A history-friendly model of the successive changes in industrial leadership and catch-up by the latecomers

Fabio Landini[a,b], Keun Lee[c], Franco Malerba[b,d]

[a]University for Foreigners of Reggio Calabria, MEDAlics, via del Torrione 95, 89125 Reggio Calabria, Italy

[b]Bocconi University, CRIOS, via G. Roenteng 1, 20136 Milan, Italy

[c]Seoul National University, Division of Economics, Seoul 151-742 , South Korea

[d]Bocconi University, Department of Management and Technology, via G. Roenteng 1, 20136 Milan, Italy

Corresponding author:
Fabio Landini, Bocconi University, CRIOS, via G. Roenteng 1, 20136 Milan, Italy. Tel: +39 02 5836 5171; e-mail: fabio.landini@unibocconi.it

Abstract

Successive changes in leadership across countries (or catch-up cycles) are common in several industries. This paper develops a history-friendly model to explore the technological conditions for the emergence of catch-up cycles. The model is inspired by two cases where the arrival of a new technology was important for catch-up, such as mobile phones and semiconductors. In the baseline setting the model is able to replicate the benchmark case of three cycles with two times of leadership change. In particular, the simulation analysis reveals that: a) the more disruptive the new technology, the greater the shake-up of market shares between the incumbents and the latecomers; and b) a leadership change is more likely to occur when it coincides with a certain response by the actors, such as a high lock-in behaviour on the side of incumbents. The counterfactual experiments show that depending on the size of windows, the degree of lock-in, the shape of technological landscape, and the incumbents' average initial capabilities, different catch-up dynamics can emerge. In particular, three other types of catch-up cycles are generated, such as an aborted cycle, a sustained leadership cycle and finally a coexistence of the latecomers with incumbents. Each of these cycles is put in relation to a specific historical case of catch up.

Key words: *catch-up cycles, leadership change, technology, shocks, history-friendly, industrial dynamics, simulations*

JEL Code: O30 (Technological Change, Research and Development, Intellectual Property Rights: General); **O10** (Economic Development: General); **L10** (Market Structure, Firm Strategy, and Market Performance: General).

1. Introduction

As noted by Schumpeter, one of the essential aspects of capitalism is creative destruction, which often lead to frequent changes in industrial leadership among firms and countries. Recently, one has witnessed the global rise of firms from emerging or latecomer countries in several industries like mobile phones, displays, shipbuilding, autos, and steel, etc. While there exist a large literature on the changes of industrial leadership, such as Mowery and Nelson (1999), and also on the rise of latecomers, such as Malerba and Nelson (2012), Amann and Cantwell (2012), Kim (1997), and Lee and Lim (2001), not much has been written on successive changes in industrial leadership within the same industries. This paper is expressly aimed at filling such gap.

Successive changes in leadership across countries are common in several industries studied in companion papers collected in this special issue, together with this paper. In steel, for instance, leadership shifted from the UK to Japan, and then from Japan to Korea (Lee and Ki, 2013); in shipbuilding from the UK to Japan and then from Japan to Korea (Lim and Kim, 2013); in mobile phone from the US to Europe, and then from Europe to Korea and (partly back to) the US (Giachetti and Marchi, 2013); in games from the US to Japan and then back to the US (Izushi and Aoyama, 2013); in semiconductors from the US to Japan and from Japan to Korea (Shin, 2013). In all these cases the arrival of new technologies (sometimes combined with government interventions and demand shocks) played an important role in favouring the leadership change. However there are also cases where, in spite of the emergence of new technologies, the incumbent managed to maintain the leadership. This is the case, for instance, in the camera industry where, after the first change from Germany to Japan, Japan succeeded to maintain leadership notwithstanding the arrival of the new SLR digital camera (Kang and Song, 2013). A similar case is also memory chips where leadership has firmly remained for more than two decades in the hands of the Korean company Samsung once it took it in the 1990s from Japan, which toppled the US in the 1980s (Shin 2013).

The above cases suggest the question that has originated this paper. Under what conditions does a leadership change occur and why it happens more than once in the same industry? In other words, what gives latecomers an opportunity to catch up with the incumbent and take industrial leadership away from them?

In answering these questions the main focus of the present paper is on the role played by the arrival of new technologies. As suggested by Perez and Soete (1988) new technologies often serve as windows of opportunities for latecomers. A window becomes an opportunity depending on the nature of the new technology and the responses of both the incumbents and the latecomers. Often incumbents tend to fall into a kind of lock-in trap, so that they stick to the old technology while delaying the adoption of the new. Relatedly, latecomers may enjoy the advantage of being free to choose the most up-to-date technologies available. But again this is not always the case.

In line with Lee and Malerba (2013) we call this phenomenon of successive changes in industrial leadership and catch-up by latecomers a “catch up cycle”. We consider this as an important subject because many industries have actually witnessed a catch up cycle in their historical evolution. During a catch up cycle the incumbent falters and a latecomer catches up with the incumbent, but then the latecomer, which has won the leadership, loses it to another latecomer.

Inspired by the empirical evidence on some cases of successive catch up (see the discussion in Lee and Malerba, 2013), we rely on a formal model to explore the technological conditions for the emergence of catch up cycles. Our model is developed along the lines of the evolutionary models of Nelson and Winter (1982) and the history-friendly tradition (Malerba et al., 1999). History-friendly models are indeed evolutionary models: firms are boundedly rational agents; their behavior is guided by routines; learning is a key process; agents and capabilities are heterogeneous. Processes of variety creation, inertia, continuity and selection characterize the industry over time. These models aim to analyse factors affecting the (short-run and long-run) dynamics of technology, innovation, market structure, industry architecture and industrial leadership. History-friendly models are complex dynamic stochastic systems, in which non-linearities are present and have a bottom up perspective: aggregate properties emerge out of the repeated interaction among agents – for a general discussion see Garavaglia (2010) and Yoon and Lee (2009). They have been used to examine the evolution of several industries, such as the computer (Malerba et al., 1999, 2001), semiconductors and computers (Malerba et al., 2008a, 2008b), pharmaceuticals (Malerba and Orsenigo, 2002), and memory chips (Kim and Lee, 2003). In those papers, a specific industry is the object of analysis and the actors and mechanisms that characterize that industry are explicitly modelled.

In this paper we take a slightly different approach because a single industry is not modelled. Rather, inspired by the cases of two industries such as mobile phones and semiconductors, we build a simulation model that is general enough to capture the gist of the catch-up cycles in more than one industry. The model focuses on the commonalities that characterize catch up cycles in these two industries, such as: the arrival of new technologies as a window of opportunities for latecomers, the working of incumbents' trap and technological lock-ins, the presence of latecomers' advantages in technological upgrade and the role of systemic and nation-wide characteristics in favouring catch up. Once the benchmark cases have been successfully replicated, we rely on counterfactual experiments to check whether our model can replicate the catch up cycles of other industries as well. In particular, we find that our model is also able to replicate three other cases of catch up, namely: the case of aborted catch up, such as Ireland in IT services (Mani, 2013), the case of persistent leadership as in camera or memory chips, with the continuing leadership by Cannon (Kang and Song 2013), and Samsung (Shin 2013), respectively, and the case of coexistence of incumbents and latecomers in a traditional industry such as wine (Morrison and Rabellotti, 2013).

Our history-friendly model is designed to address several questions concerning changes in industrial leadership at the both the firm and the country level. In this article we focus primarily on the role played by technological discontinuities, leaving other issues to future papers. We propose that a large shift of the technological frontier following the arrival of a new technology opens a large window of opportunity, because it enables innovations that are more disruptive (or competence-destroying) compared to incremental or competence-enhancing innovations (Tushman and Anderson, 1986; Christensen, 2002). Starting from this assumption, we exploit the history-friendly model to replicate a stylized pattern of catch-up in which two technological discontinuities are followed by two successive leadership changes. In particular, we show that a large window is more likely to be associated with a shift of industrial leadership from the incumbents to the latecomers (other things being equal). We also show that higher values of incumbents' capabilities with regard to the existing technologies would lead to a higher probabilities of lock-in by the incumbents and thus of leadership change from the incumbents' to the latecomers. Such possible 'lock-in' effect of the incumbents is a mirror image of the latecomers' advantages as they are freer in terms of choice of technologies. However, if the size of the technology window is substantially reduced, the lock-ins of the incumbents with respect to established technologies is low or incumbent general capabilities are very high, different scenarios are possible and different catch-up cycles can be generated, such the aborted catch-up, the sustained leadership one or the coexistence of leadership.

The paper is organized as follows. In the next section we discuss the stages of a standard catch-up cycle and the other possible types of cycles – such as aborted cycles, sustained leadership cycle and the coexistence of incumbents and latecomers, followed by a brief discussion of the two historical cases that we aim to model. Section 3 discusses the features of the model. Section 4 discusses the results of several simulation runs to verify the research hypotheses. Section 5, finally, concludes the paper.

2. Catch-up Cycles and their determinants

As mentioned in the Introduction, in the history of capitalism one can observe several successive catch up cycles in industries. Each cycle is supposed to consist of four stages, following the terms first coined by Abramovitz, namely: entry, catching up, forging ahead, and falling behind (Abramovitz, 1986). The first stage is the entry stage where the latecomers try to strike an entry by various means to overcome any disadvantages but utilizing any latecomers' advantages. The second stage is that of gradual catching-up in terms of market shares and/or productivity. The third stage is that of forging ahead based on adoption of a new technology or radical innovations in organizations, products, process and/or markets. The fourth and final stage is of falling behind where the newly emerged leaders tend to decline themselves with the rise of other new challengers or due to mistakes associated with the concept of the incumbents' trap. We call this type of cycle the "standard" catch-up cycle.

In some industry, however, the cycle of catch-up can take other forms. Some leaders, for instance, may be able to stay longer, not facing immediate decline, or to survive over several waves of new generations of technologies. In these cases we speak of "sustained leadership" cycles, where incumbents are able to retain their leadership over time. In some other cases latecomers may join incumbents in their leadership, so that we may have "coexistence of leaderships". Also, there can be cases of "aborted" catch-up where the catching-up effort fails to generate forging ahead but stay stuck somewhere at the stage of gradual catch-up (which then eventually lead to a gradual decline). Actually, many latecomer countries fall into this category of the aborted catch-up, and the critical barrier against them in reaching toward the forging ahead stage is the capability to generate upgrading into higher value-added products. Thus the discussion lead us to identify four types of cycles, a) a standard cycle experiencing fully the four stages from entry to falling behind, b) an aborted cycle of catch-up experiencing only up to the second stage of gradual catch-up for a while, c) a sustained leadership cycle, in which one may find the leadership of only the incumbents for a long time and d) a coexistence of leadership in which newcomers arrive on top, but incumbents do not decline.

The evidence at our disposal reveals that each of these distinct types of cycles is indeed a good approximation of some historical episodes of catch up. The interesting question is thus to understand the factors that effectively lead some industries to be characterized by one specific pattern of catch up as opposed to another. To address this point, previous research has placed a lot of emphasis on the concept of windows of opportunities. The literature, in particular, suggests that different types of windows of opportunity for catch-up may open up during the evolution of an industry (for a discussion see Lee and Malerba, 2013). They include major innovations or drastic technological change (Perez and Soete, 1988), changes in market demand and consumer preferences and business cycles (Mathews, 2005), and differences in the national innovation systems including public policy, laws and regulations (Guennif and Ramani, 2012). Relatedly, companies may respond in different ways to windows of opportunities depending on whether they are the existing leaders or the challengers: responses include incumbents' trap or lock-in behaviour (Chandy and Tellis, 2000) and the latecomers' advantages (for a more general discussion not related to catching up see Tushman and Anderson, 1986 and Christensen, 2002). The combination of windows of opportunity and the responses by both the incumbents and the latecomers determines which pattern of catch up is most likely to emerge.

In this paper we look at one key factor that determines catch up cycles: technological change. The rise of new technologies, pursuing the insights of Neo-Schumpeterian scholars such as Perez and Soete (1988) who discussed the emergence of new techno-economic paradigms, can create windows of opportunity for latecomers and prompt them to move toward new technologies to increase market shares.

In developing our model we take as a reference two industries in which radical changes in technologies played a major role in changing the leadership across firms and countries: mobile phones and semiconductors. We briefly present the two historical cases here. A more detailed analysis is presented in Giachetti and Marchi (2013) and in Shin (2013).

The evolution of the mobile phones industry is a clear example of a standard catch-up cycles, where two technological discontinuities led to two successive leadership changes. Here Motorola was the company that actually invented the analogue-based cell phone and thus created the sector. However, with the emergence of cell phones based on digital technologies, Nokia took over the market from Motorola, which tended to stay too long with analogue technologies rather than switching to digital cell phones. Then, in the smart phone era, Samsung and Apple toppled Nokia and became the new industry leaders. In this case, therefore, the pattern of catch up was characterized by two successive changes in leadership: first, from the US to Finland, and then from Finland to Korea and (partly) the US. In this process the rise of digital phones and subsequently the emergence of smart phones served as disruptive technologies, which opened windows of opportunities for latecomers. Faced with such windows incumbents suffered of a lock-in trap. Motorola tended to stay longer or keep investing with analog-based technologies, even after the arrival of digital wireless communication technologies. Similar behaviour was observed with Nokia, which was lukewarm to smart phones. Such trap was indeed the key factor that made it possible for latecomers to conquer the market (Giachetti and Marchi 2013).

