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Technological revolutions and economic development: endogenous and exogenous fluctuations

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Abstract

Innovation scholars have highlighted that technological revolutions generate long-run fluctuations in innovative and economic activity. This paper aims at examining whether such fluctuations are endogenous or exogenous. This question is particularly important with respect to the current debate on the productivity slowdown and a potential new technological revolution. We propose a framework that integrates both endogenous and exogenous factors. On the one hand, the economic system tends to generate endogenously, and therefore recurrently, technological revolutions, structural change and associated long-run fluctuations of production. This tendency is explained via a process of co-evolution between investment in innovation and demand, based on cumulative multiplier and accelerator feedback effects. On the other hand, exogenous factors are expected to exert a major impact upon this endogenous process by influencing the length and amplitude of fluctuations, i.e., the timing and economic impact of technological revolutions. Exogenous factors may include random historical events (e.g., wars), technical factors, public policies and socio-institutional actors. To provide a preliminary evidence supporting the framework, we have fitted the ICTs (Information and Communications Technologies) cycle and the economic cycle to patent and productivity data, respectively. Our results suggest that the current productivity slowdown may be a signal that the economic system needs to change its leading technologies. This phase of technological ferment may represent an important and rare opportunity, for public policies and socio-institutional actors, to orient future development toward socially desirable directions.

Keywords: technological revolutions, structural change, long-run fluctuations of production, co-evolution, productivity slowdown, ICTs

JEL classification: O33, O11, O40, E32

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1. Introduction

The emergence and diffusion of radically new technologies such as the steam engine, electricity and ICTs (Information and Communications Technologies), have given rise to technological revolutions that have dramatically changed economies and societies, profoundly shaping their paths of long-run development. ICTs², a cluster of technologies that emerged in the 1970s, have been widely considered at the origin of the current technological revolution. However, the recent period of slow growth and the emergence of potentially new radical technologies (e.g., artificial intelligence, robotics, IoT, etc.), have sparked a debate about the next technological revolution, its possible advent and impact, its core technologies and its relationship with some of the most important societal problems, like environmental sustainability and income inequality (Gordon 2012, Perez 2013, Archibugi 2017, Steinmueller 2017, Lundvall 2017, Schwab 2017, Lee et al. 2018, Tylecote 2019, Dosi and Virgillito 2019).

Technological revolutions have been defined as clusters of interrelated radical technologies that create new leading industries and have a widespread impact on existing industries, destroying some and rejuvenating others (Perez 2010). Hence, by definition, technological revolutions are the main factor that generates structural change. As highlighted by Schumpeter (1939) and Schumpeterian scholars (Freeman and Perez 1988, Perez 2010), technological revolutions also generate long-run fluctuations in innovative and economic activity, that is, periods of accelerated and decelerated growth of both investments in innovation and production, also called growth waves, long waves or great surges of development. Periods of high growth have been associated with the improvement and diffusion into economy of radical technologies. Periods of slow growth have been linked to the maturity of leading technologies and the installation period of emerging technologies (Schumpeter 1939, Freeman and Perez 1988).

This paper aims at examining whether the long-run fluctuations generated by technological revolutions are endogenous or exogenous. This question is important because if fluctuations in innovative and economic activity are endogenous, then the economic system would tend to recurrently generate on its own the forces that transform it and that determine its long-run development, namely technological revolutions and structural change. In addition, the economic system would tend to recurrently experience periods of accelerated growth. On the contrary, if fluctuations are exogenous, then technological revolutions, structural change and growth accelerations would be the result of historical accidents or other exogenous events that will not necessarily repeat in the future, e.g., the Second World War or exceptionally important innovations that can only be invented once, like in Gordon's (2012) analysis. This question also has important policy implications, in particular with respect to the debate sketched above, because a better understanding of the process of long-run economic development should improve the capability of public policies to orient future development paths.

