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Technological change and economic development: endogenous and exogenous fluctuations

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Abstract

This paper aims at exploring the endogenous and exogenous forces that determine long-run fluctuations of innovative and economic activity. It proposes that technological paradigm shifts, structural change and major fluctuations of production are the result of the same endogenous process. This is defined as a co-evolutionary process between technological and economic variables based on cumulative multiplier and accelerator feedback effects between investments in innovation and demand. Exogenous factors are supposed to act upon this endogenous process, influencing the length and amplitude of fluctuations. This framework contributes to extant literature as it envisages an explicit endogenous mechanism explaining cyclical fluctuations of innovative and economic activity, and, at the same time, incorporates exogenous factors. Moreover, by combining the Schumpeterian analyses of innovation dynamics with the multiplier and accelerator effects coming from Keynesian theories, the framework integrates the impact of technological variables on economic activity and vice versa. To provide a preliminary supporting evidence, we have fitted the ICT cycle and the economic cycle to patent and productivity data, respectively. Our results suggest that the growth potential of ICT could be declining. This situation may represent an important opportunity, for public policy and socio-institutional actors, to orient future development toward socially desirable directions.

Keywords: technological paradigm shift, structural change, economic fluctuations, co-evolution, productivity slowdown, ICT

JEL classification: O33, O40, O11, E32

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1. Introduction

Technological change is now considered, almost unanimously, the main source of economic growth and development. Yet, the complex relationship between technological change and economic development is still far from being fully understood. This paper aims at examining this relationship by exploring the endogenous and exogenous forces that determine long-run fluctuations of innovative and economic activity. By fluctuations of innovative activity, we refer to the existence of periods of accelerated (decelerated) growth of investments in innovation due to the emergence (decline) of clusters of radical innovations, also called technological paradigms and technological or industrial revolutions. For example, Information and Communications Technologies (ICT), a cluster of innovations including semiconductors, computers, software, telecoms and internet, are widely considered the third, current, technological revolution. By fluctuations of economic activity, we refer to the existence, in the lung-run, of periods of accelerated and decelerated economic growth, also called growth waves.

In this context, we are interested in studying whether and how the economic system tends to endogenously produce such fluctuations, and what is the role played by exogenous factors. These questions are important because if fluctuations are endogenous, then the economic system would tend to generate on its own the forces that transform it and that determine its long-run growth, namely technological paradigm shifts and structural change. Moreover, the economic system would tend to recurrently experience periods of decelerated economic growth. On the contrary, if fluctuations are exogenous, then technological paradigm shifts, structural change and fluctuations of production would be the result of random or historically unique events that will not necessarily repeat in the future. These questions also have important policy implications, as a better understanding of long-run cyclical phenomena should improve the capability of public policies to dampen and orient them.

In the 1930s, Kuznets (1930) and Schumpeter (1939) highlighted that radical innovations have a fundamental role in originating new leading industries and in determining structural change, while subsequent improvements of radical innovations are the main source of economic growth. According to both scholars, radical innovations, and their associated industries, evolve following an S-shaped curve: at first they grow slowly, then rapidly when incremental improvements occur, and slowly again once maturity is reached. However, in Kuznets' view, radical innovations are randomly distributed in time and are at the origin of "secular" growth, while in Schumpeter's perspective radical innovations tend to come about in clusters and are at the origin of Kondratiev (1935) long-waves, i.e., regular upswings and downswings of economic activity of about 50 years. Although Kuznets and Schumpeter disagree on the "clustering" issue and the associated growth waves, in the theories of both scholars, causality runs, as near as we can make out, from innovation to macroeconomic variables: (clusters of) radical innovations originate (regular waves of) economic expansion. The emergence of radical innovations, instead, is a random or exogenous phenomenon, independent of macroeconomic variables. In fact, Schumpeter conceptualized business cycles as disturbances in the equilibrium and a return to a new equilibrium point, which gives the process a cyclical character (Konstantakis and Michaelides 2017). This position is also broadly shared by neoclassical economics, according to which economic fluctuations are due to exogenous technological shocks causing acceleration/deceleration in the rate of technical change and production. As a consequence, Schumpeter's theory explains growth waves (i.e., why economic growth accelerates and then decelerates), but not their recurrence, that is, why economy recovers after the deceleration and a new wave begins. This is because the emergence of radical innovations, and therefore the beginning of a new wave or cycle, is an exogenous phenomenon, which does not depend on the macroeconomic conditions of the previous cycle.

On the contrary, in Mensch's (1979) and Kleinknecht's (1981) perspective, the emergence of radical innovations depends on macroeconomic variables. According to these scholars, during prosperity periods, firms concentrate investments on incremental, highly profitable, technologies, while they resort to the highly risky strategy of investing in radical innovations only when the growth potential of predominant technologies is exhausted and the economy is depressed. Here, as noted by Silverberg and Verspagen (2003), causality runs from macroeconomic variables (depression) to innovation (radical innovations) back to macroeconomic variables (recovery). Hence, in this case, there is an endogenous mechanism explaining the recurrence of cycles, because the emergence of radical innovations depends on the economic conditions of the previous cycle. Numerous studies have empirically tested the Mensch's hypothesis (e.g., Solomou 1986, Kleinknecht 1990, Silverberg and Leherte 1993, Silverberg and Verspagen 2003, Korotayev et al. 2011) obtaining conflicting conclusions. This hypothesis has been criticized on the theoretical side as well. For example, Clark et al. (1981) argued that the emergence of radical innovations is due to relatively exogenous factors, like scientific and technological breakthroughs, or to periods of very strong demand, including booms and wars.

In sum, scholars seem to have different views about the factors causing the emergence of radical innovations and, consequently, about the existence of an endogenous mechanism driving long-run fluctuations. Some consider that the emergence of radical innovations is due to random or exogenous factors, others believe that firms' propensity to invest in radical innovation depends on economic conditions. Among the latter, some consider that radical innovations are more likely to emerge in prosperity periods, when demand is high and risk low, while others believe that only the despair of depression periods will eventually induce firms to invest in radical innovation. We think that, although exogenous factors may importantly influence fluctuations of innovative and economic activity, still it would be important to know whether and how the system endogenously produces recurrent, but not necessarily regular, accelerations of investments in innovation and associated growth waves.

This paper proposes a framework that integrates both endogenous and exogenous factors. In particular, in this work, we define the development pattern of major technological clusters (the technological cycle) and analyze its relationship with economic activity (the economic cycle). We suggest that this relationship may be represented as a process of co-evolution between technological and economic variables. This is based, on the one hand, on the different productivity gains generated by technological clusters over their life-cycle, and, on the other hand, on continuous multiplier and accelerator feedback effects between investment in innovation and demand, which cause a cumulative amplification of any initial change in innovative investment. This process explains, at the same time, growth waves and their recurrence, thus representing an explicit endogenous mechanism generating technological paradigm shifts, structural change and long-run fluctuations of production. In this context, the emergence of radical innovations depends on unfavorable economic conditions, but, unlike Mensch (1979), such conditions affect the propensity to invest in radical innovation of only a minority of firms, mainly new firms.

We then propose that the tendency of the economic system to behave in the suggested cyclical way may be frequently perturbed by a variety of exogenous factors, which are expected to influence both the length and amplitude of fluctuations, thus determining the duration and intensity of expansive/recessive phases. Exogenous factors may include random historical events, technical factors, socio-institutional variables and public policies. To provide a preliminary empirical evidence supporting the framework, we use patent data relating to ICT and productivity data over the period 1970-2016. We fit the technological and economic cycle, identify their growth phases and test their synchronization. The rest of the paper is organized as follow. In section 2 we review the relevant literature and in section 3 we illustrate the framework by discussing both endogenous and exogenous factors. Section 4 examines the empirical evidence on the ICT cycle and section 5 concludes.