The history of memory chips is in many respects similar to the one of mobile phone. In this case too frequent changes in technology (i.e. new generations of chip sizes) served as windows of opportunities for latecomers. In particular, the industry experienced two successive leadership changes: initially, from the US to Japan, and then from Japan to Korea. Frequent but ordered shifts in generations of technologies, like 1k to 16k, 64k, and 128k bit memory chips (DRAM), played an important role in these changes, as the latecomers often made aggressive investments into the next and emerging generation technologies to take the leadership away from the incumbents. By the way, the most recent story of Samsung continuing to keep the leadership in memory chips since the late 1990s can be explained by the fact that the window seems to be getting narrower: the new technologies called flash memory replacing the DRAMs is of the nature of competence-enhancing in the sense that the existing manufacturing facilities from the DRAM do not have to be scrapped but can be used to produce flash memories (Shin, 2013).

Inspired by these two cases, our history friendly model aims at generating evolutionary path of an industry with three cycles, with each cycle representing a leadership by a different country and its firms. We therefore have two subsequent leadership changes. The logic of the model rests on the combination of three main components: technological change, firms capabilities and countries national innovation system. The nature of these components evolves following stochastic processes, which make the model nondeterministic. Rather, the emphasis is placed on the complex relationship between the technology, the actors' decisions and the country institutional setting. We propose that successive changes in industrial leadership can be explained by a combination of the arrival of an exogenous window of opportunities, the response of the actors in the industry – incumbents and new firms – and the national institutional settings in which firms operate. In our model, the arrival of new technologies is captured by a shift in the technical frontier that the firms face: a larger windows means a greater shift of the frontier, and hence a bigger opportunity for the latecomers or early adopters to catch up. We suggest that a large window is more likely to generate a change in the industry leadership (from the incumbents to the latecomers), other things being equal.

In addition to the size of the window, we look at three other factors as determinant of catch up. First, we consider the role played by the responses of the incumbents vs. latecomers to the emergence of the new technology. In particular, we focus on the lock-in or the incumbent trap, which implies a tendency for the incumbent to cling to the existing technology rather than quickly switch to the new technologies. A firm choice to adopt new technologies depends on two components: the impact that the new technology has on the capabilities accumulated by the firm with the existing technologies, and the expected gain in terms of technical merit that the firm can obtain from adopting the new technology. The former factor turns into a parameter in the model related to the extent to which firms' capabilities are specific to a given technology: the greater the parameter, the greater the "loss" in capabilities if the firm adopts the new technology. Therefore a higher value of the incumbents' capabilities with regard to the existing technologies would lead to a greater risk of lock-in and thus a higher probability that leadership shifts from the incumbents' to the latecomers. The expected gain in terms of technical merit captures instead the merit of the new technologies. In this sense, the possible 'lock-in' effects for the incumbents are therefore a mirror image of the latecomers' advantages, as they are free in terms of choice of technologies. Latecomers always tend to choose the newer technologies, which arrived most recently in the industry and present higher level of technical merits. Incumbents are instead inclined to stick to the older technologies that are characterized by lower technical merits. This difference is indeed one of the major drivers of catch up.

The second factor that we analyse refers to the impact associated with the nature of the innovation process. In industries characterized by frequent radical innovations and increasing returns to scale leadership is often challenged. Breakthroughs lead innovators to obtain significant improvements in technical merit and thus increase their market share. On the contrary, in sectors that exhibit gradual innovation and constant return to scale, market positions tend to be more stable over time and leadership changes are less frequent. Therefore we expect that by altering the features of the technological landscape the nature of the catch up process changes too. In particular we propose that in industries characterized by smooth technical change and constant returns catch up is less likely to succeed than in industries in which innovations are radicals, where this distinction is exemplified by the comparison between traditional and high tech industries.

Finally, the last aspect that we take into consideration in our analysis concerns the role of the incumbents' capabilities. In contexts where the latecomers suffer of a considerable capabilities gap with respect to the incumbents the catch up process tends to be smoother.

This is the case, for instance, when the incumbents can rely on a national system of innovation that is much more effective in sustaining firms' capabilities than the one of the latecomers. In these cases capabilities can serve as important defensive barriers that partially compensate for the incumbents' delay in adopting new technologies. As a consequence we expect that in presence of an incumbents' advantage in terms of firms' capabilities catch up is less likely to succeed.

3. The model

In this section we present a formal model of industry evolution. The main aim of the model is to test the logical consistency of the forces underlying the theory of catch up cycles. The model is general enough to account for changes in industrial leadership occurring in different industries. A set of simulations will then be carried out to check how the identified patterns of catching up vary depending on sector-specific conditions.

The model is a simplified and extended version of a previous general model developed by Capone et al. (2013). Similarly to Capone et al. (2013) we consider an industry where technological and demand conditions shape the competitive dynamics among firms. Differently from Capone et al. (2013) we consider the existence of firms that may belong to distinct countries and focus on the shift of industrial leadership among them.

3.1 The topography

We consider an industry with two main components: the market space and the technology space. The former is a characterization of consumers' preferences for the products and their characteristics. In this version of the model we assume products to differ only along one dimension, which is their perceived quality. Demand is vertically fragmented (Shaked and Sutton, 1982), with consumers having heterogeneous minimum quality thresholds. Products that do not meet these minimum requirements are not taken into consideration for purchase.

The technology space is a characterization of the technological and innovation opportunities available to firms. Following the literature on technological paradigms and technological trajectories (Dosi, 1982), we account for both continuous changes and discontinuities in technological innovation. Continuous changes are technical improvements along the trajectory defined by a given technological paradigm, while discontinuities are associated with the emergence of a new paradigm. R&D activities carried out by firms are the main drivers of continuous progress along a given trajectory (Freeman, 1974; Pavitt and Wald, 1971; Pavitt and Soete, 1980). Discontinuities are instead modelled as exogenous shocks that alter the structure and composition of the technical landscape. After a technological shock, firms face the opportunity to adopt the new technology and undertake a new technological trajectory. The extent to which this will happen depends on several factors, among which the "competence destroying" vs. "competence enhancing" effect of the discontinuity, the lock-in effects associated with the old paradigm, and the sector-specific shape of the technical landscape.

The link between the market space and the technology space is established through firms' activities. Firms search the technology space in order to improve the techniques used in production and develop products that generate utility for the consumers in the market space. Firms are heterogeneous in a substantial sense. In particular, they may differ either because they discover different techniques or because they do not have the same capabilities to serve the market.

The industry is populated by firms of three competing countries. Firms have access to the same technology space and can serve three distinct markets: one national market (namely the market of the country the firm belongs to), and two foreign markets (namely the market of the other countries). At the beginning of the simulation the industry (and the related market) is born only in one country. We call this Country A, or the incumbent. After some periods an embryonic industry is born also in the other countries, which we call Country B and Country C, or latecomers. From that period onward, firms of countries A, B and C compete to gain market shares. The country whose firms serve the largest portion of the market is defined as the "industry leader".

In line with the theory of catch-up cycles we assume the existence of significant country-level effects on firms' innovative performance. As suggested by the literature of sectoral systems of innovation (Malerba, 2002; Malerba and Nelson, 2012), in fact, the presence of country-specific organizations and institutions can directly impact on the network of systemic interactions among firms. This can in turn affect the firms' capability to perceive and take advantage of innovation opportunities. In particular, we focus on three types of country-level effects: (i) an "information effect" associated with the role that country-specific organizations and institutions play in orienting the firms' searching procedures and technical change (Mazzoleni and Nelson, 2007); (ii) a "complementarity/lock-in effect" related to the impact that the web of interactions within a given country's sectoral system has on the firms' ability to perceive discontinuities in technological trajectories (Malerba, 2002, 2004); and (iii) a "learning effect" associated with the support that national systems of innovation offer to the process of capabilities accumulation at the firm level (Lundvall, 1992).

In the following paragraphs we present a more detailed description of each of the model's components.

3.2 Technology space

The technology space consists of an ordered vector of J (>0) distinct techniques. Firms search the technology space in order to find a technique to use in production. Every period, firms can use only 1 of J techniques. Each technique can be used to develop one product (single-product firm). We call j_f the technique adopted by firm f.

The "merit" of a technique is captured by coefficient r_j ($\in$ [0,1]). The "merit" reflects how good the technique is given the technological environment in which production takes place (which is assumed to be the same for all firms). For all $j \in J$, we assume the technical coefficients r_j to be distributed according to a beta cumulative distribution function, where parameters α and β define the shape of the technical landscape. By setting α =1 and β =1 we obtain a linear landscape, where the marginal increase in merit that can be derived from the adoption of a new technique is constant over all the landscape. This shape can best reflect the case of a traditional industry where technical improvements along a given trajectory are characterized by relatively "small jumps". On the contrary, by increasing the value of α keeping constant β =1 we obtain a non-linear landscape, where the marginal increase in merit is larger the more we move up the technology space. In this case the landscape can be best suited to represent a high-tech sector where technical "jumps" are frequent. Figure 2 offers a graphical representation of these two distinct landscapes.

[Figure 1 about here]

When the industry is born, we assume that the technology space is bounded by an initial frontier ζ_1 (see Figure 1). Firms can pick any technique j such that $r_j \leq r_{\zeta_1}$. This frontier corresponds to the best technique that can be picked by firms given the technological paradigm (first-generation technology) that characterizes production at the beginning of the simulated historical episode. Following a change in the technological paradigm (*e.g.*, due to a radical innovation) this frontier can then shift, giving to firms that adopt the new technology the possibility to search an expanded technology space, *i.e.*, to pick techniques such that $r_{\zeta_1} \leq$

$r_j \leq r_{\zeta_2}$, where ζ_2 is the new frontier. The number and merit of the techniques included in the interval $\zeta_1 \div \zeta_2$ determine the extent to which the technical window opened by the new technology is valuable for firms. Shifts in the technical frontier can occur repeatedly during the industry's life.

In line with Malerba and Orsenigo (2002) we assume firms to have only limited information on the shape and composition of the technical landscape. In particular, firms don't know *ex-ante* the merit and position of potential techniques. Firms randomly search the technology space and if they find a technique with higher merit than the one that they are currently adopting they switch to the new technique. Since firms can use only one technique for every period we can indicate, without loss of generality, $r_{f,t}$ as the merit of the technique adopted by firm *f* at time *t*. The searching procedure is described in greater detail below.

3.3 Market activities

Each firm can serve both the national and the foreign markets. We assume that in all countries firms are born with the propensity to serve the national market first. To serve one of the foreign markets, in fact, firms have to face a sunk cost c_E (> 0) (where 'E' stands for 'Export'), which can be paid only once a sufficiently large amount of financial resources are accumulated in a "export account" (see below). In addition to this, firms that serve their own national market are assumed to have a price advantage over foreign firms, which can be interpreted both as a bias of the national demand in favour of local products and/or as the existence of some market restrictions.

The probability that the product of a firm *f* is sold in the market depends on three components: technical merit ($r_{f,t}$), capability ($\theta_{f,t}$), and charged price ($p_{f,t}$), together with the price advantage discussed above. To lend some credibility to the model we can imagine $r_{f,t}$ as capturing technical and objective features of the product sold by firm *f*, and $\theta_{f,t}$ as non-technical features related to how the product is marketed and distributed. The combination of $r_{f,t}$ and $\theta_{f,t}$ determines the perceived quality of the product. Let consumers be uniformly distributed along the real unit segment. As discussed above demand is vertically fragmented and thus, depending on the quality thresholds of consumers, distinct market segments exist. In any of such segment, the probability that the product of firm *f* coming from country *k* ($\in$ {A, B, C}) is sold to consumer *i* ($\in$ [0,1]) of country *l* ($\in$ {A, B, C}) at time *t* takes the following form:

$$U(i)^{k,l}_{f,s,t} = \begin{cases} 0 & , if \quad q_{f,t} < Q_l(i) \\ \dfrac{q_{f,t}}{(1-\sigma_k)p_{f,t}} & , if \quad q_{f,t} \geq Q_l(i) \wedge k = l \\ \dfrac{q_{f,t}}{p_{f,t}} & , if \quad q_{f,t} \geq Q_l(i) \wedge k \neq l \end{cases} \tag{1}$$

where s stands for the market segment, σ_k ($\in$[0,1]) captures the price advantage when serving the national market, $q_{f,t} = \theta^{\delta}_{f,t} \cdot r^{\rho}_{f,t}$ is the perceived quality of the product, with δ ($\in$[0,1]) and ρ ($\in$[0,1]) being sector-specific weights, and $Q_l(.)$ is a country-specific beta cumulative distribution that assigns to each consumer i a minimum perceived quality requirement $Q_l(i)$. Changing the parameters of the distribution we can have different degree of vertical fragmentation in the demand. In this version of the model we assume both parameters to be equal 1 in all countries.

For a given degree of vertical fragmentation, market shares are computed as follows (see Capone et al., 2013). Consider the market of country l and assume that at time t there exist F^l (>0) firms that sell a product with strictly positive perceived quality. Assume that firms are arranged in a non-descending order by quality, in such a way that $q_{1,t} \leq q_{f,t} \leq q_{F^l,t}$ for all $f \in F^l$. Let $Q_l^{-1}(q_{f,t})$ be the fraction of consumers whose quality threshold is no higher than $q_{f,t}$. On this basis, we can define $G^l = F^l$ groups of consumers such that $G^l_1 = Q_l^{-1}(q_{1,t})$ and $G^l_g = Q_l^{-1}(q_{f=g,t}) - Q_l^{-1}(q_{f=g-1,t})$. Then, the market share of a generic firm f coming from country k in group g is:

$$m^l_{f,g,t} \begin{cases} \dfrac{U^{k,l}_{f,g,t}}{\sum_{f=g}^{G^l} U^{k,l}_{f,g,t}} & if \quad f \geq g \\ 0 & if \quad f < g \end{cases} \tag{2}$$

On this basis, the market share of firm *f* in the whole country *l* is simply the sum of its shares in the groups weighted by group size, that is:

$$m_{f,t}^{l} = \sum_{g=1}^{F^l} m_{f,g,t}^{l} \cdot \frac{G_g^l}{Q_l^{-1}(q_{F^l,t})} \tag{3}$$

Firm *f*'s market share in the whole industry can be thus written as:

$$m_{f,t} = \frac{m_{f,t}^{A}\chi_t^A + m_{f,t}^{B}\chi_t^B + m_{f,t}^{C}\chi_t^C}{\chi_t^A + \chi_t^B + \chi_t^C} \tag{4}$$

where $\chi_t^l (> 0)$, for $l = A, B, C$, is the number of consumers in country *l*. It follows that the total portion of the market covered by the firms of country *k* at time *t* is simply the sum of all the shares of the firms that belong to that country, that is:

$$m_t^k = \sum_{f=1}^{F_{k,t}} m_{f,t} \tag{5}$$

where $F_{k,t}$ (≥0) is the number of firms that belong to country *k* and are alive at time *t*. Whenever m_t^k is greater than the market share of all the other countries that are active in the industry, we say that country *k* is the "industry leader".