In the literature there seems to be a certain consensus on the idea that radical innovations, and the associated long-term fluctuations in innovative and economic activity, are exogenous, though some scholars have put forward arguments in favor of endogenous radical innovations. In Kuznets's (1930) and Schumpeter's (1939) analysis, as near as we can make out, radical innovations are caused by random or exogenous factors, independent of macroeconomic variables. If so, Schumpeter's theory would explain growth waves (i.e., why economic growth accelerates and then decelerates), but not their recurrence, that is, why the economy regularly recovers after the deceleration and why a new wave begins. In fact, the existence of an endogenous mechanism explaining the recurrence of waves

² ICTs include semiconductors, computers, software, telecoms and internet (Perez 2010)

is a necessary requirement for a theory of long waves (Rosenberg and Frischtak 1983). Schumpeter, instead, 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 basically shared also 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.

Mensch (1979), instead, proposed that firms' propensity to invest in radical innovation is endogenous, that is, dependent on general macroeconomic conditions. According to Mensch, only the exhaustion of the growth potential of predominant technologies and the consequent despair of depression periods will induce firms to invest in radical innovations, which will eventually give rise to a new growth wave. This position allows explaining the recurrence of waves, but has been highly criticized. For example, Clark et al. (1981) argued that the emergence of radical innovations is mainly due to relatively exogenous factors, including scientific and technological breakthroughs, and periods of very strong demand, such as booms and wars. Finally, also economic history scholars have stressed the importance of exogenous "macroinventions" in order to explain the observed acceleration of productivity growth during industrial revolutions (Mokyr 1993, Craft 1995).

Although we share the view that historical accidents and other exogenous factors have a major impact upon long-run fluctuations, we think that theories based solely on purely exogenous factors risk ignoring those endogenous forces that could be part of the explanation. Therefore, in this paper, we propose a framework that integrates both endogenous and exogenous factors: while endogenous factors are at the origin of the tendency of the economic system to grow in a cyclical way, exogenous factors are expected to influence the length and amplitude of cycles, which, therefore, are not regular. More in particular, in this work we use the notion of technological paradigm (Dosi 1982), and, following Perez (2010), we apply it at macro-level. By relying on Schumpeterian studies of innovation dynamics, we first define the development pattern of a technological paradigm (the technological cycle) and its growth phases. Then, by combining such studies with Keynesian theories of demand generation, we analyze the relationship between technological cycle and economic activity (the economic cycle). We suggest that this relationship may be represented as a process of co-evolution between investment in innovation and demand. This is based, on the one hand, on the different productivity gains generated by a technological paradigm over its life-cycle, and, on the other hand, on continuous multiplier and accelerator feedback effects between innovation and demand that cause a cumulative amplification of any initial change in innovative investment.

The co-evolution between innovation and demand has already been considered as the main endogenous mechanism driving structural change and long-run economic development (Saviotti and Pyka 2012, 2013). Here, in a complementary way, the process of co-evolution between innovation and demand is also the main endogenous mechanism explaining technological revolutions, growth waves and their recurrence. In this context, the emergence of radical innovations depends on unfavorable economic conditions, but, unlike Mensch (1979), such conditions affect the propensity of only a minority of new firms to invest in radical innovation. Yet, because of the multiplier and accelerator effects, the behavior of this minority may explain why a new cluster of radical technologies emerges and why the economy recovers. This is coherent with numerous studies showing that incumbent firms possess sunk investments, as well as specific knowledge and managerial practices that make either difficult or disadvantageous for them to invest in radical innovation (Anderson and Tushman 1990, Christensen 1997, Kemp et al. 1998, Breschi et al. 2000, Markard et al. 2012).

On the other side, a number of exogenous factors may have a major impact upon the above-mentioned endogenous process by influencing both the length and amplitude of fluctuations, that is,

the timing and economic impact of technological revolutions. Exogenous factors may include random historical events (e.g., wars, financial crisis, international factors, demographic dynamics, etc.), technical factors, socio-institutional actors and public policies. Hence, due to exogenous factors, some expansive (recessive) phases may be long and may exhibit very high (low) growth rates, while others may be shorter and weaker. Exogenous factors are also expected to play a role in selecting new technological paradigms and trajectories among the set of notionally possible ones (Dosi 1982), and, therefore, they may influence technological change directions. To provide a preliminary empirical evidence supporting the proposed framework, we have used patent data relating to ICTs and productivity data over the period 1970-2016. We have fitted to these data the logistic curves representing the technological and economic cycle, then we have identified the growth phases of both the technological and the economic cycle, and tested their synchronization. The rest of the paper is organized as follow. In section 2 we review the relevant literature, while in section 3 we illustrate the framework, discussing both endogenous and exogenous factors. Section 4 examines the empirical evidence on the ICTs cycle and section 5 concludes.