2. Literature review

The idea that economic growth depends on the emergence of new leading industries initiated by fundamental innovations dates back to Kuznets. In his *Secular Movements in Production and Prices* (1930), Kuznets observed that the growth of new industries tends to follow an S-shaped curve and argued that technical change is the main determinant of this growth pattern: "In many industries there comes a time when the basic technical conditions are revolutionized. When such a fundamental change takes place, a new era begins. ... In all these cases we observe a revolutionary invention or discovery applied to the industrial process which becomes the chief method of production. … When such a change occurs, the industry grows very rapidly. The innovation is rarely perfect at the start, and further improvements take place continually after the main invention or discovery. The use of the continually improving and cheapening commodity spreads to larger areas, overcoming obstacles which may have limited demand in the past. ... But with all this, after a time the vigorous expansion slackens and further development is not so rapid" (Kuznets 1930, p. 9-10[2]). In this perspective, technical change is also the most important factor explaining structural change: "what concentrates the forces of growth and development in one or two branches of production at a given time, and what shifts the concentration from one field to another as time passes" (p. 5).

According to Kuznets, fundamental innovations are randomly distributed in time and are at the origin of the "secular" upward movement of production. Schumpeter (1939), instead, advanced the hypothesis that radical innovations, and their associated S-shaped curves, tend to come about in clusters because of the existence of technical interdependencies among innovations. Such clusters, occurring approximately every 50 years, create new fast growing leading sectors and are at the origin of Kondratiev (1935) long-waves. In Schumpeter's view radical innovations are introduced by extraordinary individual entrepreneurs that create "new combinations" using exogenously generated inventions. Temporary monopoly profits assured by radical innovations and bandwagon imitation by other entrepreneurs trigger a wave of investment that drives the diffusion into society of the new technologies and induces upswings of economic activity. After some time, imitators erode monopoly profits and new markets saturate, thus the economy enters in the downswing phase of long-waves. In a later work, Schumpeter (1942) claimed that large companies, through their R&D laboratories, would assume a more important role than individual entrepreneurs in innovative processes. In both cases, the emergence of radical innovations remains a relatively exogenous factors.

Mensch (1979) further elaborated the Schumpeter hypothesis, proposing that radical innovations cluster during depression periods. In Mensch's model, Kondratiev upswings and downswings are the result of the subsequent emergence and decline of clusters of S-shaped products life-cycles. When markets opened-up by the new products saturate and, due to diminishing returns, a few new market can be created on the basis of predominant technologies, society enters in a period of "technological stalemate" that leads the economy into recession. However, recession is not sufficient to stimulate investment in radical innovation. Only during depression periods, when the growth potential of existing product lines is exhausted, firms resort to the highly risky strategy of investing in radical innovations, which eventually will stimulate a new wave of growth. Kleinknecht

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[2] Also cited in Kleinknecht and Van der Panne (2006)

(1981) and Kleinknecht and Van der Panne (2006) expanded this perspective considering the lack of radical innovations during upswings as the result of a rational, rather than myopic, behavior of firms with respect to the opportunity cost of the different industries. According to these scholars, so long as an industry is expanding and its productivity gains are high, the opportunity cost of developing uncertain new breakthroughs in other industries is high. Consequently, during prosperity periods, firms will concentrate investment on incremental innovations within existing, highly profitable, industries. Only when diminishing returns of innovations, saturation of demand and declining profits reduce the opportunity cost of switching to new industries, firms will take the risk of investing in radical innovations[3].

Clark et al. (1981) have instead criticized the Mensch's hypothesis both on the empirical and theoretical side. These scholars attribute economic upswings to the swarm of imitation and improving innovations following the appearance of technically related families of radical innovations, rather than to a "depression-induced bunching of a set of individual basic innovations" (p.321). They also argue that deep depressions would delay, rather than stimulate radical innovations, because adverse economic conditions increase the risk of innovative investment. The emergence of radical innovations is then viewed as the result of relatively exogenous factors, i.e., breakthroughs in fundamental science and technology, or of periods of very strong demand, including booms and wars. Consequently, it should be expected that radical innovations are more likely to occur in periods of recovery and boom, when markets promise high profits and low risk.

In sum, there seems to be a quite general consensus on the idea that new industries evolve following an S-shaped curve, as well as on the crucial role played by radical innovations in originating such new industries and by incremental innovations in driving their rapid growth. There seems to be sufficient consensus also on the existence of clusters of interrelated radical technologies, also called technological paradigms and technological or industrial revolutions. Conversely, there is not agreement on the existence of clusters of not-related radical technologies and on their occurrence with fixed periodicity or during depression periods. Although many studies have dealt with the task of empirically testing these issues (e.g., Mensh 1979, Solomou 1986, Kleinknecht 1990, Silverberg and Leherte 1993, Silverberg and Verspagen 2003, Korotayev et al. 2011), they have obtained conflicting conclusions. Most importantly for this work, scholars disagree on the factors that determine the emergence of radical innovations. Some consider radical innovations as a random or exogenous phenomenon, while others believe that firms' propensity to invest in radical innovations depends on economic conditions. Among the latter, some argue that radical innovations are more likely to emerge in prosperity phases, when demand is high and risk low, and others claim that only depression periods will eventually convince firms to invest in radical innovations. As discussed in section 1, this divergence has important consequences because it implies that there is not agreement on the existence of an explicit endogenous mechanism causing fluctuations of innovative and economic activity.

In the framework that we propose, general economic conditions do affect firms' propensity to invest in radical innovation. More specifically, we share the view that unfavorable economic conditions, i.e., falling productivity, income and profitability due to the maturity of prevailing technologies, reduce firms' profit expectations on these technologies, thus providing incentive to invest in radically new technological areas. However, unlike Mensch (1979), we also believe that such incentive is generally not sufficient to induce the majority of firms to invest in radical innovation. By definition, radical innovations have a strong disruptive impact on existing technologies, competences

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[3] Note that, by replying to the observation that R&D activity generally declines during depression periods, Kleinknecht pointed out that it is the relative propensity to embrace radical versus incremental innovations that is at issue here (Silverberg 2002).

and organizational structures. The majority of firms are relatively established firms that have built their core competences and production facilities on the basis of prevailing technologies. Therefore, they may not be interested in stimulating a competing technology and risking their core capabilities and production facilities become superfluous (Kemp et al. 1998). This point has been highlighted by numerous studies (e.g., Anderson and Tushman 1990, Christensen 1997, Kemp et al. 1998, Breschi et al. 2000, Markard et al. 2012), showing that incumbents possess specific knowledge, complementary assets and managerial practices that make either difficult or disadvantageous for them investing in radical innovation. If this is true, economic conditions will have a minor impact on the propensity of the majority of firms in established industries to invest in radical innovations and will only affect their propensity to invest in incremental innovations on prevailing technologies. Economic recession reduces expected demand and business confidence, decreases resources available for investment and makes innovation investment riskier, therefore it will induce existing firms to shrink their investment in predominant technologies. Prosperity periods, by acting in the opposite direction, will increase investment along established trajectories. This is the Schmookler (1966) demand-pull effect, which, nevertheless, concerns uniquely incremental innovations.

Unlike established firms, new firms have not sunk investments in prevailing technologies and are not burdened with the legacy of existing technologies and ways of operating (Tushman and Romanelli 1985). It is therefore more likely that such firms will respond to declining productivity and profitability of established technologies by searching for innovations in radically new technological areas. As we will illustrate in section 3, the behavior of this minority of firms may be sufficient to active a co-evolutionary process between technological and economic variables that eventually will lead to the emergence of new paradigms and industries. This also explains why radical innovations involve at first the erosion of incumbent's advantage and, later on, the replacement of established leaders by new actors. Such co-evolutionary process represents an endogenous mechanism explaining fluctuations of innovative and economic activity. Exogenous factors are expected to act upon this process, influencing the length and the amplitude of fluctuations. In the next section, we examine both endogenous and exogenous factors.