3.4 Price, profit and industry dynamics

Firms set price according to a mark-up rule. In particular, when serving the market of country *l* price is set as follows:

$$p_{f,t}^{l} = c \cdot (1 + w_{f,t}^{l}) \tag{6}$$

where *c* is the marginal cost of production, that we assume to be equal across all firms and countries, and constant over time. At time *t* firm chooses the mark-up $w_{f,t}^{l}$ in order to maximize profit, given the elasticity of demand η^l (>1) and the local competitive pressure at time *t*–1 as expressed by market share:

$$w^l_{f,t} = \frac{m^l_{f,t-1}}{\eta^l - m^l_{f,t-1}} \tag{7}$$

The profit of firm *f* at time *t* is thus defined as the sum of the profits obtained in the three countries, as follows:

$$\pi_{f,t} = (p^A_{f,t} - c)\cdot \chi^A_{f,t} + (p^B_{f,t} - c)\cdot \chi^B_{f,t} + (p^C_{f,t} - c)\cdot \chi^C_{f,t} \tag{8}$$

where $\chi^l_{f,t} = m^l_{f,t} \cdot \chi^l_t$, is *f*'s number of consumers in country *l* ($\in$ {A, B, C}).

Firms enter and exit the industry depending on their performance. In particular, every period there is a probability ω_k ($\in[0,1]$) that a new firm enter the industry in country *k*. A new entrant starts by searching the technology space, and if she finds a suitable technique she has the chance to serve the market. Firms that at the end of the period have a total market share lower than exit threshold m^e_k ($\in[0,1]$) are considered bankrupt and exit the industry. This exit threshold is assumed to be country-specific.

The total number of consumers in the three countries changes over time. In this version of the model we assume that such changes are due to causes not explicitly modelled, such as population growth or poverty reduction. In particular, the number of consumers follows a logistic growth path:

$$\chi^l_t = \frac{\Phi^l \chi^l_0 e^{g_l t}}{\Phi^l + \chi^l_0 (e^{g_l t} - 1)} \tag{9}$$

where Φ^l (>0) is the carrying capacity of country *l*, χ^l_0 is the initial number of consumers in country *l* and g_l is the country-specific growth rate.

3.5 Innovation activities

All firms invest the profit earned in the previous period in two distinct accounts: an R&D account, $R_{f,t}$, which is used to finance innovation activities; and an export account, $E_{f,t}$, which is used to finance export, *i.e.*, to cover the sunk cost c_E when gaining access to one of the foreign markets. We assume that initially all firms invest a fixed fraction τ_f ($\in[0,1]$) of their profit in $R_{f,t}$, while the remaining part $(1-\tau_f)$ is accumulated in $E_{f,t}$. This fraction is the same across all firms in all countries, and does not vary over time. Once $E_{f,t}$ is sufficiently large to cover the sunk cost c_E, the firm gains the opportunity to serve one of the foreign markets. The firm, in particular, starts by serving the foreign market that, in the given period, has the greatest number of consumers. From that period onward the export account is set to zero and the firm starts to accumulate new resources to gain access to the market that is not yet served. When all the foreign markets are served the firm invest all profit in innovation activities, *i.e.*, τ_f is set equal to 1.

Innovation activities consist of searching procedures within the technical landscape. Every period, firms have the chance to extract a number of techniques. The probability that a technique is extracted is uniformly distributed. The number of tries that firm *f* of country *k* disposes of is equal to $floor(R_{f,t} / \boldsymbol{c_R^k})$, where $\boldsymbol{c_R^k}$ (>0) is the unit cost of search for a new technique. Once a new technique is discovered it is allocated a patent and no other firm in the industry can use it. If in a given period more than one new technique is found, firms adopt the one with the highest merit.

Although the technology space is assumed to be common to all countries, the portion of the space that firms search is not. In particular, we assume that there exists a country-specific "information effect" that determines the pace and direction of searching. Whenever firms are faced with the opportunity to innovate, they don't know their actual position in the technology space. The only information they have is the merit of the technique they are currently adopting. At the beginning of every period, however, thanks to the set of institutions and organizations that populate the country's sectoral system, firms obtain an additional piece of information, which consist of the position of the firm that adopts the worst technique in the country. This allows firms to restrict their searching procedures to the window that goes from the position of the worst performing firm to the available frontier. As a consequence, although at the beginning of the simulation all firms face the exact same technology space, country-specific differences start to emerge as the innovation process proceeds. Depending on the type and number of firms that survive in any given country, the rate at which the technical frontier is approached will differ, and so will the dynamics of technical change.

3.6 Discontinuities

Industry evolution is market by technological discontinuities. For reasons not explicitly modelled at certain points in time a new technology emerges, which shifts the technological frontier rightwards. Firms adopting the new technology have access to an expanded technical landscape and thus have the chance to extract techniques with a greater technical merit. The parameter ψ_t ($\psi_t \in [0,1]$) measures the percentage shift in the technical frontier that occurs at period *t* and it is thus a proxy of the size of the technological shock.

The probability that the firm of a given country perceives the existence of the new technology depends on the country's performance while using the old technology. Such an assumption captures the role that country-level "technological complementarities" and "lock-in effects" play in restricting the firm's ability to recognize the emergence of a new technology (Perez and Soete, 1988). In particular, we consider the possibility of a "competence-destroying discontinuity" (Tushman and Anderson, 1986; Henderson and Clark, 1990), which tends to make firms that use the old technology unfit to take advantage of the new technology and can thus be the source of delay (*i.e.*, lock-in) in adoption. We write the probability that firm *f* of country *k* perceives the new technology at time *t* as follows:

$$a_{f,t}^{k} = \left(1 - m_t^k\right)^{\lambda} \qquad (10)$$

where λ (>0) is a parameter that measures the general difficulty of perceiving the new technology. If a firm enters the industry once the new technology has already emerged we assume that the firm perceives the existence of the new technology with probability 1.

If a firm perceives the existence of the new technology, the choice to adopt depends on two components: the impact that the new technology has on the capabilities accumulated by the firm within the old paradigm; and the expected gain in terms of technical merit that the firm can obtain from adopting. In particular, we assume that at time *t* firm *f* will choose to adopt whenever the following inequality satisfies:

$$\theta_{f,t}^{\delta} \cdot r_{f,t}^{\rho} < (\phi \theta_{f,t})^{\delta} \cdot \bar{r}^{\rho} \qquad (11)$$

where δ and ρ are sector-specific weights that capture the effect of capabilities and technique on the perceived quality of the product (see above), ϕ ($\in [0,1]$) is a parameter that measures the extent to which firms' capabilities are specific to a given technology (the lower ϕ, the more specific capabilities and thus the greater the "loss" in capabilities if adopting) and $\bar{r}$ is the expected merit of technique over the support [ζ_1, ζ_2], with ζ_1 and ζ_2 being the old and new technical frontier, respectively.

3.7 Learning

The model is built on the assumption that firms learn. Learning is cumulative and systemic in nature. Firms are born with a given set of heterogeneous capabilities. Capabilities accumulate over time following a pre-specified learning path, which combines both increasing returns and long-run saturation. The latter, in particular, reflects the fact that, being developed within the frame of a given technological paradigm, capabilities tend to run into diminishing return as the innovative potential of a given technology gets exhausted. At the same time, firms' learning benefits from systemic interactions with other firms, as well as from the support received from country-specific organizations and institutions. To capture both the cumulative and systemic effects jointly we assume that the capabilities of a generic firm *f* coming from country *k* evolve following the logistic process:

$$\theta_{f,t} = \frac{\theta_{f,0} e^{\gamma^k \bar{\theta}_t^k t}}{1 + \theta_{f,0}(e^{\gamma^k \bar{\theta}_t^k t} - 1)} \tag{12}$$

where $\theta_{f,0}$, *i.e.*, the firm's initial capabilities, is a random draw from a uniform distribution over the support [0, $\theta^k_{\max}$] with $\theta^k_{\max}$ being the maximum level of initial capabilities in country *k*, $\bar{\theta}_t^k$ is the average level of capabilities in country *k* at time *t*, and γ^k is a parameter that captures the strength of country-level effect on learning. From a careful inspection of equation (12) we observe that the greater the average level of capabilities in country *k*, the faster the process of capability accumulation at firm level. This in turn implies that, although in the long run the capabilities of both countries will tend to converge, the speed at which such convergence proceeds will differ.

4. The simulations runs

4.1 'History-friendly' runs

We run a set of simulations to analyse the role of technological discontinuities in favouring catch up. The aim of the simulation is twofold. First, we try to replicate a stylized episode of successive catch up, such as the one observed in semiconductors and mobile phone industries. Second, we develop some theoretically driven counterfactual exercises. In practice, we ask if the identified patterns of catch up could have been different had the value of some key parameter – as suggested by the appreciative theory underlying our model – taken alternative values.

The parameterization used for our 'history-friendly' simulations (see Appendix) reflects both some fundamental theoretical hypotheses and – in a highly qualitative way – some empirical evidence on the industries. The specification of the value of the parameters of the model also include some strongly simplifying assumptions and reflects our ignorance about the 'true' value of some key parameters. As a consequence, we consider our simulation runs as only broadly 'history-friendly'. They serve the purpose to produce a benchmark against which different hypotheses on the factors affecting catch up – coherent with our theoretical framework – can be tested.

To begin with, we define a baseline shape for the technical landscape, which includes a minor but positive degree of non-linearity (*i.e.*, α =3, β =1). Then, we set the remaining parameters so as to achieve two main objectives: first, to ensure the viability of the industry under the given technological configuration and second, to portray a typical process of industry evolution. In such a process, country A enters the industry first and soon becomes the industry leader. After 50 periods an embryonic industry is born also in country B, which then becomes the follower. Later, at period 150, also firms of country C enter the industry. Firms of all countries enjoy a symmetric advantage in serving their national market, which gives to latecomers' industry the opportunity to grow. At the same time firms of country B and C face a capability gap when they enter the industry, since firms of country A have already experienced some learning. Moreover, the market size of country B and C is very small at its inception and it achieves the same size as the one of A only by the end of the simulation. This makes a change in industrial leadership difficult to occur. The industry is assumed to last 300 periods.

Starting from this condition, we base our 'history-friendly' exercise on the assumption that two technological discontinuities arise, one at period 100 – *i.e.* after the entrance of country B, and the other at period 200 – *i.e.*, after the entrance of country C. In both cases, and in line with the historical cases that we want to replicate, we assume that in choosing the timing of entrance latecomers are capable of anticipating the windows of opportunities. The discontinuities are modelled as follows. At the beginning of the industry firms are borne with a technology that allows them to search only the initial 20% of the technical landscape. At period 100 a second-generation technology emerges that moves the technical frontier rightward, making it possible to search the 60% of the landscape (i.e. ψ_{100} = 40%). At period 200, then, a third-generation technology becomes available, which enable firms to search for techniques within the remaining 40% (i.e. ψ_{200} = 40%). Under a wide range of parameter settings, such discontinuities will open windows of opportunities for latecomers to catch up with the incumbent. In our program of history-friendly modelling we set parameters so as to 'replicate' a case of successive catch up where industrial leadership shifts first from the incumbent to one of the latecomers, and then from this latecomer to another latecomer.

[Figure 2 about here]

Figure 3 reports the evolution of countries' market shares (Panel I) and Herfindal index (Panel II) for our history friendly runs (results refer to averages over 200 runs). At the beginning of the industry nearly 6 firms are active in country A (A-firms). They are the only players in the market and can easily obtain the industrial leadership. The firm who finds the best techniques soon becomes the industry leader and industry concentration increases. As the time goes by more A-firms enter the industry and conquer some portions of market. In period 25 nearly 10 A-firms are active in the industry. This leads to a gradual reduction in industry concentration. This process goes on until period 50 when, following the entrance of country B, A-firms experience a slight reduction in their market shares. At the industry-level this translates into a sudden decrease of concentration, with the Herfindal index that drops by one sixth (from .43 to .36). Such a reduction, however, is only temporary. As soon as the less efficient among the new entrants exit the market, A-firms regain their market position and concentration increases. At period 100 A-firms control more than the 98% of the market and the Herfindal index has increased above the value it had before country B's entrance.

The structure of the industry radically changes when the second-generation technology emerges, at period 100. Due to the existence of complementarities and sectorial system effects, firms of country B (B-firms) are faster in adopting than A-firms. The latter, in particular, tend to be locked into the old paradigm and perceive the existence of the new generation technology with some delay. Such a delay gives to B-firms an advantage in searching the new expanded landscape, which lead to a significant increase of their market share. In a few periods the share of the market controlled by B-firms goes from less than 2% to nearly 55%, and country B becomes the new industry leader. At the same time the Herfindal index increases by on third (from .46 to .63), with the total number of firms operating in the industry that drops by half, moving from 10 to 5. After few periods of structural adjustment during which A-firms regain part of their market, the distance between the two countries starts to expand. Industrial concentration reduces following the gradual adoption of the second-generation technology by A-firms and the entrance of country C. At period 200, *i.e.* right before the second technological discontinuity, the Herfindal index takes value .44 and country B controls nearly the 59% of the market.