2. Literature review

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. 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 because of the existence of technical interdependencies among innovations. The emergence and decline of such clusters generate fluctuations of investments in innovation, which are at the origin of Kondratiev (1935) long-waves, i.e., regular fluctuations of economic activity of 40-60 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. If so, Schumpeter's theory would explain growth waves (i.e., why economic growth accelerates and then decelerates), but not their recurrence, that is, why the economy regularly recovers after the deceleration and why a new wave begins.

On the contrary, in Mensch's (1979) perspective the emergence of radical innovations depends on macroeconomic variables and it is therefore endogenous. According to Mensch, firms resort to the highly risky strategy of investing in radical innovations only during depression periods, when the growth potential of dominant technologies is exhausted. Kleinknecht and Van der Panne (2006) further expanded this perspective considering the lack of radical innovations during upswings as the result of a rational behavior of firms with respect to the opportunity cost of the different industries. 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

innovations³, which eventually will stimulate a new growth wave (Kleinknecht and Van der Panne 2006). 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.

The Mensch's hypothesis has been criticized, among the others, by Clark et al. (1981). 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: scientific and technological breakthroughs, and periods of very strong demand, including booms and wars, when markets promise high profits and low risk.

In sum, there seems to be a quite general consensus on the idea that radical innovations evolve following an S-shaped curve and generate structural change. In addition, there seems to be sufficient consensus on the existence of clusters of technically interrelated radical technologies, also called technological paradigms or technological revolutions, and on their importance in generating long-run fluctuations of innovative and economic activity. Conversely, there is no agreement on the existence of clusters of unrelated radical technologies and on their occurrence with fixed periodicity or during depression periods. Many studies have dealt with the task of empirically testing these issues (e.g., Mensch 1979, Solomou 1986, Kleinknecht 1990, Silverberg and Leherte 1993, Silverberg and Verspagen 2003, Korotayev et al. 2011), but they have obtained conflicting conclusions. Lastly, although some authors have put forward arguments in favor of endogenous radical innovations, most scholars seem to agree that radical innovations are exogenous. This implies that there is not any endogenous mechanism explaining the recurrence of technological revolutions, structural change and growth waves, which would also be exogenous. In fact, as highlighted by Rosenberg and Frischtak (1983), the existence of an endogenous mechanism explaining the recurrence of waves is a necessary requirement for a theory of long waves.

In the framework that we propose, there is an endogenous mechanism explaining the recurrence of waves, but a number of exogenous factors exert a major influence on it. In this context, radical innovations are endogenous because general economic conditions affect firms' propensity to invest in radical innovation. More specifically, we share the view that unfavorable economic conditions due to the maturity of prevailing technologies (falling productivity, demand and profitability) reduce firms' profit expectations on these technologies, thus providing incentive to invest in radically new technological areas. However, unlike Mensch (1979), we also think 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 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.

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).

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 essentially incremental innovations.

Unlike established firms, new firms have no 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 active a co-evolutionary process between innovation and demand that eventually will lead to the emergence of new paradigms and industries. This co-evolutionary process would represent an explicit endogenous mechanism explaining the recurrence of technological revolutions, structural change and growth waves. Exogenous factors, including random historical events (e.g., wars, financial crisis, international factors, demographic dynamics, etc.), technical factors, socio-institutional actors and public policies are expected to play a major role upon this endogenous mechanism by influencing the length and amplitude of waves, that is, the timing and economic impact of technological revolutions. 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 technically interrelated and mutually supporting radical technologies that have the capability of initiating new leading industries and a widespread impact on existing industries (Perez 2010). In addition to being a new set of technologies and industries, a paradigm is also a collectively shared cognitive framework (Dosi 1982). Therefore, 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). ICTs are a cluster of technologies that emerged during

the 1970s and include semiconductors, computers, software, telecoms and internet. ICTs have generated new leading industries and have profoundly transformed existing sectors. Hence, they have been widely considered at the origin of the current technological revolution.