3. Theoretical framework

3.1. Endogenous forces

In this section, we first define the technological cycle, the economic cycle and their growth phases. We then analyze the relationship between technological and economic cycle, which is represented as a co-evolutionary process between subsequent growth phases of the two cycles. In order to define the technological cycle, we rely on Schumpeterian analyses of innovation dynamics (Nelson and Winter 1982, Dosi 1982, Freeman and Perez 1988, Anderson and Tushman 1990, Utterbak and Suárez 1993, Perez 2010). We use, in particular, the notion of technological paradigm (Dosi 1982), and, following Perez (2010), we apply it at macro-level. Hence, in the proposed framework, a technological paradigm, also called technological revolution, is a cluster of interrelated and mutually supporting radical technologies that have the capability of initiating new leading industries and a widespread impact on existing industries.

In addition to being a new set of technologies and industries, a paradigm is also a collectively shared cognitive framework (Dosi 1982). Hence, each paradigm entails a common definition of the important technological problems and a heuristic based on common scientific, engineering and organizational principles. For this reason, a technological paradigm embodies strong prescriptions on the directions of change to pursue. Such prescriptions “operate as an inclusion-exclusion mechanism to encourage compatible innovations and discourage incompatible ones” (Perez 2010). According to many researchers, we are now experiencing the so-called ICT revolution, a technological cluster that emerged in the 1970s with the invention of the integrated circuit. ICT have originated current leading industries, i.e., the semiconductor industry, the computer industry, the software, telecoms and the internet (Perez 2010), and have profoundly transformed existing sectors.

Following Dosi et al. (2010), we try to combine Schumpeterian theories on innovation with Keynesian theories on demand generation, envisaging both multiplier and accelerator effects: investment decisions induce demand propagation effects and adaptive expectations on demand drive investment decisions (Dosi et al. 2010). However, here we put particular emphasis on the innovative nature of investment and stress the role played by the technological cycle in influencing demand expectations and investment decisions. Hence, in the proposed framework, the primary effect of innovative investment is not on employment level, but on productivity growth. By creating new markets, innovative investment creates new jobs, but assuming that it typically also destroys existing markets and jobs, its impact on total employment may be negligible in the long-run[4]. The growth of productivity induced by innovative investment generates a surplus income (wages and profits increase, prices reduction) and has a positive impact on expected demand and production (the multiplier effect), which, in turn, have a positive impact on innovative investment (the accelerator effect). In these circumstances, technological change, by allowing to productivity, income and demand to increase, positively acts on firms’ profit expectations and confidence, thus stabilizing investment. As we will see more in detail below, in other circumstances, technical change has an opposite effect on investment. This happens when a technological paradigm reaches the maturity phase and the productivity growth induced by innovative investment slackens, leading to a slower increase of income and expected demand (the multiplier effect), which, in turn, undermines business confidence and destabilizes investment (the accelerator effect).

Fig. 1 shows the technological and economic cycle. The technological cycle is measured by the stock of investment in the technological paradigm (I_S) and is represented by a logistic curve decomposed in four phases: emergence (EM), growth (GR), maturity (MT) and decline (DEC). The stock of investment in the paradigm grows slowly during the phase of emergence, rapidly during the phases of growth and maturity, and slowly again during the phase of decline, when the potential of growth of the paradigm approaches to exhaustion and a new paradigm, represented by the subsequent logistic curve, starts to emerge[5]. The technological cycle can also be represented by the evolution over time of the level of investment in the technological paradigm (I, the derivative of I_s). The level of innovative investment increases during the phases of emergence and growth, reaching a peak at the end of the growth phase, and then decreases during the phases of maturity and decline, when it approaches to its minimum level. Fig. 1 also represents the growth rate of investment (g_I, the derivative of I), which can be considered as a proxy of the growth rate of technological change. We can see that the phases of emergence and growth display positive growth rates, while the phases of maturity and decline are

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[4] Assuming that investment in innovation has also a positive impact on total employment would reinforce the proposed co-evolutionary process between technological and economic variables.

[5] Note that, although a new paradigm may start emerging during the decline phase of the previous paradigm (dotted curve), the proper phase of emergence begins later, when the stock of investment has reached a minimum threshold (the logistic curve is indeed asymptotic to 0). Symmetrically, the decline of a paradigm is supposed to asymptotically continue (dotted curve) after the end of the proper phase of decline.

characterized by negative growth rates. The growth rate of innovative investment has a peak at the beginning of the growth phase and a trough at the beginning of the phase of decline.

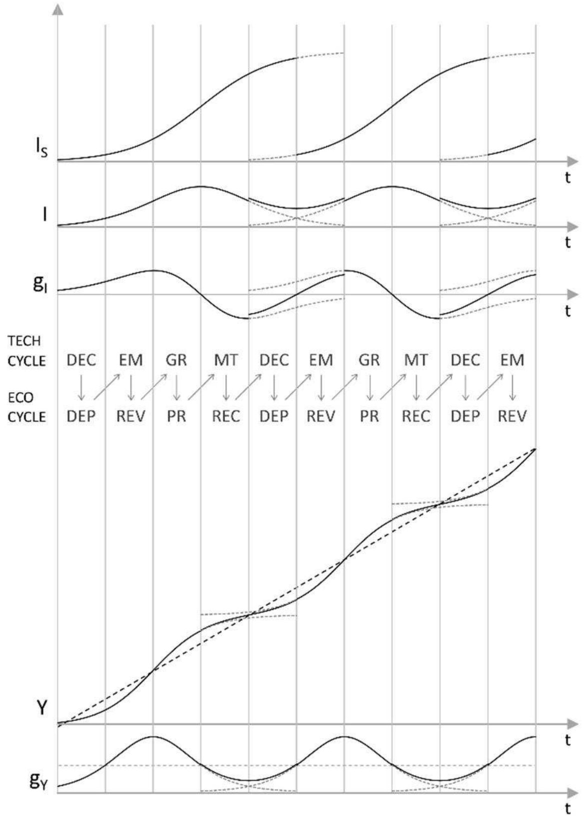

Fig. 1. Technological cycle (I_S, I, g_I), economic cycle (Y, g_Y), and their growth phases (EM=emergence, GR=growth, MT=maturity, DEC=decline, REV=revival, PR=prosperity, REC=recession, DEP=depression). N.B. When logistic functions overlap (dotted curves), their first and second derivatives are summed (continous curves).

The economic cycle is measured by the evolution over time of the level of production (Y) and is represented as a succession of logistic curves. Being logistic curves always not negative, the level of production never decreases and fluctuates around a positive trend[6]. To define cyclical units (i.e., when a cycle starts and ends), we base on the work of Andersen (1999) and use troughs and peaks as turning points. Between the turning points, indicating the growth cycle from trough to peak, the cycle passes through four cyclical phases: depression (DEP), revival (REV), prosperity (PR) and recession (REC) (Andersen 1999). The level of production is above its long-period trend during prosperity and recession, and below it during revival and depression. Fig. 1 also shows the growth rate of production ($g_{Y,}$ the derivative Y). This is above its average value (the dotted line) during revival and prosperity, while it falls below it during depression and recession.