The leadership of country B, however, does not last for long. When the third-generation technology becomes available, in fact, a new radical change of industrial leadership occurs. In this case, the firms of country C (C-firms) are in the best position to adopt the new technology, since they have accumulated less experience in producing within the old technological paradigms. For these firms the switch to the third-generation technology is less costly than for A-firms and B-firms. As a result, C-firms adopt early and rapidly improve their market positions. In few periods their overall market share goes from less than 1% to nearly 40%, and around period 210 country C finally takes industrial leadership away from country B. As in the previous case industrial concentration increases in correspondence with the discontinuity and then it stabilizes. At the end of the simulation 7 firms are alive in the industry: 2 in country A, 3 in country B, and 2 in country C. Country C is the industry leader with the 45% of the market, followed by country B and country A with the 35% and 20% respectively.

The impact of technological discontinuities on the evolution of both market shares and industry concentration raises some intriguing questions concerning the firm-level competitive dynamics. Given that at the country-level discontinuities lead to successive changes of industrial leadership, it is interesting to investigate whether a similar process characterizes also the competitive struggle at firm level. Indeed, in most of the historical episodes that inspired our model (see for instance the case of mobile phone) the competitive dynamics was characterized by substantial changes of leadership also among firms.

[Figure 3 about here]

Although our simulation model makes it difficult to track the behaviour of each single firm across distinct runs, we can get some insights on the firm-level competitive dynamics by looking at some aggregate statistics. In Panel I of Figure 4 we plot the probability that a change of firm's leadership occurs. This probability is computed by taking into consideration all the 300 runs performed under the 'history-friendly' parameter setting and counting the times a change in firm's leadership occurs in every period. As one can easily observe such probability tends to be characterized by three main peaks. The first peak is at the beginning of the industry, when the initial leader emerges. Then, the second and third peaks coincide with the two technological discontinuities that open at period 100 and 200 respectively. In both cases, the shift of the technical frontier opens new opportunities for technical improvements, which in turn increase the likelihood that a new leader emerges.

In addition to the probability of a change in firm's leadership, Figure 4 reports two further statistics that concerns the evolution of firm-level competition. Panel II shows, for every period, the probability that the leader of the industry is a firm of a given country. Panel III reports instead the markets shares dynamics of each of the countries' leader. The latter statistics, in particular, is computed as follows. In each run we first identify the leading firm of country A and B in period 99 and 199 respectively (i.e. before the two discontinuities). Then, we identify the leading firm of country C at the end of the simulation. For each leader, we track the evolution of market share throughout all industry's life and compute the average over the 300 runs. The result is a statistic that shows the market behaviour of each country's leader, where each leader is identified at the peak of the country's market potential.

The statistics reported in Panels II and III reveal two interesting results. Firstly they show that in our history-replicating scenario the changes of industrial leadership at country-level tend to be associated with correspondent changes in firm's leadership. While after the first discontinuity a B-firm is more likely to be the industry leader than an A-firm, after the second discontinuity the highest chances are for a C-firm. This result reflects quite closely the competitive struggle that have characterized some real word industries, such as the shift of leadership from Motorola to Nokia and then from Nokia to Samsung/Apple in the mobile phone industry. Secondly, Panel III shows that after the two technological discontinuities both country A's and country B's leaders experience a drastic reduction in their market share. In the case of country A this contraction is such that the leader is eventually forced to exit the industry right after the third-generation technology emerges. With reference to country B, instead, the leader is able to survive until the end of the simulation, although with a marginal market share.

Combining the evidence reported in Figures 3 and 4, we conclude that our 'history-friendly' runs do a relatively good job in reproducing a stylized case of normal catch up cycles, with two times of leadership change. In particular, following two technological discontinuities, industrial leadership shifts first from country A to country B, and then from country B to country C. This is true if we look both at the firm-level and country-level competitive dynamics. From the historical point of view the simulation replicates quite closely the cases of both semiconductor and the mobile phone industry, where a series of technological discontinuities favoured the cyclical shift of industrial leadership among few global players.

4.2 Sensitivity analysis

Before proceeding with the analysis of counterfactuals we check the robustness of our ‘history-friendly’ runs by the mean of sensitivity analysis. The latter is organized as follows. First we divide the parameters of our model into two categories: focal parameters and general parameters. Focal parameters are the elements that we choose in a systematic way in the counterfactual experiments to answer the research questions of this paper: they include size of the window, probability of lock-in, shape of the technical space and firm’s capabilities. We include in this category also some parameters that we believe may have important theoretical underpinnings but for reasons of space were not considered here– *e.g.* most of the parameters that are associated with policy interventions. General parameters are instead the elements that do not change across different runs and define the main structure of the model. They include: size of the technology space, initial size of the market, country’s carrying capacity, market’s growth rate, demand elasticity, degree of vertical segmentation, probability of new firm creation, market exit threshold, firm’s initial budget, marginal cost of production and learning coefficient.

Once these two categories of parameters are identified we follow Richiardi et al. (2006) and Windrum et al., (2007) and perform a local investigation on general parameters, *i.e.* an analysis of how the model behaves for variations in a restricted region of the parameters’ space. For each parameter we run several simulations in which we vary the original value in a range that goes from +50% to –50% with respect to the value of the parameter in the baseline (see Appendix). In doing so we pay particular attention not to alter the parametric asymmetries that exist among countries, which are specific to the historical episode that we want to replicate (*e.g.* different initial size of the market in the three countries). Moreover, we make sure that under all possible combinations of parameters the viability of the industry is preserved.

The results of the sensitivity analysis are encouraging.[1] Under all combinations of parameters we are still able to reproduce a normal cycle with two times of leadership change: first form country A to country B, and then from country B to country C. The only exception is the case in which the probability of new firms creation is drastically reduced with respect to the baseline. In this setting there is no clear change of industrial leadership following a discontinuity and the three countries tend to peacefully co-exist (probably as a consequence of the relatively slow pace with which technology opportunities are probed). If we exclude this relatively extreme case, however, the model seems robust, *i.e.* results do not seem to depend on *ad hoc* parameter conditions.

4.3 Counterfactuals: theory-driven experiments

Once a set of 'history-replicating' parameters is identified, our second aim is to check how the overall catch up dynamics changes when some of these parameters vary. To do so we define a second group of simulations where, while taking our 'history-replicating' parameterization as a baseline, we experiment with some parameter changes. In particular, we focus on the parameters that Lee and Malerba (2013) put forth as causal factors behind the emergence of catch up cycles.

We run four distinct experiments. First of all, we reduce the size of the windows (ψ) associated with the discontinuities to see if this will damp down on the tendency of industrial leadership to shift. A smaller size of the windows implies that the degree of technical improvement available for firms who adopt the new technologies is relatively limited. Everything else equal, this should reduce the probability that a change in industrial leadership occurs. Secondly, we reduce both the difficulty of perceiving the new technology (λ) and the capability loss ($1 - \phi$) associated with its adoption. These two factors should reduce the risk for incumbent firms to get locked into the old technology and thus make it easier for them to defend their leadership. Third, we change the shape of the technical landscape increasing the degree of linearity (*i.e.*, we reduce the value of α while keeping β constant). A linear landscape implies that R&D investments are characterized by constant return and thus less radical improvements in technical merits can be obtained. For a given size of the technological discontinuity this should make catch up less likely to succeed. Finally, we run one last experiment where we increase the average level of capabilities incumbent firms are endowed with at their birth. In this case we are interested in evaluating the extent to which

[1] For reasons of space we do not provide a complete description of the results here. The interested readers can contact the authors.

capabilities can help the incumbents to retain their leadership. This scenario is analysed both in the case of a non-linear technical landscape and in the case of a linear technical landscape.

In all experiments we try different specifications for the parameter values. For the sake of brevity we report here evidence only for the specifications that give the most significant results.

Experiment 1: changing the size of the window. Let us first consider the role played by the size of the windows. According to the appreciative theory of the catch up cycles, the opening of windows of opportunities is one of the major drivers of successful catch up. If adequately exploited, such windows offer the possibility for latecomers to improve their competitiveness and gain market shares. Obviously, one implication that follows from this consideration is that, whenever these windows are absent or too small, catch up is less likely to succeed.

To test this hypothesis we run two distinct sets of simulations: in the first one we reduce only the size of the first window; in the second one we reduce the size of both windows. We call the former setting *1S* and the latter setting *2S*, where "*S*" stands for small. In particular we assume that, instead of a shift in the frontier for about the 40% of the technical landscape as in the baseline, a small window produces a shift only for about the 10% of the landscape, i.e. ψ_t = 10%. The remaining set of parameters is kept the same as in the 'history-friendly' runs.

[Figure 4 about here]

Figure 4 reports the evolution of countries' market shares (Panels I and III) and Herfindal index (Panels II and IV) in settings *1S* and *2S*. As we can notice in both settings the evolution of market shares is very similar to the baseline until period 100. After that period, however, the opening of a smaller window makes it easier for A-firms to defend their leadership. B-firms do profit from the discontinuity and increase their market share, moving from almost zero to nearly 38% in both *1S* and *2S*. Such an increase, however, is not sufficient to take industrial leadership away from country A. The reduced size of the window allows early adopters to obtain only a marginal increase in technical merit and thus it limits the possibility of a leadership change. After the second discontinuity, however, the dynamics in the two settings differs remarkably. When the second window is large (Panel I) C-firms can profit from the technical improvements ensured by the third-generation technology, and eventually become the new industry leader. When the second window is small, on the contrary, C-firms improve their market position, but not enough to overcome incumbents (see Panel III). At the end of the simulation B-firms are the industry leaders, followed closely by C-firms and A-firms. Overall the dynamics simulated in these two settings reproduces two different cases of half or aborted catch up, where right after the discontinuity latecomers fail to overcome incumbents.

In addition to the evolution of market shares, the emergence of technological discontinuities significantly impacts also on the degree of industry concentration. In our 'history-friendly' replications we observed that the opening of a windows of opportunities is usually associated with a remarkable increase in industry concentration. Our interpretation is that, as the window opens, only the few firms that are fast in adopting can obtain significant technical improvements and gain market share. This leads to an initial peak in industry concentration. As the time passes, however, more firms adopt and the technical gap between the latter and the early adopters reduces. As a consequence an increasing number of firms can gain some portion of the market and industry concentration gradually diminishes.

If our interpretation is correct we should expect that, as the size of the window of opportunities reduces, also the impact on the degree of industry concentration weakens. The reason is that a smaller window offers fewer opportunities for substantial increase in technical merits and thus it reduces the competitive advantage enjoyed by early adopters. As shown by the evolution of the Herfindal index reported in Figure 4 this is indeed what we find. When the size of the window is reduced compared to the baseline (see Panels II and IV) we observe a much smaller increase in industry concentration.

[Figures 5 and 6 about here]

Similarly to the analysis carried out for the 'history-friendly' replications it is interesting to look also at the impact that the size of windows has on the firm-level competitive dynamics. On this respect Figures 5 and 6 report the same statistics as the one reported in Figure 3. In this case too the probability of a change in firm's leadership (Panels I) exhibits three main peaks: one at the beginning of the industry, and the other two in coincidence with the technological discontinuities. In coincidence with a small window, however, the size of the peaks is significantly smaller than in the baseline. This result suggests the existence of a positive relationship between size of the discontinuities and probability of leadership change also at the firm level. The data on the probability of firm's leadership distinguished by countries confirm this intuition (Panels II). Differently from the baseline, in fact, in both setting *1S* and *2S* the probability that the industry leader is an A-firm remains the highest until period 200, when the third-generation technology emerges. Moreover, as shown in Panels III, country A's initial leader does experience a remarkable reduction in market share, but the fall is relatively smooth compared to the baseline. In addition, both country A's and country B's initial leader are able to survive until the end of the simulation. This suggests that in the two settings with reduced size of the windows there exist a greater degree of stability in industry composition compared to the baseline.

Experiment 2: lock-in effect. The second experiment that we run looks at the role played by lock-in effects. As we noted earlier, one of the factors that makes latecomer countries in a better position to exploit windows of opportunities is associated with the incumbents' delay in perceiving the discontinuities. This, together with the competence destroying effect of the new technology, tends to make incumbents locked into the use of the old paradigm and reduces their chances to retain industrial leadership. Similar factors, for instance, played an important role in the memory chip segment of the semiconductor industry where US companies did not realize the potential of new generations of memory chips (like 16k, 64k, and 128k) and let Japanese companies to pioneer the new technology. A similar process characterized also the mobile phone industry, when at the outset of the digital revolution Motorola continued to rely heavily on analog technology, believing that that consumers would prefer analog phones to digital phones. This made it possible for Nokia to become the new leader.

In order to test the importance of lock-in effect in favouring (or undermining) a process of catch up we run a set of simulations where we gradually decrease both the incumbents' difficulty in perceiving the new technology (λ) and the competence destroying effect associated with the new paradigm ($1 - \phi$). All the other parameters are kept the same as in our 'history-replicating' baseline setting. If anything, we expect these changes to make catch up less likely to succeed.

[Figure 7 about here]

Figure 7 reports the evolution of countries' market share (Panel I) and industry concentration (Panel II) for the runs where parameters λ and $1 - \phi$ are significantly reduced with respect the baseline (respectively, from 3 to 1 and from 0.9 to 0.5). We notice that, in line with our expectations, no change of industrial leadership occurs during the entire industry's life. After the first discontinuity, B-firms profit from the adoption of the second-generation technology and improve their market position. In this case, however, A-firms perceive the emergence of the new paradigm with relatively little delay and adopt too. As a result the distance between the two countries reduces, but not enough to lead to a change of leadership. At period 200 A-firms still control nearly the 60% of the market and B-firms the remaining 40%. Then, as the third-generation technology emerges, it is the turn of C-firms to gain market share. Being relatively new in the industry C-firms have an advantage in adopting the new technology with respect to both A-firms and B-firms. Similarly to the previous case, however, this advantage does not suffice to make early adopters to obtain the leadership. A-firms and B-firms perceive the discontinuity relatively early and adopt rapidly. By the end of the simulation a super cycle with no change of leadership emerges: country A is remains the industry leader with the 42% of the market, followed by country B and C with the 37% and 21% respectively.