In order to analyze the relationship between technological and economic cycle, we follow recent studies that combine Schumpeterian analyses of innovation with Keynesian theories of demand generation (Dosi et al. 2010, Saviotti and Pyka 2012, 2013, Caiani et al. 2014). We envisage both multiplier and accelerator effects, so that investment decisions induce demand propagation effects and adaptive expectations on demand drive investment decisions (Dosi et al. 2010). However, here, in a long-run perspective, we emphasize 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 minor in the long-run⁴. The growth of productivity induced by innovative investment engenders higher wages and profits, and lower prices. This generates a surplus income that has a positive impact on demand (the multiplier effect), which, in turn, has a positive impact on innovative investment (the accelerator effect). In these circumstances, technological change, by allowing productivity, income and demand to increase, positively acts on firms' profit expectations and confidence, thus stabilizing investment. As we will see in more 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 a stylized representation of the technological cycle and the 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 growth potential of the paradigm approaches to exhaustion and a new paradigm, represented by the subsequent logistic curve, starts to emerge⁵. 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 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.

⁴ Assuming that investment in innovation also has 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.

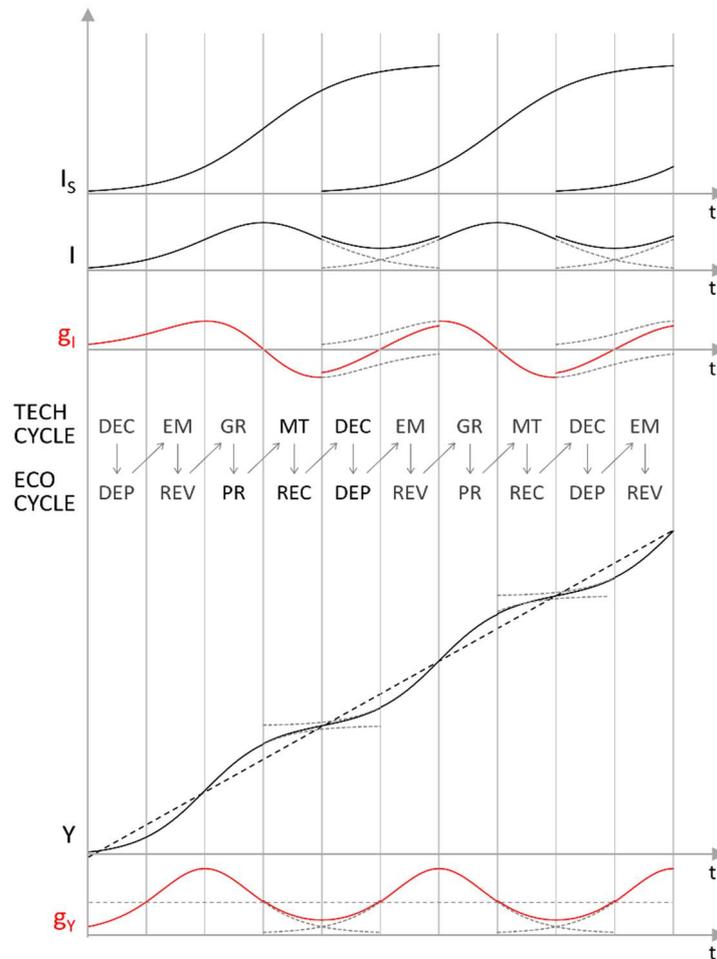


Fig. 1. Technological cycle (I_s , I , g_i), economic cycle (Y , g_y), and their growth phases (EM=emergence, GR=growth, MT=maturity, DEC=decline, REV=revival, PR=prosperity, REC=recession, DEP=depression). N.B. When logistic functions overlap (dotted curves), their first and second derivatives are summed (continuous 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 trend⁶. 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 phases of emergence, growth, maturity and decline of the technological cycle occur during the phases