In order to define the relationship between technological and economic cycle, we have positioned the corresponding logistic curves on the time axis so that the growth rate of production (g_Y) has the same troughs and peaks of the growth rate of innovative investment (g_I). It results that the

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[6] Following Andersen (1999), instances of negative growth are disregarded and considered as periods of crisis.

phases of emergence, growth, maturity and decline of the technological cycle occur during the phases of revival, prosperity, recession and depression of the economic cycle, respectively. We shall now explain such relationship by analyzing how the growth phases of the two cycles interact with each other in a co-evolutionary process, which generates a cumulative upward spiral characterized by positive feedback effects between technology and economy, and a cumulative downward spiral characterized by negative feedback effects between technology and economy. Technological variables (investment in innovation) have a multiplier effect on economic variables (demand and production), which, in turn, have an accelerator effect on technological variables. In fig. 1, these feedback effects are represented by the arrows linking the cyclical growth phases.

I. From emergence to revival. The phase of emergence of a new paradigm is a period characterized by great uncertainty about the directions of change to follow, as well as about the technical and commercial success of different competing technologies. The failure rate of innovative projects, and of firms that embark on them, is very high. As discussed in section 2, at this stage only a minority of firms, mainly new firms, undertake the highly risky strategy of investing in radically new technologies. In spite of uncertainty and failures, as some innovations prove to be successful, opening new profit opportunities, investment starts slowly increasing. The technological ferment (Anderson and Tushman 1990) in the new sectors grows, and a variety of new products and technological variants appear. The growth of innovative investment, albeit modest, has a positive impact on productivity, income, expected demand and production (the multiplier effect). The economy comes out from depression and enters in a phase of revival. As shown in fig.1, during the emergence phase of the technological cycle, the level of investment is still low and production is still below its long-term trend. However, the growth rate of investment becomes positive and is increasing, and the growth rate of production goes above its average value and is increasing as well.

II. From revival to growth. The improvement of the economy positively affects demand expectations and business confidence, triggering investment in the paradigm (the accelerator effect). This allows accumulating knowledge about the new technologies and, as a result of this process, some of the different technological variants generated during the phase of emergence, become locked-in to attractors or regions (David 2001), establishing dominant designs or standards (Utterback and Suàrez 1993). The selection of dominant technological standards marks the takeoff of the new paradigm and opens its growth phase. The technological trajectories to follow are now clear, and uncertainty about the technical and commercial success of the new technologies has greatly reduced. During the growth phase, innovation focuses on developing an increasing number of incremental innovations that improve on the basic dominant standards. Incremental innovations are typically less risky and expensive, therefore the majority of firms see now as possible and profitable to invest in the new paradigm. As shown in fig. 1, the growth rate of innovative investment has a peak at the beginning of the growth phase and then remains positive during the whole phase, while the level of investment is increasing and reaches its maximum level at the end of the phase.

III. From growth to prosperity. Incremental innovations produce high productivity gains as they allow quality improvement and price reduction. Incremental innovations also allow to expand the areas of application of initial technologies, creating new markets and rejuvenating older sectors. So long as investment in incremental innovations rapidly increases during the growth phase of the technological cycle, also productivity, income, demand and production grow fast (the multiplier effect). The economy experience a phase of prosperity, with the level of production going above its long-term trend. At this stage, a few (once new) companies strengthen their market share and position themselves as market leaders.

IV. From prosperity to maturity. As we can see in fig.1, during the prosperity phase both the level of production and its growth rate are above their long-term average value, but the growth rate of production is decreasing. This is because, due to diminishing returns of innovative investments, the productivity growth after some time slows down: the rate at which, on the basis of predominant technologies, costs can be lowered, quality can be improved and new markets can be created slackens after some time. The deceleration of productivity has a negative impact on income and demand, which is further reduced by the tendency to saturation of the new markets opened by the paradigm. The expected slowdown of demand leads firms to contract their innovative investments (the accelerator effect) and the technological cycle enters in its phase of maturity: although the level of innovative investments is still high during this phase, it is now decreasing.

V. From maturity to recession. As innovative investments decrease, also the growth of productivity, income, demand and production slackens (the multiplier effect), and the economy comes into a recessive phase. The level of production is still above its long-term trend, but its growth rate goes below its average value and keeps decreasing. Market selection becomes stronger and the least productive firms do not survive to it.

VI. From recession to decline. The low growth rate of production affects negatively the confidence of firms, which expect a further slowdown of demand and continue to shrink their innovative investment in the paradigm (the accelerator effect). Recession also reduces resources available for investment and makes innovation riskier. The technological cycle enters a phase of decline: the stock of innovative investments grows very slowly, approaching its growth limit, and the level of investment keeps declining, reaching its lowest level at the of the phase.

VII. From decline to depression. The decline of investments leads to a further slowdown of productivity, income, demand and production (the multiplier effect). The level of production and its growth rate are both below their long-term trend and the economy is in a phase of depression. At this stage many firms exit the industry.

VIII. From depression to emergence. Depression makes clear the exhaustion of the profit opportunities of predominant technologies, thus lowering the opportunity cost of investing in radically new areas. However, as discussed in section 2, we believe that such incentive is generally not sufficient to induce the majority of firms in established industries to invest in radical innovations. Even when prevailing technologies have reached their limit of growth, existing firms, being highly engaged in the established paradigm, in terms of both fixed investments and "cognitive framework", may not be interested in stimulating a competing disruptive technology or may not have the competences for developing it. If so, depression will only (negatively) affect incumbents' investment in prevailing technologies, which, as you can see in fig. 1, keeps decreasing. It is therefore more likely that only a minority of new firms will respond to declining productivity of established technologies by searching for innovations in new technological areas. Nevertheless, the behavior of this minority of firms may be sufficient to create a new technological ferment and to re-activate the proposed co-evolutionary process, especially if favorable exogenous factors intervene. This explains why the economy recovers after recessive phases and a new cycle begins.

3.2. Exogenous factors

Fig. 1 is a stylized representation of the technological and economic cycle, where cycles and their growth phases have a fixed length of time and amplitude. However, in our framework, several exogenous factors are expected to affect the length and amplitude of fluctuations. Therefore, some expansive (recessive) phases may be long and exhibit highly positive (negative) growth rates, while others may be shorter and weaker[7]. Exogenous factors may include random historical events (e.g., wars, financial crisis, international factors, demographic dynamics, etc.), technical factors, socio-institutional variables and public policies. In the following, we focus on the last three factors. Exogenous factors are also expected to play a role in selecting new technological paradigms and trajectories among the set of notionally possible ones, and therefore they may influence technological change directions.

The length and amplitude of technological cycles may differ because each paradigm typically embraces a varying quantity of innovations and because the nature and impact of each innovation is different, in particular with respect to the amount of investment in fixed capital and infrastructures it requires. Therefore, due to purely technical factors, technological paradigms may have a varying "degree of radicalness". For this reason, some technological paradigms may have a faster or slower development pattern and may produce greater or lower productivity waves than others. For example, by analyzing the growth path of different technological groups through patent data, Andersen (1999) found no evidence for fixed periodicity of the time-span of cycles. By influencing the length and amplitude of technological cycles, these technical factors would also affect, via multiplier and accelerator effects, the length and amplitude of the associated economic fluctuations.

Concerning socio-institutional variables, several institutions and societal actors may be at play. By expanding the stock of scientific knowledge that serves as a basis for developing innovations, scientific institutions (universities and research laboratories) allow increasing technological opportunities and can therefore affect the length and amplitude of cycles. Financial institutions are important both during the early emergence phase of a new paradigm when, to come out from recession, it is necessary to finance new highly risky projects, and later on, when the growth rate of investment accelerates and easily available credit may trigger over-investment, over-production and technological bubbles. The amount and the price of financial resources available for investment during these phases of the technological cycle may contribute to determine their length and impact on economic activity. Like in the framework proposed by Freeman and Perez (1988), the wider institutional framework, including the educational and training system, labor market institutions, the IP system, and, more in general, political and cultural institutions may accelerate or slow down the development pattern and the impact of a technological paradigm by either favoring its diffusion and assimilation into society or acting as deterrent to change. By making clear specific needs and problems to be solved (potential demand), socio-institutional factors may also act as selection force of new paradigms and trajectories.