The trend of industry concentration follows very closely the one observed in the 'history-replicating' runs. The opening of a technological discontinuity is always associated with an increase in industry concentration, which is then followed by a gradual adjustment. In this case, however, we notice that for both discontinuities the rise in the Herfindal index tends to be of a smaller magnitude compared to the baseline. Our interpretation is that the weakening of the lock-in effects reduces the technical advantages enjoyed by early adopters, because many firms rapidly undertake the same technological trajectory. This in turn weakens entry barriers and eventually diminishes concentration.

[Figure 8 about here]

Panels I to III of Figure 8 report the evolution of the firm-level competitive dynamics. In line with the 'history-replicating' runs we observe that the probability of a change in firm's leadership increases in correspondence with the technological discontinuities (Panel I). In this case, however, it is highly likely that an A-firm retain the leadership throughout all the industry's life (Panel II). The weaker lock-in effect, in fact, make it possible for such firms to adopt early and thus to exploit their stronger market position. This aspect is reflected also in the market behaviour of each country's leader (Panel III). Although after the discontinuities both country A's and country B's leader experience a significant reduction in their market share, they can still survive until the end of the simulation and maintain a market share close to 20%.

Experiment 3: shape of the technical landscape. In our third experiment we test the robustness of the simulated catch up dynamics with respect to a change in the shape of the technical landscape. As previously stated, the shape of the technical landscape reflects some implicit assumptions about the way in which innovation activities proceed in the industry considered. A linear landscape, for instance, implies that technical improvements are manly gradual and radical “jumps” in technical merit are difficult to obtain. This shape is best suited when we want to represent traditional industries. On the contrary, a non-linear landscape allows firms to undertake substantial technical breakthroughs. This type of landscape is best suited to represent high-tech industries. Since in our ‘history-replicating’ setting we referred to industries where technology plays a relatively important role, such as semiconductor and mobile phone, we assumed a small but positive degree of non-linearity. Now we want to see what happen to the simulated dynamics when the degree of non-linearity is reduced.

To test the effect of a reduced degree of non-linearity in the technical landscape we run a set of simulations where we gradually lower the α-parameter of landscape’s Beta distribution. All the other parameters are kept the same as in our ‘history-replicating’ runs. Moreover, we run a second set of simulations where in addition to the lowering of α we reduce the size of the two technological discontinuities. This makes it possible to match even more closely the case of a low-tech industry where in addition to innovation activities also technological discontinuities tend to be less radical than in a high-tech industry.

[Figure 9 about here]

Figure 9 reports the evolution of countries’ market shares and Herfindal index when the value of α is decreased from 3 to 1. Panels I and II report the results for the case in which the size of the two discontinuities is left unchanged with respect to the baseline (i.e., ψ_{100} = 40% and ψ_{200} = 40%). Panels III and IV refer instead to the case in which the size of both discontinuities is reduced (i.e., ψ_{100} = 10% and ψ_{200} = 10%). As we can notice the shape of the technical landscape does impact on the overall pattern of catch up among countries, making the overall process relatively smooth compared to the baseline. Overall, however, the presence of a linear landscape does not prevent successive catch up cycles to emerge, especially when windows of opportunities are large (Panel I). When the size of the windows is reduced (see Panel III) a change of industrial leadership is harder to obtain. In this case, in particular, we observe only one change of leadership from country A to country B. The latter dynamics matches quite closely with the one observed in setting *S2* of Experiment 1.

One dimension that seems to be severely affected by the shape of the technical landscape is the degree of industry concentration. If we compare the results reported in Panels II and IV of Figure 9 to the ones obtained in both the 'history-friendly' runs (Figure 2) and Experiment 1 (Figure 4), we observe two main differences: firstly, in presence of a linear landscape technological discontinuities (both large and small) tend to be associated with smaller increases in industry concentration; secondly, throughout all industry's life span, a more linear landscape is associated with a relatively lower degree of industry concentration. Our interpretation of these results is that in presence of linear landscape innovation activities tend to be characterized by constant returns. This implies that, compared to a context with increasing returns, new entrants face a relatively smaller technical gap with respect to incumbents. As a result entry barriers are lower and more firms are able to enter and survive in the industry. In this sense our original intuition according to which a linear landscape is a good approximation for low-tech and traditional industries seem to find support in the data.

[Figure 10 about here]

In addition to the degree of industry concentration, the shape of the technical landscape has an important effect also on the firm-level competitive dynamics. On this respect Figure 10 reports both the probability of a leadership change and the probability of firm's leadership when the technical landscape is linear. These two statistics are computed both in the case of large windows (Panels I and II) and in the case of small windows (Panels III and IV). Overall these graphs reveal that, compared to the baseline, the peak in the probability of leadership change that is associated with the opening of a new window tends to be smaller in the presence of a linear landscape. This is particularly evident in the setting with large windows (Panel I). At the same time, however, if one looks at the periods between one window and the other, the average probability of a leadership change is higher in the setting with a linear landscape than in the one with non-linear technology. Moreover, as it is shown in Panels II and IV, the switches in the probability of firm's leadership across countries tend to be much more accentuated in presence of a linear landscape compared to the baseline. In our view these results can be explained by the low degree of industry concentration. Indeed, the existence of several firms of relatively small size increases the probability that in every period distinct firms undertake technical improvements, which in turn makes the market position of a leader difficult to defend. When a window of opportunities opens, early adopters can surely obtain some significant technical advances. The latter, however, are somewhat smaller compared to those obtainable under a non-linear landscape, and are in any case insufficient to ensure a significant increase in the likelihood of a leadership change. As a result we observe both a relatively small impact of the technological discontinuities on the probability of a leadership change and a relatively high frequency of firm-level leadership changes between one discontinuity and the other.

Experiment 4: Incumbent's capabilities. In the fourth and last experiment we explore the role played by firm's capabilities. In the appreciative theorizing that inspires our model capabilities are seen as one of the major drivers of firm's competitiveness. The larger the capabilities the more firms are able to size the opportunities available in the surrounding environment and the better their performance. In this sense high capabilities can be expected to play a role both as a tool that allows incumbents to defend their acquired leadership, and as device that facilitates the catch up by latecomers. For the sake of brevity in the present paper we focus mainly on the contribution of incumbent's capabilities, leaving the analysis of latecomer's capabilities for future research.

In order to test the role played by incumbent's capabilities we run two distinct sets of simulations. In the first one we increase the maximum level of capabilities A-firms can be endowed with at their birth (i.e. $\boldsymbol{\theta}^{A}_{\mathbf{max}}$), while keeping all other parameters constant. Compared to our 'history-friendly' runs this amounts to assume that on average firms of the incumbent country tend to enjoy a favourable capabilities gap with respect to latecomers, which can be due for instance to a more effective national system of innovation. Then, we run a second set of simulations where in addition to $\boldsymbol{\theta}^{A}_{\mathbf{max}}$ we change also the shape of the technical landscape – making it more linear (i.e. α =1), and the size of the windows – making them smaller (ψ_{100} = 10% and ψ_{200} = 10%). With this second set of simulations our main aim is to verify the contribution that capabilities can offer as a defensive barrier favourable to incumbents in low-tech sectors as opposed to high-tech sectors.

[Figure 11 about here]

Figure 11 reports the results on both the firm-level and country-level competitive dynamics, when the value of $\boldsymbol{\theta}^{A}_{\mathbf{max}}$ is doubled (i.e. raised from 0.3 to 0.6). Panel I reports the evolution of the countries' market share. Panel II shows the probability of firm's leadership distinguished by countries. At the country-level we notice that, in spite of the incumbent's advantage in terms of capabilities, countries B and C are still capable of recursively gaining industrial leadership. After the first discontinuity country B's market share jumps from less than 1% to nearly 45%, and it becomes close to 54% by period 190. After the second discontinuity the catch up process of country C is even faster with industrial leadership that is achieved in less than 10 periods. This suggests that even if capabilities are important drivers of firms' competitiveness, they may not be enough to protect the incumbent country against the threat of latecomers when the size of technological discontinuities is sufficiently large.

At the firm-level the competitive dynamics presents some important differences with respect to the country-level, especially after the first discontinuity. Although the emergence of the second-generation technology drastically increases the probability that a B-firm obtains the leadership, in the majority of the cases an A-firm remains the industry leader until period 200. This result differ remarkably from the one obtained in the baseline setting where changes of leadership at the country-level are always accompanied by changes of leadership at the firm-level. Our interpretation is the following. After the technological discontinuity the competitive dynamics tends to be shaped manly by new entrants. The latter can come either from the incumbent country or from the latecomer country. New entrants are faster in adopting then incumbents and have the chance to become the industry leader. When A-firms enjoy an advantage in terms of initial capabilities new entrants from the incumbent country tend to play a major role, since they can combine high capabilities with high technical merits. However, they are few and their competitive advantage is not enough to lead the whole country to retain her leadership. In this case, therefore, we will observe a change of leadership at the country-level but not at the firm-level. The story is different, however, when the initial advantage in terms of capabilities is either absent (as in the baseline) or levelled out by the firm's learning (as after the second discontinuity). In these cases the changes of leadership at the country-level will tend to correspond to a change of leadership at the firm-level.

[Figure 12 about here]

The differences between firm-level and country-level competitive dynamics are even clearer if we move from a non-linear landscape to a linear landscape, i.e. (in our interpretation) from a high-tech sector to a traditional sector. On this respect Figure 12 reports the evolution of market shares and the probability of firm's leadership for the cases in which parameter α is set equal 1. These results are reported both for the case of large discontinuities (Panels I and II) and for the case of small discontinuities (Panels III and IV). As we can notice the existence of a linear technical landscape amplifies the dichotomy that exist between firm-level and country-level competitive dynamics. In particular it makes firm's leadership much more difficult to switch across countries. Independently of the size of the windows, in fact, we find that the probability an A-firm is the industry leader remains largely the highest until period 200. At the country-level, on the contrary, the market position of country A rapidly deteriorates. In the setting with large windows this process eventually lead to a change of leadership even at the country-level before the third-generation technology emerges. In the setting with small windows industrial leadership switch from country A to country B only after the second discontinuity. In both cases, however, the market distance among the countries at the end of the simulation tend to be smaller compared to the baseline and especially in the setting with small windows it points towards a peaceful co-existence of the three countries. This result reinforces the idea that in traditional and low-tech sectors the existence of an initial advantage in terms of capabilities can make the incumbent country in a better position to defend leadership.

5. Discussion and concluding remarks

Inspired by successive catch-up cycles in mobile phones and semiconductors, the paper has developed a history-friendly model that aims to investigate how and why catch-up cycles happen, what gives latecomers an opportunity to catch up with the incumbent and take over industrial leadership from them and why the new incumbent often fails to maintain its new leadership with respect to new latecomers.

The model has been able to generate the benchmark scenario of thee cycles with two times of leadership changes when there are exogenous arrivals of new technologies. The simulation analysis with (counter-factual) experiments has shown that the more disruptive the new technology, the greater the shake-up of market shares between the incumbents and the late entrants. In our model, a more disruptive technology is captured by a large shift of the technological frontier. The model also shows that a leadership change is more likely to occur when it coincides with a certain response by the actors, such as a high lock-in behaviour on the side of incumbents whose capabilities are highly specific with regard to the existing technologies. A basic room for the possibility of catch-up by the latecomers is also given by the existence of certain latecomer advantages such as the rapid adoption of new technologies.

The model has also shown that depending on the size of windows, the degree of lock-in, the shape of technological landscape, and the incumbents' average initial capabilities, different catch-up dynamics can emerge. In particular, the experiments have been able to generate four distinct types of catch-up cycles, such as a standard cycle with clear change of the market leadership (which has constituted our benchmark cases of mobile phones and semiconductors), an aborted cycle of catch-up with only a limited rise of the market shares by the late entrants, a sustained leadership cycle where the incumbents maintained its leadership, and finally a coexistence of the latecomers with incumbents. The aborted catch-up cycle is illustrated by the case of IT services (see Mani 2013) where Ireland made a successful entry based on an initial window of opportunity but failed to sustain its market shares due to problems in upgrading into higher-end segments and the required innovation effort, associated with weak local ownership of the firms. Instead, substantial and steady increase in the market shares was eventually achieved by another latecomer country, India, which was more successful in subsequent learning, upgrading and innovations. In our model the aborted catch-up case of Ireland with its failure to become a leader is associated to a window of limited size, which does not allow latecomers to gain momentum and reach the leaders (see in particular Panel I of Figure 4). The case of persistence of leadership is the one of Japanese firms, Cannon, in Camera industry or Korean firms, like Samsung, in memory chips industry, in which these firms have maintained their leadership (at least so far) in spite of the presence of technological discontinuities or generation changes. In our model, the persistence of leadership is given by a lower lock-ins by incumbents with respect to the new technological windows that allow them to respond rapidly to the technological discontinuities (see Panel I of Figure 7). The case of coexistence of incumbents and latecomers in a leadership position after the opening of windows is represented by the case of wine. Wine is a traditional industry in which the old leader France was joined by new leaders such as latecomers countries (United States, Australia and so on) as well as Italy (Morrison and Rabellotti, 2013). In our model the coexistence is obtained by combining a more linear technical landscape (that is moving it to a more incremental and less radical change) with discontinuities of smaller size and a higher initial level of the incumbents' capabilities (due to the effectiveness of their national innovation system) (see Panel III of Figure 12).