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

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 process of co-evolution between investment in innovation and demand. Co-evolution occurs when two variables influence each other in such a way that as one of them grows or falls, it induces a corresponding growth or fall in the other one (Saviotti and Pyka 2013). The process of co-evolution between innovation and demand has been considered by Saviotti and Pyka (2012, 2013) as the main driving force of structural change and long-run economic development. Here, in a complementary way, the co-evolution between innovation and demand generates a succession of cumulative upward and downward spirals that would allow explaining technological revolutions, growth waves and their recurrence. Upward and downward spirals are determined by feedback effects between technology and economy: technological variables (investment in innovation) have a multiplier effect on economic variables (demand), 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, while 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 Suarez 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 experiences 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, 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 technologies. However, as discussed in section 2, we believe that such incentive is generally not sufficient to induce the majority of firms 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. On the contrary, it is more likely that new firms will respond to falling productivity of established technologies by searching for innovations in new technological areas. The behavior of this minority of firms may then create a new technological ferment that re-activate the proposed co-evolutionary process, especially if favorable exogenous factors intervene. Hence, the behavior of new firms, coupled with the multiplier and accelerator effects, would allow explaining endogenously why the economy recovers after recessive phases and why a new growth wave, with new industry leaders, begins.

3.2. Exogenous factors

In Fig. 1, 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. Hence, some expansive (recessive) phases may be long and may exhibit very high (low) growth rates, while others may be shorter and weaker⁷. 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 (Dosi 1982), 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.

With respect to 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 their impact on economic activity. Like in 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. Here, in addition, we would like to emphasize that socio-institutional factors may also act as selection force of new paradigms and trajectories, both through their consumer preferences and by making clear specific problems to be solved (potential demand).

Public policies are one of the major exogenous factors that may influence long-run fluctuations. In order to do that, policies should take into account more explicitly 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 areas, radical innovations and new firms’ innovative projects, while they should avoid to sustain established technologies. When a paradigm takes off,

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, if favorable exogenous factors intervene. This implies that logistic curves representing in fig. 1 the stock of investment in the paradigm may be partially overlapping.

policies should support its diffusion into society, in particular by providing adequate investments in infrastructures and promoting changes in the wider socio-institutional framework. Instead, during expansive phases, policies should discourage the over-investment possibly arising 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. In addition, as discussed in more detail in section 5, here, public policies can play an even more important role in shaping technological change directions through active technology orientation policies. Hence, public policies are also responsible for the quality of innovative investment, that is, for the directions of change that innovative investment takes.

On the demand side, public policies should contrast the possible income inequality 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 income surplus generated by productivity gains, but also on its repartition between wages and profits, which is the result of exogenous institutional variables (e.g., public policies, strength of labor unions, etc.). 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 models (Dosi et al. 2010, Saviotti and Pyka 2013), which show that demand is a necessary condition allowing long-run development 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 2012⁸. We observe that both variables have considerably fluctuated over the time period considered, creating a succession of growth waves, of different length and amplitude, that is compatible with our framework. Moreover, both variables display the same pattern of evolution (i.e., the same troughs and peaks). This suggests that fluctuations of labor productivity, which is the main determinant of production, are largely driven by fluctuations of productivity gains originated by technological change. The last wave showed in fig. 2, which accelerates during the 1980s and the 1990s, is commonly associated to the ICTs revolution. There is instead less consensus on both the number of technological revolutions preceding the ICTs one and their leading technologies⁹. In this work, we focus on the analysis of the ICTs wave and base our study on the US, the leader country. More in particular, in this section we provide empirical evidence on the ICTs cycle and the associated economic cycle, identify their growth phases, and test their

⁸ Data have been provided by Bergeaud et al. (2016). Following Bergeaud et al. (2016) data have been smoothed by using the HP filter ($\lambda = 500$).

⁹ Most scholars identify one big wave that would expand from the end of the XIX century to the 1970s and that would correspond to the second industrial revolution, based on innovations like electricity, internal combustion engine and chemistry. Freeman and Perez (1988), instead, identify two waves corresponding to the electrification from 1890 to 1930, and to the motorization from 1940 to 1980.

synchronization according to what has been proposed by our framework. The synchronization test, however, only provides an indirect evidence for the proposed explanatory process of such synchronization because it is not able to test causality and its direction. In addition, on the basis of this test, we are not able to analyze the impact of exogenous factors, which are supposed to determine the length and amplitude of fluctuations. Doing that would require to compare the length and amplitude of at least two waves (e.g., the ICTs wave and the second revolution wave), a task made difficult by the scarcity of reliable data.