Public policies could play a major role on cyclical movements. In order to do that, they should take more explicitly into account the long-term pattern of technological development and its impact on economy activity. On the supply side, public policies may intervene on the level of investment in innovation. During recessive phases, they should support innovative investments in new technological

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[7] Also note that in this context depressions do not necessarily need to occur since recessions may be sufficient to trigger the emergence of a new technological cluster, especially if favorable of exogenous factors intervene. This implies that logistic curves that in fig. 1 represent the stock of investment in the paradigm may be partially overlapping.

areas, radical innovations and new firms' innovative projects, while they should avoid to sustain established technologies. When a paradigm takes off, policies should support its diffusion into society, in particular by providing adequate investments in infrastructures and promoting changes in the wider socio-institutional framework. During expansive phases, policies should discourage the possible over-investment that could arise when the productivity gains of leading technologies are very high. In this context, like in the Keynesian one, public policies are responsible for the overall level of investment. However, here we put emphasis on the innovative nature of investment and its cyclical pattern of development, pointing out the different role that public policies should play during each cyclical phase. Moreover, here, by selecting the technologies to support, public policies can play an important role in the process of selection of new paradigms and trajectories, thus orienting technological change directions. Therefore, public policies are also responsible for the quality of innovative investment, that is, for the directions of change that innovative investment takes.

Finally, on the demand side, public policies should contrast the possible income inequalities resulting from an unequal distribution between profits and wages of the productivity gains generated by innovative investments. Indeed, the multiplier and accelerator effects envisaged in this framework depend not only on the surplus of income generated by productivity gains, but also on its repartition between wages and profits because high levels of income inequality typically lead to low levels of demand, which may turn out to be insufficient to sustain innovative investment. This may interrupt or dampen the cumulative upward spiral and the associated growth wave. Hence, an insufficient level of demand typically has a permanent long-term effect on the length and amplitude of the whole wave. This is in tune with the findings of recent agent-based models (Dosi et al. 2010), which show that demand is a necessary condition allowing changes in technology to fully propagate and that demand shocks bear persistent long-term effects upon the rate of innovation and economic growth.

4. Empirical evidence

Fig. 2 shows observed and smoothed values of the annual growth rate of labor and total factor productivity per hours worked in the US from 1891 to 2012[8]. We observe that the two variables display the same pattern of evolution, which suggests that most of labor productivity gains are originated by technological change. We can also see that both variables have considerably fluctuated over the time period considered, showing a pattern compatible with that of the growth rate of production proposed by our framework. Although there are some disagreements on the dates, scholars (e.g., Gordon 2012, Bergeaud et al. 2016) often identify two growth waves in this pattern. The first big wave would expand from the end of the XIX century (or the beginning of the XX century) to approximately the 1970s and should correspond to the second industrial revolution, based on innovations like electricity, internal combustion engine and chemistry. The second wave, smaller and shorter, accelerates during the 1980s and the 1990s, and should correspond to the ICT revolution. In this work, we focus on the analysis of the ICT wave and base our study on US data, the leader country. More in particular, in this section we provide empirical evidence on the development pattern of the ICT cycle and the economic cycle, identify their growth phases, and test their synchronization according to what has been proposed by our framework.

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[8] Following Bergeaud et al. (2016), data have been smoothed by the HP filter (lambda = 500).

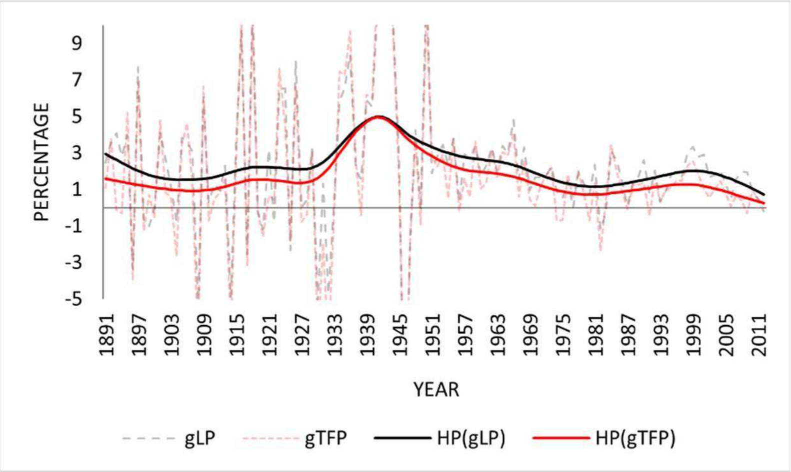

Fig. 2. Annual growth rate of labor productivity per hours worked (gLP) and total factor productivity per hours worked (gTFP): observed and smoothed values. Source: Bergeaud et al. (2016).

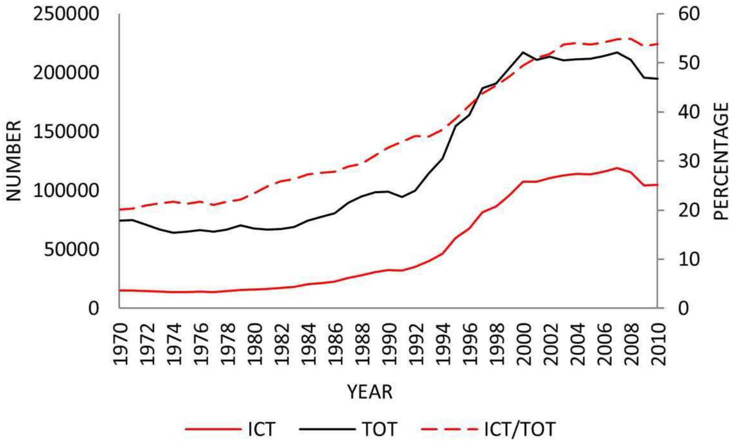

Fig. 3. ICT patents, total patents, and percentage of ICT patents over total patents. Patents granted by the USPTO by priority year. Source: Eurostat and CRIOS (Coffano and Tarasconi 2014)

Fig. 3 displays the time evolution of total and ICT patents granted by the USPTO from 1970 to 2010, together with the share of ICT patents over total patents[9]. The figure shows that both ICT and total patents have considerably grown over time. The growth has been particularly high during the 1990s, while it flattens out since 2000s and is negative or stagnant in the last 3 available years (from 2008 to 2010). The share of ICT patents over total patents has considerably grown as well, from 20.1% in 1970 to 53.8% in 2010. Its growth begins in the 1980s and is rapid during the 1990s, but it slackens since the early 2000s and after having reached a peak in 2008 (54.8% out of total patents), it decreases or stagnates in the last two available years. Overall, these data show that ICT patents have importantly contributed to determine the growth of total patents. This confirms that innovative investments in ICT have considerably pushed total innovative investments and that, consequently, ICT can be considered

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[9] Data since 1977 have been extracted from Eurostat, data before 1977 have been extracted from the CRIOS dataset (Coffano and Tarasconi 2014) by using the IPC codes provided by OECD (https://www.oecd.org/sti/inno/40807441.pdf).

as the leading technologies over the time period covered by this analysis. However, the slowdown of the growth of both total patents and the share of ICT patents during the 2000s suggests that total innovative activity and the ICT leadership may be declining.