Thus the diverse cases that can be explained by our model suggest that our model is able not only to replicate the catch up cycles of the two industries that inspired its construction, but also to replicate other types of cycles present in other industries. This was possible by giving different values to parameters related to factors such as size of the technological window, the role of incumbents' lock-ins, the level of incumbents' initial capabilities and the shape of the technological landscape.

While this paper has focused more on the role of exogenous windows of opportunity related to the introduction of new technologies, a next step would be to incorporate other types of windows such as government and demand, and other aspects of the actors' responses and strategies, such as stage skipping or path creating strategies. Another route is to make the technological windows endogenous and responsive to the efforts either of the latecomers or the incumbents. Of course, in these cases the actor that is the source of the window has an initial advantage with respect to the competitors – be the incumbent or the latecomer. Finally, a third route is the modelling of firms in a finer grained way, introducing their production cost and marketing dimension, in order to take into account the early advantages of latecomers due to low labour cost or the knowledge of domestic firms with respect to their domestic markets.

Acknowledgment

We thank Gianluca Capone and the participants of the 2013 Globelics Conference held in Ankara, and the Seoul Conference on Successive Catch Cycles (May 2013) for useful comments.

Appendix

[Table A.1 about here]

References

Abramovitz, M., 1986. Catching-up, forging ahead, and falling behind. Journal of Economic History 46 (2), 385–406.

Amann, E., Cantwell, J., 2012, Innovative firms in the emerging market countries. Oxford University Press, Oxford.

Capone, G., Malerba, F., Orsenigo, L., 2013. Are switching costs always effective? The moderating role of technological and demand regimes. Long Range Planning 46(4-5), 348-368.

Chandy, R.K., Tellis, G.J., 2000. The Incumbent's Curse? Incumbency, Size, and Radical Product Innovation. Journal of Marketing 64, 1-17.

Christensen, J.F., 2002. Incongruities as a source of organizational renewal in corporate management of R&D. Research Policy 31(8-9), 1317-1332.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and direction of technical change. Research Policy 11, 147-162.

Freeman, C., 1974. The economics of industrial innovation. Penguin, Harmondsworth.

Garavaglia, C., 2010. Modelling industrial dynamics with "History-friendly" simulations. Structural Change and Economic Dynamics 21(4), 258-275.

Giachetti, C., Marchi, G., 2013. Changes in industrial leadership over the life cycle of the worldwide mobile phone industry. Paper presented at the conference on 'Changes in the industry leadership and catch-up cycles', Seoul, Korea.

Guennif, S., Ramani, V. S., 2012. Explaining divergence in catching-up in pharma between India and Brazil using the NSI framework. Research Policy 41(2), 430-441.

Henderson, R. M., Clark, K. B., 1990. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. Administrative science quarterly 35(1), 9-30.

Izushi, H., Aoyama, Y., 2013. Evolution of country-specific demand preferences and international leadership: case of the video game industry. Paper presented at the conference on 'Changes in the industry leadership and catch-up cycles', Seoul, Korea.

Kang, H., Song. J., 2013. Catch-up repeats itself: lessons from successive shifts in market leadership in the camera industry. Paper presented at the conference on ‘Changes in the industry leadership and catch-up cycles’, Seoul, Korea.

Kim, C. W., Lee, K., 2003. Innovation, technological regimes and organizational selection in evolution of industry: a ‘history friendly model’ of the DRAM industry. Industrial and Corporate Change 12(5), 1195-1221.

Kim, L., 1997. Imitation to innovation: the dynamics of Korea's technological learning. Harvard Business School Press, Boston.

Lee, K., Ki, J., 2013. Changes in industrial leadership and catch-up by latecomers in the world steel industry. Paper presented at the 2013 Globelics conference, Ankara, Turkey.

Lee, K., Lim, C. 2001. Technological regimes, catching-up and leapfrogging: findings from the Korean industries. Research Policy 30(3), 459-83.

Lee, K., Malerba, F. 2013. Successive changes in industrial leadership and the catching up by latecomers: Toward a theory of catch-up cycles from studies of selective sectors. Paper presented at the 2013 Globelics conference, Ankara, Turkey.

Lim, C., Kim, Y. 2013. Changes in industrial leadership and catch-up by latecomers: the case of the shipbuilding industry. Paper presented at the 2013 Asialics conference, Tokyo, Japan.

Lundvall, B., 1992. National systems of innovation: toward a theory of innovation and interactive learning. Printer, London.

Malerba, F., Nelson, R., 2012. Economic development as a learning process. Edward Elgar, Cheltenham.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 1999. ‘History-friendly’ models of industry evolution: the computer industry. Industrial and Corporate Change 8, 3-40.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 2001. Competition and industrial policies in a ‘history friendly’ model of the evolution of the computer industry. International Journal of Industrial Organization 19, 635-664.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 2008a. Public policies and changing boundaries of firms in a “history-friendly” model of the co-evolution of the computer and semiconductor industries. Journal of Economic Behavior & Organization 67, 355-380.

Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 2008b. Vertical integration and disintegration of computer firms a history-friendly model of the coevolution of the computer and semiconductor industries. Industrial and Corporate Change 17 (2), 197–231.

Malerba, F., Orsenigo, L. 2002. Innovation and market structure in the dynamics of the pharmaceutical industry and biotechnology: towards a history friendly model. Industrial and Corporate Change 11(4), 667–703.

Malerba, F., 2004. Sectoral systems of innovation: concepts, issues and analyses of six major sectors in Europe. Cambridge University Press, New York, NY.

Malerba, F., 2002. Sectoral systems of innovation and production. Research Policy 31(2), 247-64.

Mani, S., 2013. Changing leadership in IT services: emergence of India as the current world leader in IT services. Paper presented at the 2013 Asialics Conference, Tokyo, Japan.

Mathews, J. A., 2005. Strategy and the crystal cycle. California Management Review 47 (2), 6-32.

Mazzoleni, R., Nelson, R., 2007. Public research institutions and economic catch-up. Research Policy 36(10), 1512-1528.

Morrison, A., Rabellotti, R., 2013. Catch up in the wine industry: the rise of the new world and the revenge of the old guys. Paper presented at the 2013 Globelics conference, Ankara, Turkey.

Mowery, D.C., Nelson, R., 1999. Sources of industrial leadership: studies on seven industries. Cambridge University Press, Cambridge, Cambridge, UK.

Nelson, R. Winter, S., 1982. An evolutionary theory of economic change. Harvard University Press, Cambridge, MA.

Pavitt, K., Wald, S., 1971. The conditions for success in technological innovation. OECD, Paris.

Pavitt, K., Soete, L. 1980. Innovative activities and export shares: some comparisons between industries and countries, in: Pavitt, K. (Ed.), Technical Innovation and British Economic Performance. Macmillan, London.

Perez, C., Soete, L., 1988. Catching-up in technology: entry barriers and windows of opportunity, in: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds.), Technical Change and Economic Theory. Pinter Publishers, London.

Richiardi M., Leombruni, R., Saam, N., Sonnessa, M., 2006. A common protocol for agent-based social simulation. Journal of Artificial Societies and Social Simulation 9(1).

Shaked, A., Sutton, J., 1982. Relaxing price competition through product differentiation. Review of Economic Studies 49(1), 3-13.

Shin, J., 2013. Successive catch-up cycles in the semiconductor industry: the case of the memory industry. Paper presented at the 2013 Asialics conference. Tokyo, Japan.

Tushman, M., Anderson, P. 1986. Technological discontinuity and organizational environments. Administrative Science Quarterly 31(3), 439-65.

Windrum, P., Fagiolo, G., Moneta, A., 2007. Empirical validation of agent-based models: alternatives and prospects. Journal of Artificial Societies and Social Simulation 10(2-8).

Yoon, M. Lee, K. 2009. Agent-based and history-friendly models for explaining industrial evolution. Evolutionary and Institutional Economics Review 6(1), 45-70.

Figures and Tables

Figure 1 – Shape of the technology landscape

Traditional (α =1 and β =1) *High-Tech* (α >1 and β =1)

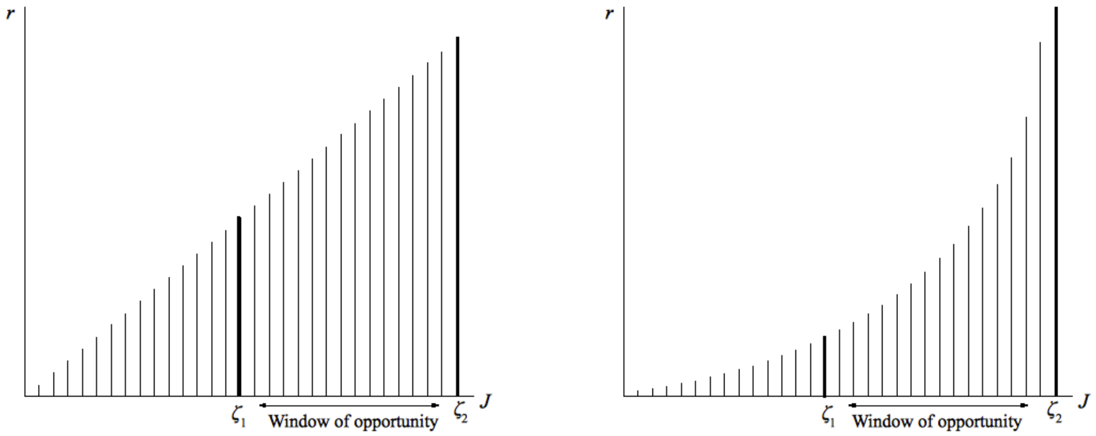
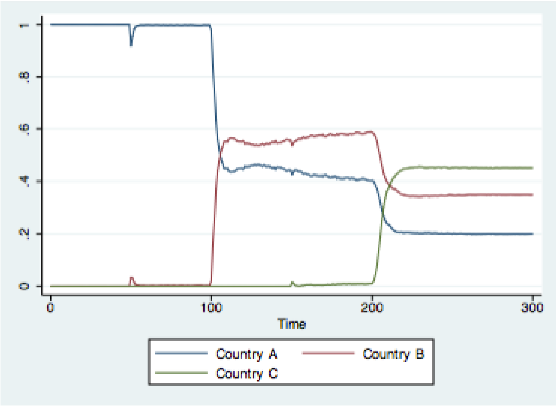


Figure 2 – Successive catch-up cycles, 'history-friendly' runs

(I) Market shares



(II) Herfindal index,

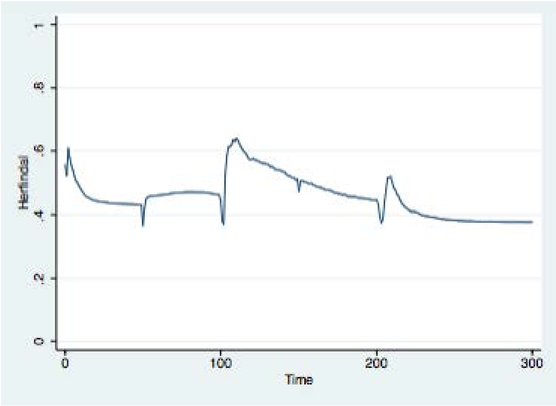
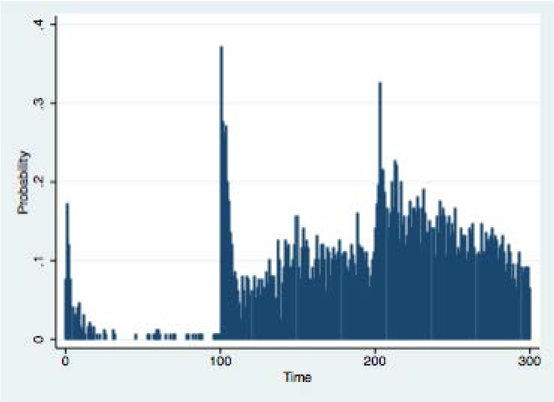
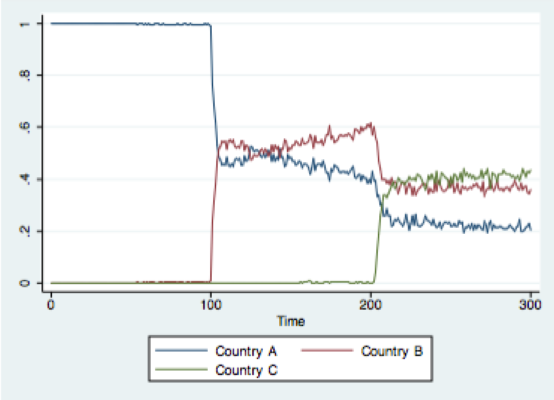


