:

$$d\xi^m = \left(\Gamma^2 - 1\right)dz_\xi, \tag{A.8}$$

and replace the corresponding variables in Eq. (A.2) according to:

$$\begin{aligned} & \mathbf{x} = \xi, \\ & f_1(\mathbf{x}) = [1], \\ & f_2(\mathbf{x}) = 0, \\ & g(\mathbf{x}) = V(\mathbf{x}), \\ & \sigma_1(\mathbf{x}) = \left(\Gamma^2 - 1\right), \\ & a_1 = \theta_{(\gamma,n)}, \\ & a_2 = 0, \end{aligned} \tag{A.9}$$

in order to obtain [we have assumed that $\xi = 1$ within a given innovator country in order to simplify the presentation]:

$$E\left(\frac{dV(\xi)}{dt}\right)V_\xi(\xi)[1] + \theta_{(\gamma,n)}\left[V\left(1 + (\Gamma^2 - \xi)\right) - V(1)\right]. \tag{A.10}$$

As in the laggard case, we substitute the expected temporal evolution of the value function in the corresponding Bellman equation

$$\rho V(\xi) = \max_n\left[\pi(n|\gamma) + E\left(\frac{dV(\xi)}{dt}\right)\right], \tag{A.11}$$

to obtain the final Bellman equation optimized by an innovator country

$$\rho V^n(\xi) = \max_n\left[\pi(n|\gamma) + V_\xi(\xi) + \theta_{(\gamma,n)}[V(\Gamma^2) - V(1)]\right]. \tag{A.12}$$

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ibusrev.2016.05.005.

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