In order to detect the development pattern of the technological and economic cycle, we have fitted to data the corresponding logistic functions (I_S and Y in fig. 1). To fit the economic cycle, we have used data on labor productivity, namely GDP per hours worked (hereafter "GDPHW"). To fit the technological cycle, we have used patent data, and, more in particular, the stock of ICT patents granted by the USPTO (by priority year). Patent data are widely considered a good, although not perfect, measure of innovative activity and patent stocks have been used by previous studies (e.g., Andersen 1999) to fit the technological cycle. Patent data have limitations because not all innovations are patented and not all patented inventions reach the market. Moreover, the propensity to patent is not constant over time and may be affected by a variety of factors (strategic behavior of firms, changes in IP legislation, wars, etc.). And yet, patent data remain the best proxy of innovative activity available for long time periods, and, as pointed out by Andersen (1999), the effect these limitations may have on the results is reduced by working with stocks rather than patent flows.

The logistic function is defined by:

$$Y(t) = K + \frac{C - K}{1 + e^{-b(t-t0)}}$$

where *C* is the curve's maximum value or ceiling (the upper asymptote), t_0 is the x-value of the logistics' inflection point, *t* is the time variable, *b* represents the growth rate coefficient, and *K* is a constant that positions the curve on the vertical axis (the lower asymptote). The curve is asymptotic to *K* and *C*, and symmetric around the inflection point t_0. The procedure of fitting logistic curves to data describing the growth pattern of technologies and industries has been employed, among the others, by Kuznets (1930), Grilices (1957) and Andersen (1999). Here, we rely on these studies and use computational statistics based on non-linear least squares regression that simultaneously fit the parameter values of the logistic function (*K*, *C*, t_0 and *b*). Following (Grilices 1957), the origin and the end of the cycle have been identified by calculating the date at which the logistic growth curve passes through the 5% and the 95% of the ceiling, respectively. Following Andersen (1999), the growth phases of each cycle have been identified by calculating the date at which the logistic growth curve passes through the 25%, the 50% and the 75% of the ceiling. Accordingly, with respect to the technological cycle:

- emergence if $0.05 \leq \frac{Y(t)-K}{C-K} < 0.25$
- growth if $0.25 \leq \frac{Y(t)-K}{C-K} < 0.50$
- maturity if $0.50 \leq \frac{Y(t)-K}{C-K} < 0.75$
- decline if $0.75 \leq \frac{Y(t)-K}{C-K} < 0.95$

With respect to the economic cycle:

- depression if $0.05 \leq \frac{Y(t)-K}{C-K} < 0.25$
- revival if $0.25 \leq \frac{Y(t)-K}{C-K} < 0.50$
- prosperity if $0.50 \leq \frac{Y(t)-K}{C-K} < 0.75$
- recession if $0.75 \leq \frac{Y(t)-K}{C-K} < 0.95$

Fig. 4 shows the ICT patent stock, the corresponding fitted logistic curve (R^2= 0.99) and the identified growth phases of technological cycle. The overall duration of the cycle is 45 years, from 1986 to 2030, the estimated inflection point is 2007 and the estimated rate of growth coefficient *b* is 0.13. We can see that the emergence phase of the ICT cycle is relatively long, from 1986 to 1999 (14 years), while the subsequent phases of growth and maturity are shorter (8 or 9 years). The growth phase lasts from 2000 to 2007, and the maturity phase from 2008 to 2016. The 2017 is the year when the decline of ICT is estimated to begin. Fig. 5 contains the first and second derivative of the fitted logistic function, which, according to our framework, represent the level and the growth rate of innovative investment in the paradigm, respectively (I and g_I in fig. 1). The level of innovative investment in ICT increases until 2008 and decreases afterward, while the growth rate of innovative investment reaches a peak in 1998 and remains positive until 2008; it is instead negative afterward.

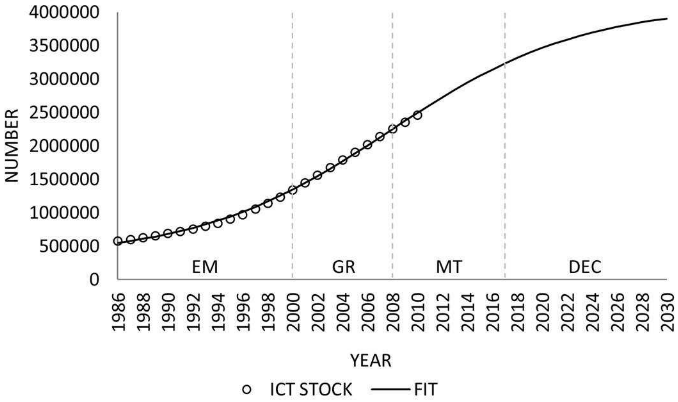

Fig. 4. ICT patent stock: observed and fitted values. Growth phases of the technological cycle (EM=emergence, GR=growth, MT=maturity, DEC=decline).

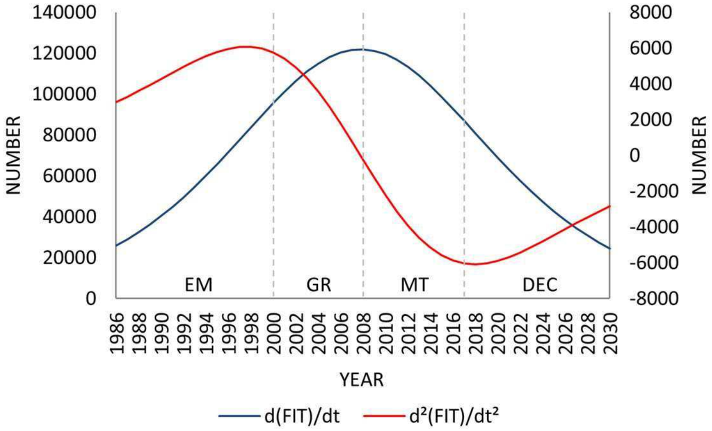

Fig. 5. Estimated innovative investment in ICT: level [d(FIT)/dt] and growth rate [d^2(FIT)/dt^2]

These results are consistent with previous studies showing that the second half of the 1990s has been a period of fast ICT performance improvement (Jorgenson 2001, Basu et al. 2001, Jorgenson et al. 2006, Byrne et al. 2013), as well as with other works indicating that the growth of ICT performances may have slowed down during 2000s (Cette 2014). In particular, the rate of ICT price decrease, which is considered a measure of ICT productive performances, has rapidly decreased in the second half of the 1990s and has slackened afterward (see Cette 2014). The second half of the 1990s exactly corresponds to our estimated phase of highest ICT growth, while the 2000s correspond to period when, according to our analysis, the growth rate of ICT investment slows down. Similar findings are obtained by Pillai (2011), which by looking at the performance improvement of microprocessors (i.e., the Moore law) produced by Intel and AMD from 1971 to 2009, shows that the improvement accelerates in the second half of 1990s and decelerates since 2001.

We now proceed to fit the logistic curve representing the economic cycle. In order to identify the starting year of the cyclical unit, we have used the growth rate of GDPHW, whose trough, according to our framework, should mark the end of the previous cyclical unit and the beginning of the subsequent one (see fig. 1). Fig. 6 shows the time evolution of GDPHW from 1970 to 2016, its growth rate and its HP smoothed growth rate (lambda=500). We can see that the level of GDPHW fluctuates around a positive trend (the dotted line) and while its growth rate is negative twice (in 1974 and in 1982), the smoothed growth rate is always positive. The smoothed growth rate has a trough in 1982, which is also the year when the level of GDPHW falls below its trend over the period. We have therefore fitted the logistic curve to GDPHW data taking the 1982 as starting year.