Figure 3 – Firm-level competition dynamics

(I) Probability of a change in firm's leadership,



(II) Probability of firm's leadership



(III) Market shares of the country's leader

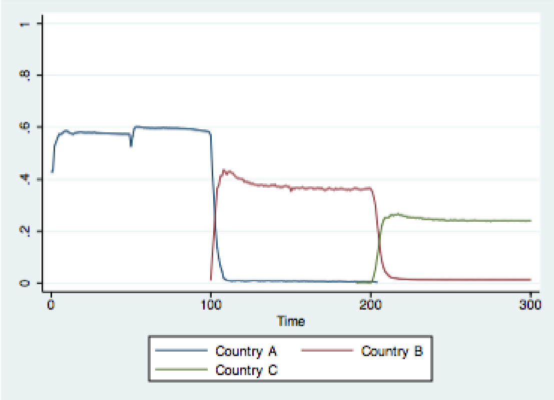


Figure 4 – Evolution of market shares, industry concentration, and small windows

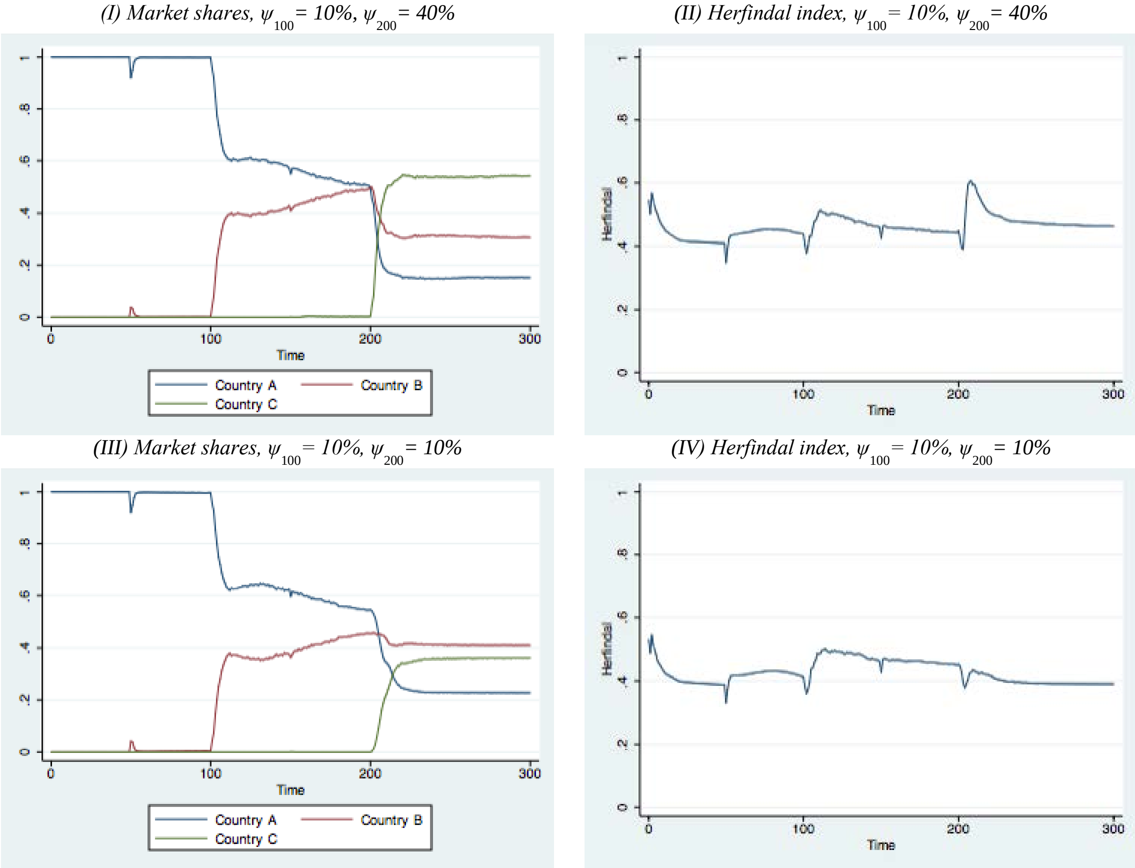
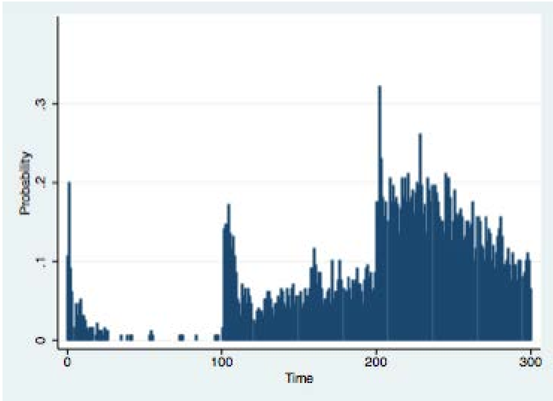
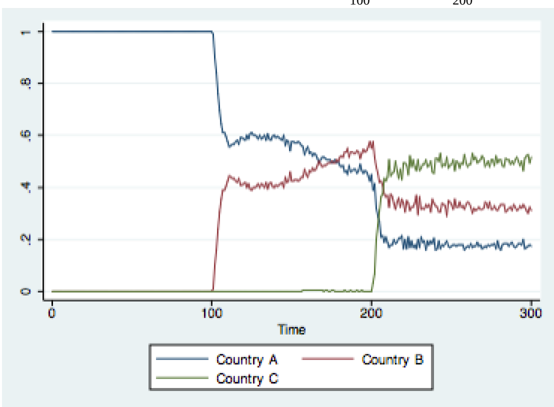


Figure 5 – Firm-level competition dynamics with one small window

(I) Probability of a change in firm's leadership (ψ_{100} = 10%, ψ_{200} = 40%)



(II) Probability of firm's leadership (ψ_{100} = 10%, ψ_{200} = 40%)



(III) Market shares of the country's leader (ψ_{100} = 10%, ψ_{200} = 40%)

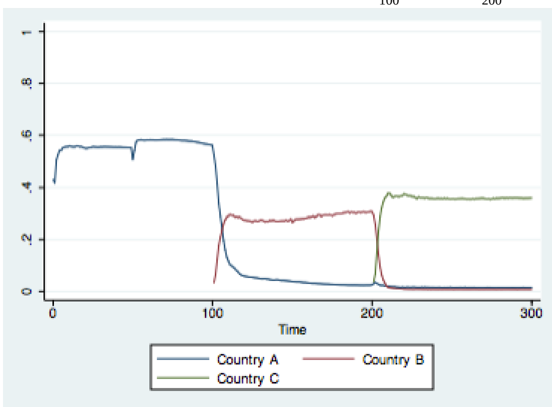
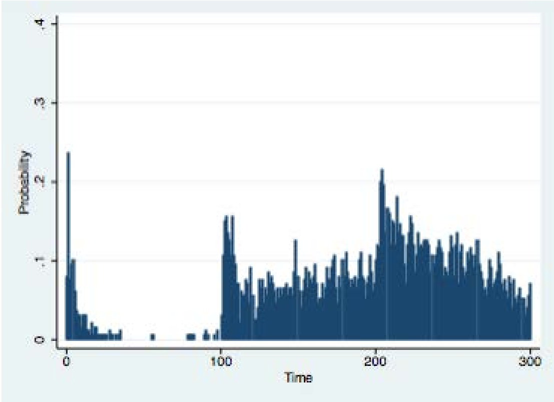
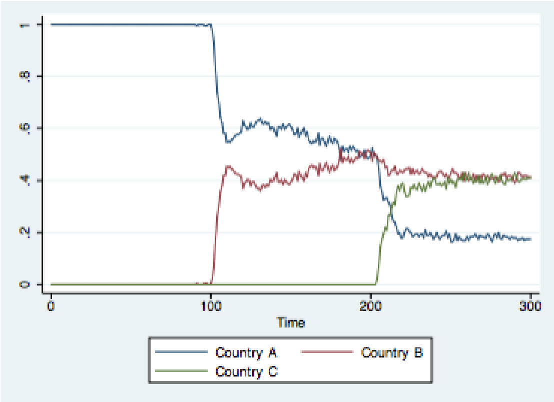


Figure 6 – Firm-level competition dynamics with two small windows

(I) Probability of a change in firm's leadership (ψ_{100} = 10%, ψ_{200} = 10%)



(II) Probability of firm's leadership (ψ_{100} = 10%, ψ_{200} = 10%)



(III) Market shares of the country's leader (ψ_{100} = 10%, ψ_{200} = 10%)

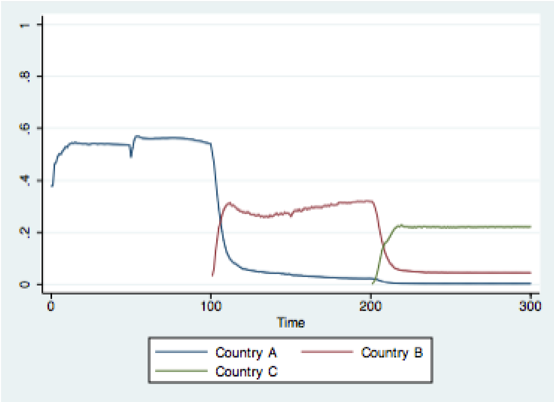
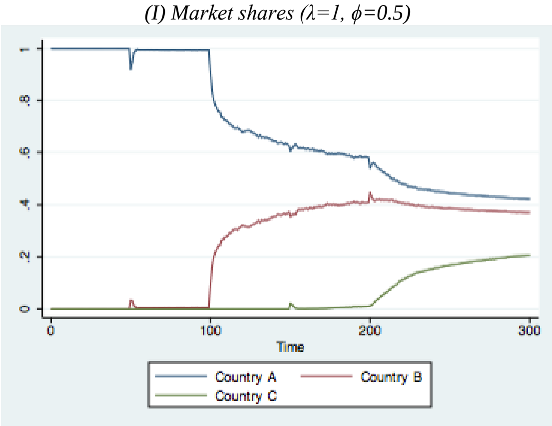


Figure 7 –Market shares, industry concentration and lock-in

(I) Market shares (λ=1, ϕ=0.5)



(II) Herfindal (λ=1, ϕ=0.5)

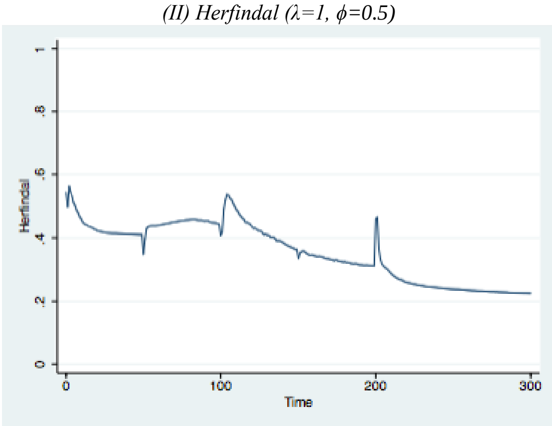
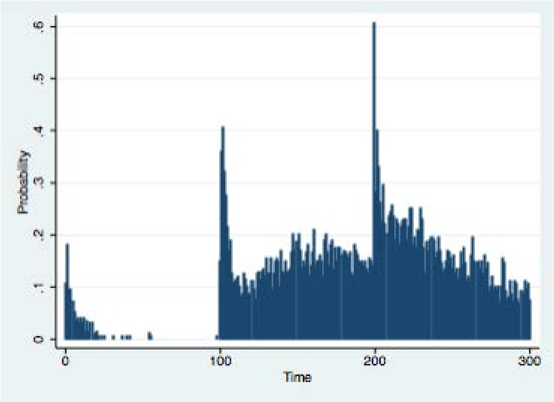
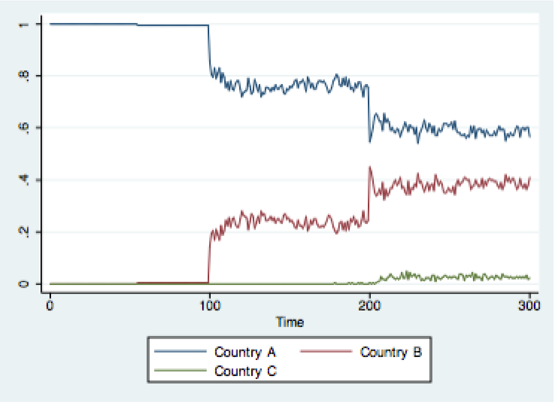


Figure 8 – Firm-level competition dynamics and lock-in

(I) Prob. change firm's leadership (λ=1, ϕ=0.5)



(II) Prob. firm's leader (λ=1, ϕ=0.5)



(III) Mkt share country's leader (λ=1, ϕ=0.5)