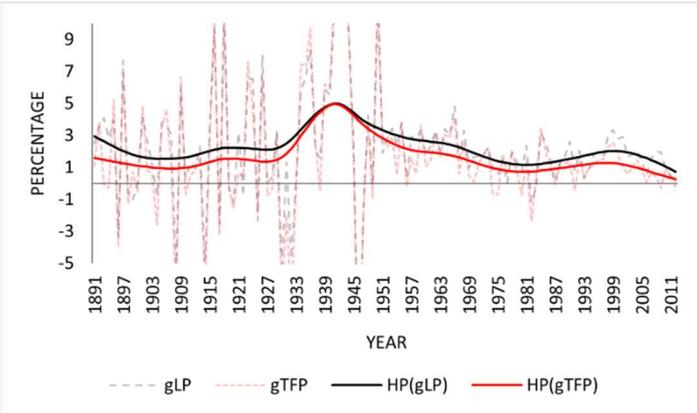


Fig. 2. Annual growth rate of labor productivity per hours worked (gLP) and total factor productivity per hours worked (gTFP): observed and smoothed values.

Fig. 3 displays the time evolution of total patents and ICTs patents granted by the USPTO from 1970 to 2010, together with the share of ICTs patents over total patents¹⁰. The figure shows that both ICTs 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 ICTs 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 ICTs patents have importantly contributed to determine the growth of total patents. This confirms that innovative investments in ICTs have considerably pushed total innovative investments and that, consequently, ICTs can be considered 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 ICTs patents during the 2000s suggests that total innovative activity and the ICTs leadership may be declining.

¹⁰ 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>).

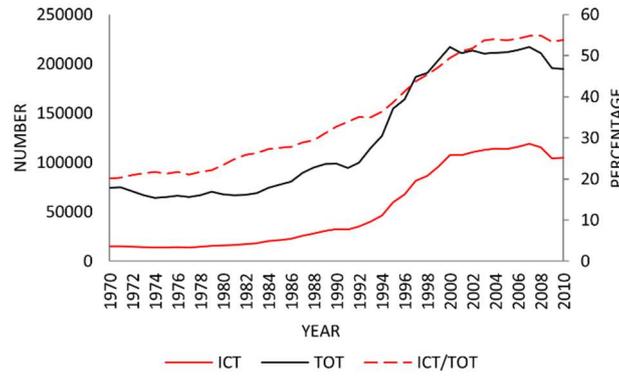


Fig. 3. ICTs patents, total patents, and percentage of ICTs patents over total patents. Patents granted by the USPTO by priority year.

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 ICTs 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 to fit the technological cycle (e.g., Andersen 1999). 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 patent stocks rather than flows.

The logistic function is defined by:

$$Y(t) = K + \frac{C - K}{1 + e^{-b(t-t_0)}}$$

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 ICTs 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 ICTs 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 ICTs 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 in fig. 1). The level of innovative investment in ICTs 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.

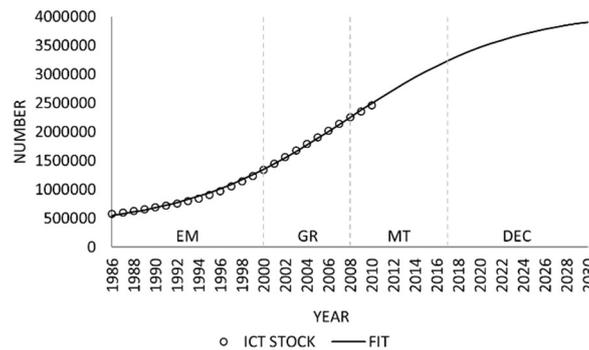


Fig. 4. ICTs patent stock: observed and fitted values. Growth phases of the technological cycle (EM=emergence, GR=growth, MT=maturity, DEC=decline).