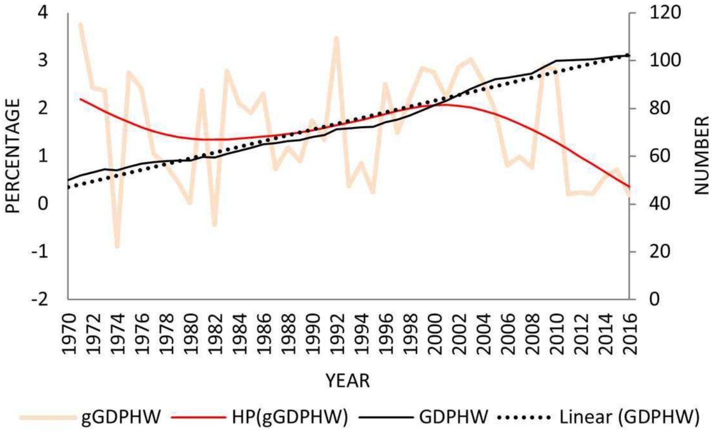

Fig. 6. GDPHW: level, growth rate and smoothed growth rate. Source: OECD (2010=100).

Fig. 7 shows GDPHW, the fitted logistic curve ($R^2 = 0.99$) and its derivative, which represents the growth rate of the economy (g_Y in fig. 1). The figure also contains the identified phases of the economic cycle, whose overall duration is 38 years, from 1982 to 2019. The estimated inflection point of the curve is 2000, and the estimated rate of growth coefficient *b* is 0.15, very close to the rate of growth coefficient of the logistic curve fitting the technological cycle. The cycle starts with a 12-year phase of depression (from 1982 to 1993), which is followed by a 7-year phase of revival (from 1994 to 2000), and by a prosperity phase of the same duration (from 2001 to 2007). In 2008 the cycle enters a recessive phase, which is estimated to last until 2019. The economic cycle seems therefore characterized by a relatively short phase of accelerated growth (revival and prosperity), lasting 14 years, and by a longer phase of decelerated growth (depression and recession), lasting 24 years. By looking at the estimated growth rate of the economy, we can see that it reaches a peak in 2001 and decreases afterward. These results are in accordance with several works that have documented the acceleration of US productivity growth in the second half of the 1990s and its slowdown during the mid-2000s, before the economic crisis of 2008 (see, e.g., Gordon 2012, 2013, Bergeaud et al. 2016, OECD 2015).

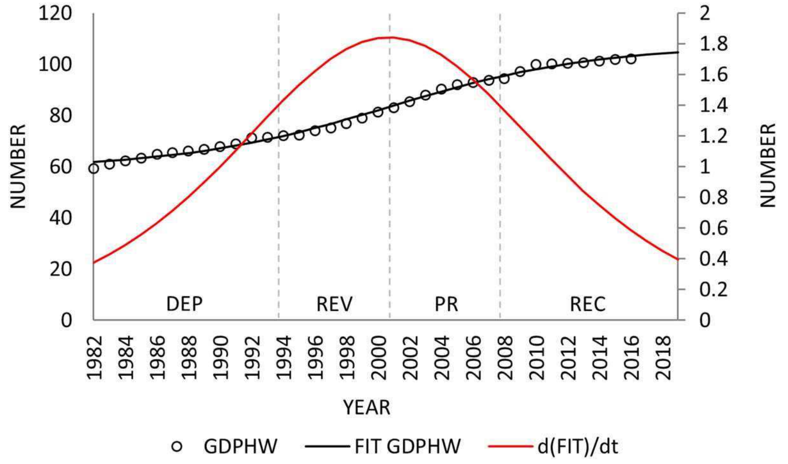

Fig. 7. GDPHW: observed values, fitted values, and growth rate of fitted values [d(FIT)/dt]. Growth phases of the economic cycle (REV=revival, PR=prosperity, REC=recession, DEP=depression).

Fig. 8 shows the identified phases of technological and economic cycle (in parentheses we have reported the duration of each phase). We observe that these phases are highly synchronized according to what has been proposed by our framework in section 3.1. More in particular, the beginning of the prosperity phase of the economic cycle, when the growth rate of the economy is maximum, is just one year later than the beginning of the growth phase of technological cycle in 2000. Also, the year when the level of innovative investment reaches its peak (2008) coincides with the year when the prosperity phase of economic cycle ends, as supposed by our framework. However, the phase of economic revival begins 8 years later than the emergence phase of the ICT cycle. This may be due to the low productivity gains engendered by ICT investment in the late 1980s and early 1990s, and to the consequent week multiplier effect of such investment on the economy. Indeed, at that time, many scholars were perplexed by the observed slow productivity rates and the simultaneous raise of ICT investment (David 1990). The so-called "productivity paradox" was summarized by the formulation attributed to Robert Solow: "We see the computers everywhere but in the productivity statistics." (quoted in David 1990).

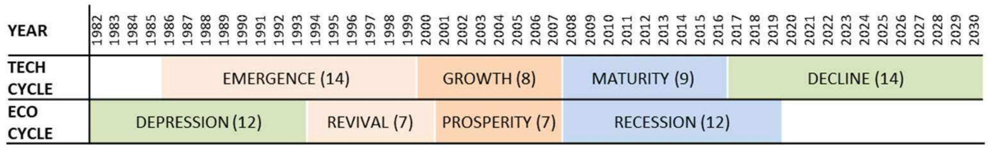

Fig. 8. Estimated growth phases of the technological and economic cycle.

Lastly, fig. 9 shows the estimated growth rates of innovative investment and production (i.e., (the second derivative of the logistic curve fitting the patent stock and the first derivative of the logistic curve fitting GDPHW, respectively) over the time period in which we have observations for both cycles (1986-2019). According to our framework these growth rates should be synchronized. We can see that the former reaches a peak in 1998 and the latter in 2001. This suggests that the technological and economic cycle, as estimated by our procedure, are highly synchronized. More in particular, it seems that the economic cycle follows the technological cycle with a delay of about 3 years. The Pearson correlation coefficient, used in business cycle synchronization studies (e.g., Baxter and Kouparitsas 2005, Imbs 2006), between the two growth rates is equal to 0.76 and significant at 0.05.

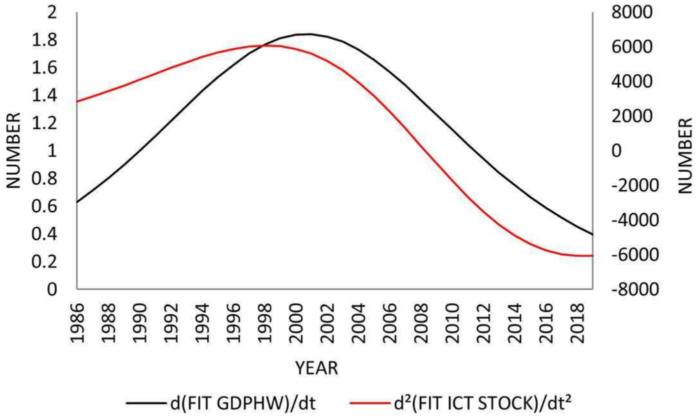

Fig. 9. Estimated growth rates of production [d(FIT GDPHW)/dt] and innovative investment in ICT [d^2(FIT ICT STOCK)/dt^2].