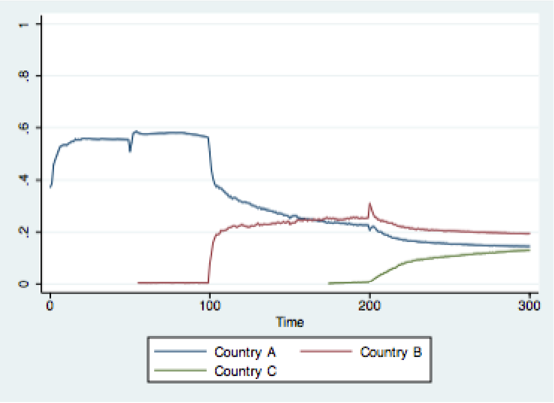


Figure 9 –Market shares, industry concentration and shape of technical landscape

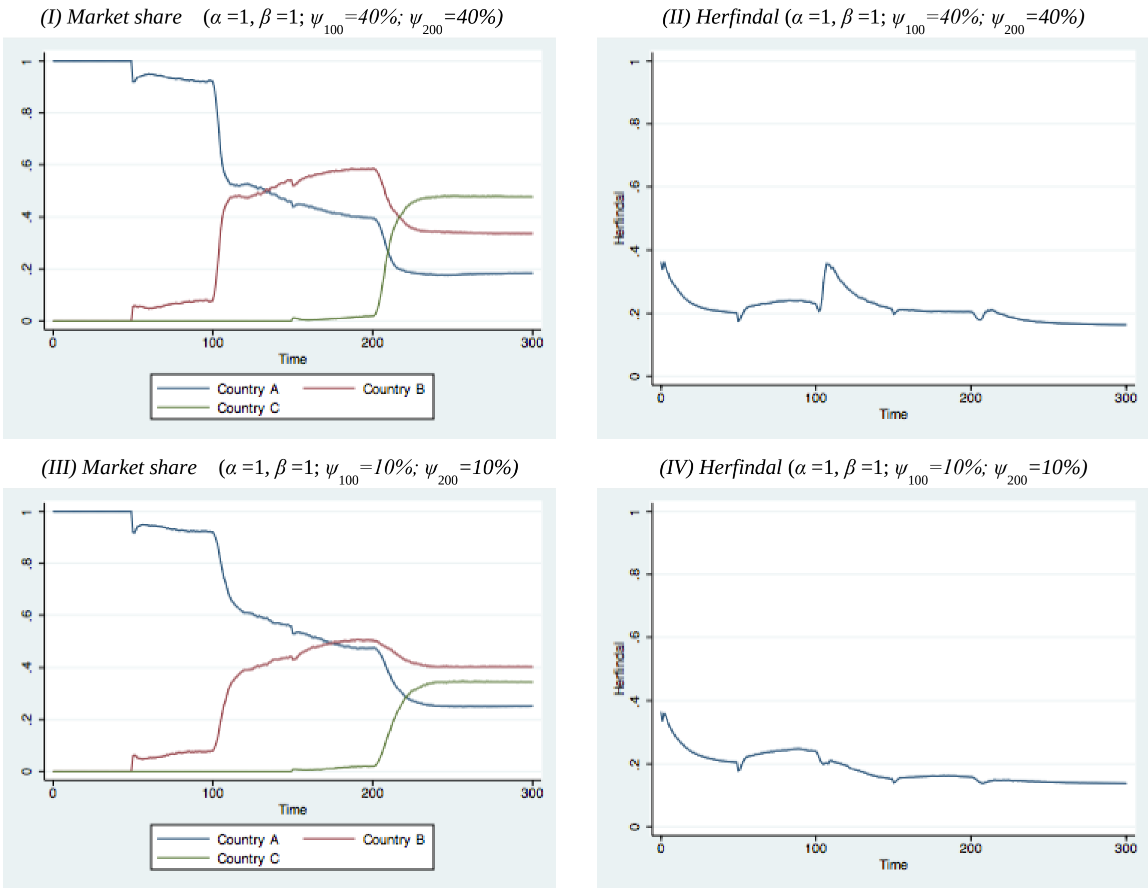
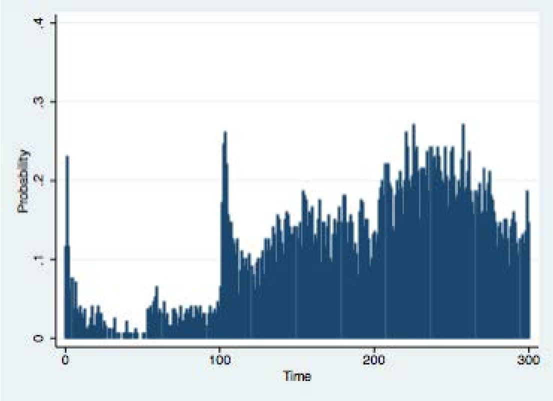
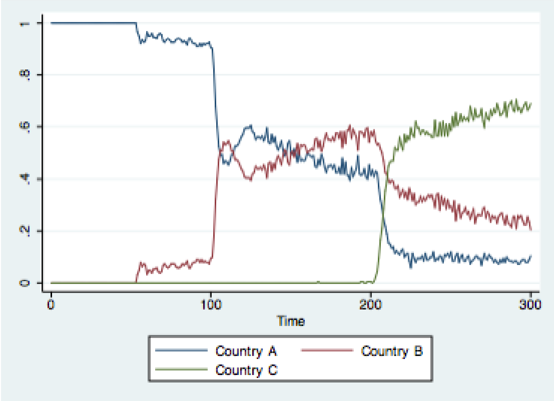


Figure 10 – Probability of firm's leadership, leader survival and shape of technical landscape

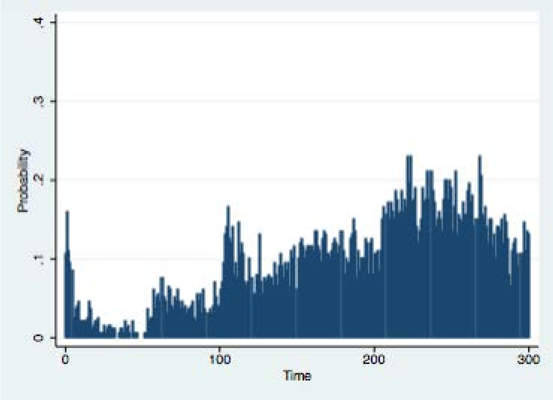
(I) Prob. change firm's leadership (α =1, β =1; ψ_{100}=40%; ψ_{200}=40%)



(II) Probability of firm's leadership (α =1, β =1; ψ_{100}=40%; ψ_{200}=40%)



(III) Prob. change firm's leadership (α =1, β =1; ψ_{100}=10%; ψ_{200}=10%)



(IV) Probability of firm's leadership (α =1, β =1; ψ_{100}=10%; ψ_{200}=10%)

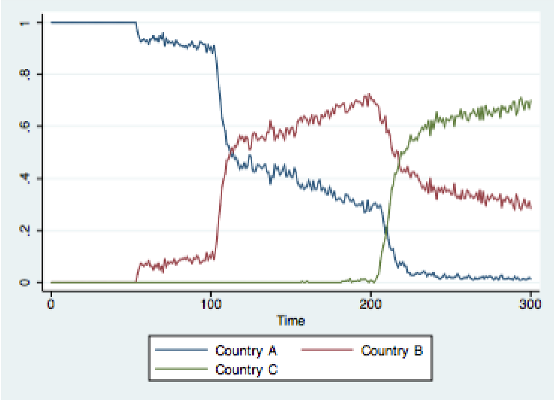
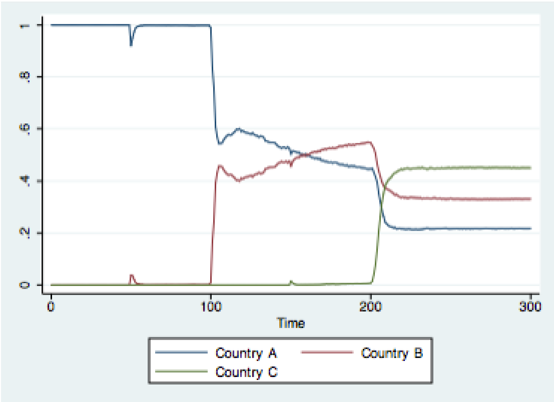


Figure 11 – Competition dynamics and incumbent's capabilities

(I) Market shares (θ^A_{max} *= 0.6)*



(II) Prob. firm's leader (θ^A_{max} *= 0.6)*

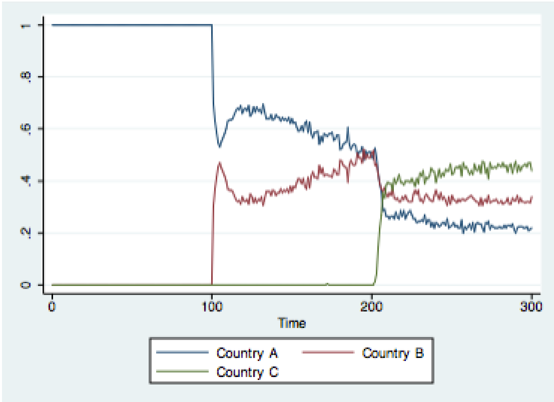
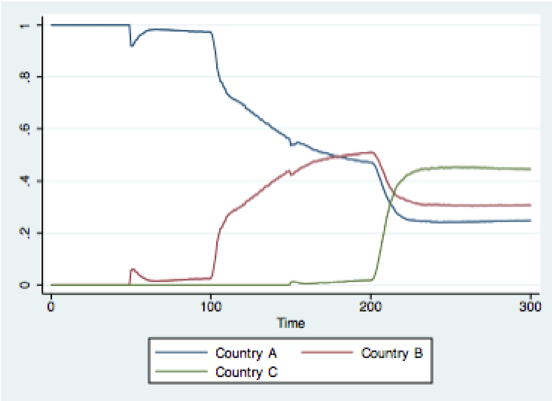
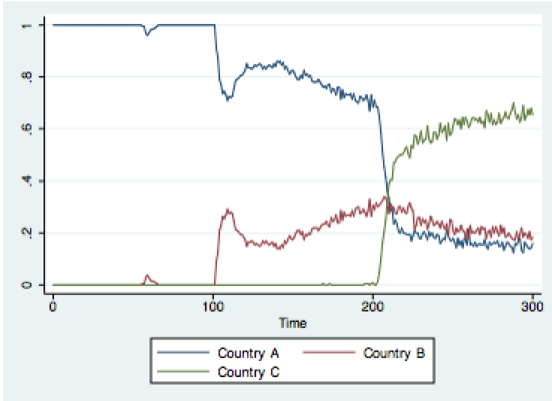


Figure 12 – Market shares, incumbent's capabilities and technical landscape

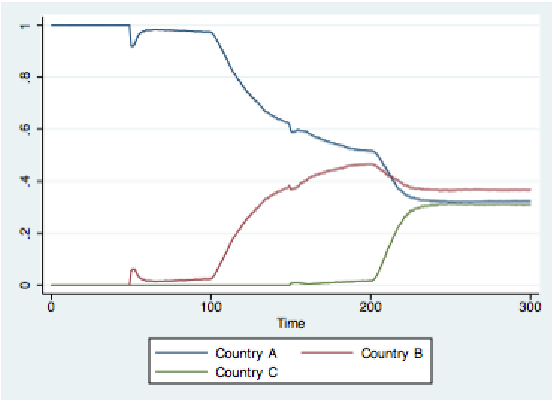
(I) Market shares (θ^{A}_{max} = 0.6, α =1, β =1; ψ_{100}=40%; ψ_{200}=40%)



(II) Prob. firm's leader. (θ^{A}_{max} = 0.6, α =1, β =1; ψ_{100}=40%; ψ_{200}=40%)



(III) Market shares (θ^{A}_{max} = 0.6, α =1, β =1; ψ_{100}=10%; ψ_{200}=10%)



(IV) Prob. firm's leader. (θ^{A}_{max} = 0.6, α =1, β =1; ψ_{100}=10%; ψ_{200}=10%)

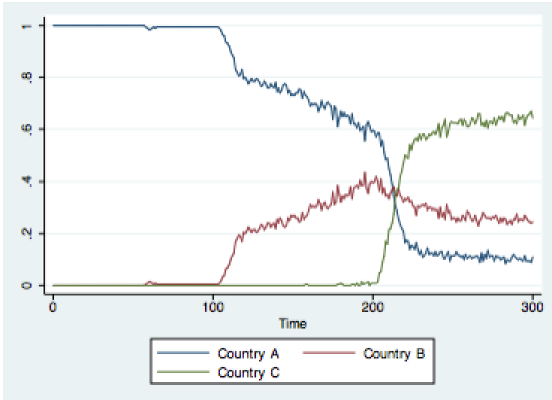


Table A.1 – Parameters of the model

Name of the parameter	*HF setting*	*Sens. Min*	*Sens. Max*
Size of technology space (J)	2000	1000	3000
Periods	300	None	None
Capability weight (δ)	1	None	None
Perceived quality weight (ρ)	1	None	None
α – Demand function	1	0.5	None
β – Demand function	1	0.5	None
Marginal cost of production (c)	10	5	15
Probability new entrant – Country A (ω_A)	0.01	0.005	0.015
Probability new entrant – Country B (ω_B)	0.01	0.005	0.015
Probability new entrant – Country C (ω_C)	0.01	0.005	0.015
Exit threshold – Country A (m_A^e)	0.002	0.001	0.003
Exit threshold – Country B (m_B^e)	0.002	0.001	0.003
Exit threshold – Country C (m_C^e)	0.002	0.001	0.003
Consumers, carrying capacity – Country A (Φ^A)	600	300	900
Consumers, initial number – Country A (χ_0^A)	100	50	150
Consumers, growth rate – Country A (g_A)	0.09	0.045	0.135
Consumers, carrying capacity – Country B (Φ^B)	600	300	900
Consumers, initial number – Country B (χ_0^B)	50	25	75
Consumers, growth rate – Country B (g_B) = 0.09	0.09	0.045	0.135
Consumers, carrying capacity – Country C (Φ^C)	600	300	900
Consumers, initial number – Country C (χ_0^C)	50	25	75
Consumers, growth rate – Country C (g_C)	0.09	0.045	0.135
Initial budget	10	None	15
Fraction of profit invested in R&D (τ)	0.8	None	None
Maximum level of initial capabilities – Country A (θ_{max}^A)	0.3	None	None
Maximum level of initial capabilities – Country B (θ_{max}^B)	0.3	None	None
Maximum level of initial capabilities – Country C (θ_{max}^C)	0.3	None	None
Learning coefficient – Country A (γ^A)	0.03	0.015	0.045
Learning coefficient – Country B (γ^B)	0.03	0.015	0.045
Learning coefficient – Country C (γ^C)	0.03	0.015	0.045
Entry of Country B	Period 50	None	None
Entry of Country C = period 150;	Period 150	None	None
Cost of export (c_E)	100	None	None
Price advantage in national market – Country A (σ_A)	0.3	None	None
Price advantage in national market – Country B (σ_B)	0.3	None	None
Price advantage in national market – Country C (σ_C)	0.3	None	None
Cost of R&D – Country A (c_R^A)	10	None	None
Cost of R&D – Country B (c_R^B)	10	None	None
Cost of R&D – Country C (c_R^C)	10	None	None
α – technical landscape	3	None	None
β – technical landscape	1	None	None
Elasticity of demand (η)	4	2	6
First-generation frontier (ζ_1)	0.2 * J	None	None
Second-generation frontier (ζ_2)	0.6 * J	None	None
Third-generation frontier (ζ_3)	1.0 * J;	None	None
Period of the first discontinuity	100	None	None
Period of the second discontinuity	200	None	None
Size of the first discontinuity (ψ_{100})	40%	None	None
Size of the second discontinuity (ψ_{200})	40%	None	None
Perception of new technology (λ)	3	None	None
Capability loss after adoption ($1 - \phi$)	0.9	None	None