These results are consistent with previous studies that attribute the acceleration of US productivity growth in the mid-1990s to the rapid growth of technical improvement in ICT (Jorgenson 2001, Basu et al. 2001, Jorgenson et al. 2006). By using a growth accounting approach, other works (Byrne et al. 2013, Cette et al. 2015) have found that the contribution of ICT to labor productivity growth rose significantly in 1994-2004 compared to 1974-1994, but since 2004, it has fallen off considerably. These works, however, are cautious in ascribing the 2000s productivity slowdown to a deceleration of ICT performances. Gordon (2012, 2013), instead, considers the decline of the ICT revolution as an important explanation of the 2000s productivity slowdown and points out to the low importance of inventions developed after 2001, which rather than replacing human labor by machine power, replaced one form of entertainment or communication by another. The scholar also argues that the ICT revolution, by delivering only 8 years of relatively low growth, has had a much lower economic impact than the previous revolution and prognosticates the end of major technological revolutions. Bergeaud et al. (2016) and Cette (2014) confirm that the ICT productivity wave may have been smaller and shorter than the previous one, but remain open to the possibility of a second ICT wave, pushed by future major ICT improvements. Finally, according to Perez (2013), the 2007-08 crisis may mark, if accompanied by effective policies, the beginning of the high growth phase of the ICT paradigm. In short, the 2000s productivity slowdown may be interpreted as the end of major technological revolutions, as a recession period between two peaks of sustained growth based on the same ICT revolution, or as the declining phase of the ICT revolution. Our results seem to provide evidence for the last hypothesis, although, because of the limitations of our methodology, we cannot exclude a second wave of ICT-related innovations. According to our framework, the ICT decline, if confirmed, should provide incentive for the emergence of a new technological cluster. Our analysis also seems to confirm that the expansive phase engendered by ICT has been relatively short.

5. Conclusions

The study of the endogenous and exogenous forces that determine fluctuations in innovative and economic activity is important for both understanding the long-term pattern of development of the economic system and envisaging effective public policies. In this paper, we propose that the economic system tends to endogenously generate periods of accelerated and decelerated growth of innovative investments and production. This is explained by the existence of a process of co-evolution between technological and economic variables based on multiplier and accelerator feedback effects between investments in innovation and demand: the productivity gains produced by investments in innovation over the technological cycle drive demand growth, while adaptive expectations on demand drive investments in innovation. These feedback effects generate a succession of cumulative upward and downward spirals that allows explaining why new technological clusters and associated industries from time to time emerge and radically transform the economy. In the upward spiral, the growth of productivity induced by innovative investments generates a surplus income that has a positive impact on expected demand, which, in turn, has a positive impact on innovative investment. In these circumstances, technological change positively acts on firms' profit expectations and confidence, thus stabilizing investment. The downward spiral arises when a technological paradigm reaches its maturity phase and the productivity growth induced by innovative investments slackens, leading to a slower increase of income and expected demand, which undermines business confidence and destabilizes investment. Falling growth of productivity and income reduces firms' profit expectations on prevailing technologies and provides incentive for a minority of firms, mainly new firms, to invest in radically new technological areas, which will eventually stimulate a new cycle.

In this perspective, the economic system, by endogenously generating technological paradigm shifts and structural change, would tend to grow in a cyclical way. However, we also suggest that exogenous factors may importantly influence this cyclical behavior as they may have a considerable impact on the length and amplitude of fluctuations, and therefore on the duration and intensity of cyclical phases. Hence, in this framework, periods of slow economic growth endogenously occur in the system and provide incentive to change leading technologies and industries. Yet, if favorable exogenous factors, and more in particular public policies, do not intervene in this process, changes may require a long time to take place and recessive phases may be long-lasting. We have provided a preliminary empirical evidence supporting this framework by fitting the ICT cycle and the economic cycle to patent and productivity data, respectively. Although the results of this analysis are subject to a number of limitations (see section 4), they provide evidence for the existence of a cyclical (S-shaped) development pattern of ICT and for associated fluctuations of production. We also found that the estimated functions of the technological and economic cycle are highly synchronized according to what has been proposed by our study. This, however, provides only an indirect and partial evidence for the proposed explanatory process of such synchronization.

This work provides the following contributions to extant literature. First, it envisages an explicit endogenous mechanism explaining the recurrence of cycles and, at the same time, integrates the role played by exogenous factors. Moreover, by combining the Schumpeterian analyses of innovation dynamics with the multiplier and accelerator effects coming from Keynesian theories, this study allows taking into account both the impact of technological variables on economic activity and vice versa. In this context, investments in technology drive demand and demand drives investments in technology in a process of continuous mutual interaction. We thus take a process approach in which there is not a single cause or driver, but rather processes of cumulative causation which link-up with, and reinforce, each other in a circular way.

Second, by emphasizing the different behavior of new and established firms with respect to radical innovation, we contribute to the issue of whether firms' propensity to invest in radical innovation depends on economic conditions. In our framework, unfavorable economic conditions affect the propensity to invest in radical innovation of only a minority of new firms. Nevertheless, because of the multiplier and accelerator effects, the behavior of this minority of firms may be sufficient to create a new technological ferment and stimulate a new growth wave. This allows explaining how small gradual changes (the technological ferment introduced by a minority of firms) become radical aggregate changes producing paradigm shifts, structural change, changes in industry leaders and fluctuations of production.

Third, our empirical analysis contributes to the innovation literature as no recent efforts have been made to study empirically the long-term evolution pattern of major technological clusters and its relationship with economic activity. The results of this analysis also contribute to the debate on the impact of ICT on productivity growth. More in particular, our findings are consistent with previous studies that attribute the acceleration of the US productivity growth in the mid-1990s to the rapid growth of technical improvement in ICT (Jorgenson 2001, Byrne et al. 2013, Cette et al. 2015). Concerning the most recent time period, our analysis indicates that the growth rate of innovative investment in ICT has slackened since the early 2000s, before the 2008 crisis. This suggests that the growth potential of ICT may be declining, as already highlighted by other works (Gordon 2012, 2013, Cette 2014, Bergeaud et al. 2016). This situation, according to our framework, should provide incentive for the emergence of a new cluster of radical technologies and its associated growth wave. Potential candidates could be represented by environmental technologies, as well as by artificial intelligence technologies, which are sometimes considered as the possible forth industrial revolution. However, as mentioned above, changes of predominant technologies may last a long time and recessive phases may prolong if favorable exogenous factors do not intervene in this process.

Public policies are one of the major exogenous factors that may influence cyclical fluctuations. As discussed in section 3.2, public policies are responsible for both the overall level of investment in innovation over the cycle and the directions of change that investment in innovation takes. Therefore, policies should take more explicitly into account the long-term pattern of technological development and envisage different types of intervention according to the phase of technological evolution. This is particularly important during the declining phases of leading technologies, when the core technologies and the cognitive framework of the future paradigm start taking shape, thus defining the technological problems to be solved and the future directions of change. During these phases, public policies should avoid to sustain established technologies; rather they should support investment in radical innovations and orient it toward socially desirable directions. Technology orientation policies are also important during the emergence phase of new technologies, when different paradigms may compete with each other. Establishing the type, variety and duration of the technologies to support, and therefore the directions of change to sustain, is not obvious because of the intrinsically uncertain nature of technological change processes. However, more efforts could be done to widen the public debate on this issue and to democratize the process of selection of the technologies to support. In addition, some socially desirable directions of change are now clear and relate to one of the most serious problems created by economic growth, namely environmental pollution and degradation.

If the productivity slowdown that many economies experience since the 2000s is a signal that the economic system needs to change its leading technologies, as our analysis seems to suggest, then this situation may represent an important opportunity, for public policies and socio-institutional actors, to orient future development toward environmental sustainability. On the contrary, policies supporting vested interests in established polluting technologies may be particularly dangerous as they would slow down both sustainability transition and economic recovery. Policies favoring or not contrasting income inequality may be very dangerous as well, because a high level of income inequality typically leads to a low level of demand, and demand, in our framework, is a necessary condition to motivate investment in innovation. Hence, an insufficient level of demand typically has a permanent long-term effect on the length and amplitude of the whole growth wave. Since many economies exhibit high and increasing levels of income inequality, current demand may turn out to be insufficient to sustain the take-off of environmental technologies, again slowing down both sustainability transition and economic recovery.

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