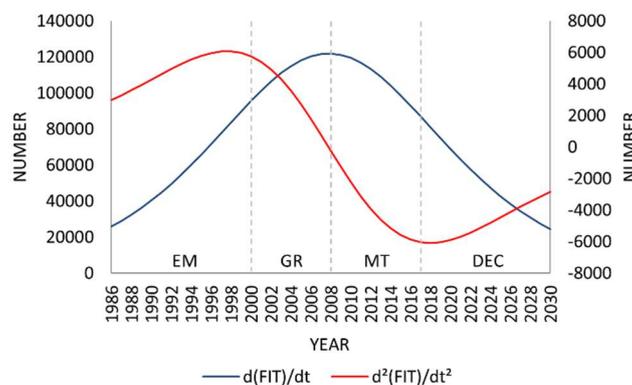


Fig. 5. Estimated innovative investment in ICTs: level $[d(FIT)/dt]$ and growth rate $[d^2(FIT)/dt^2]$

These results are consistent with previous studies, which using alternative theoretical and methodological approaches, show that the second half of the 1990s has been a period of fast ICTs performance improvement (Jorgenson 2001, Basu et al. 2001, Jorgenson et al. 2006, Byrne et al. 2013). Our results are also consistent with other works indicating that the growth of ICTs performances may have slowed down during 2000s (Cette 2014). In particular, the rate of ICTs price decrease, which is considered a measure of ICTs productive performances, has rapidly decreased in the second half of the 1990s, while it has slackened afterward (see Cette 2014). The second half of the 1990s exactly corresponds to our estimated phase of highest ICTs growth, while the 2000s correspond to period when, according to our analysis, the growth rate of ICTs 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.

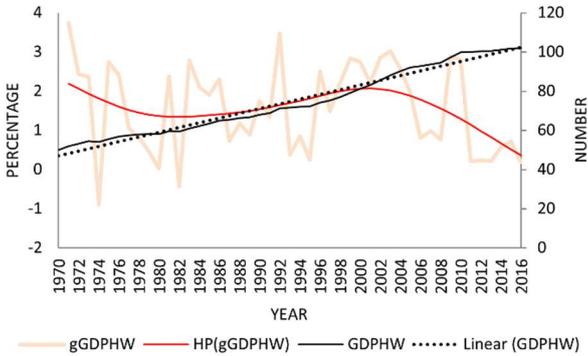


Fig. 6. GDPHW: level, growth rate and smoothed growth rate. Source: OECD (2010=100).

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 that 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

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), between the two growth rates shows a strong synchronization (equal to 0.76 and significant at 0.05).

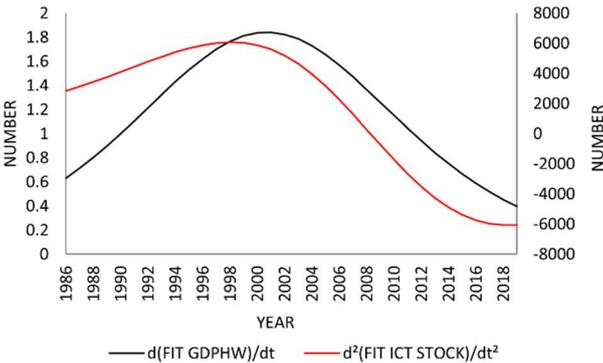


Fig. 9. Estimated growth rates of production [$d(\text{FIT GDPHW})/dt$] and innovative investment in ICTs [$d^2(\text{FIT ICTS STOCK})/dt^2$].

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 ICTs (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 ICTs 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 ICTs performances. Gordon (2012, 2013), instead, considers the decline of the ICTs 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. Gordon also argues that the ICTs revolution, by delivering only 8 years of relatively low growth, has had a much lower economic impact than the second revolution, marked by important innovations that can only be invented once. On this basis, the scholar prognosticates the end of major technological revolutions.

Bergeaud et al. (2016) and Cette (2014) confirm that the ICTs productivity wave may have been smaller and shorter than the previous one, but remain open to the possibility of a second ICTs wave, pushed by future major ICTs improvements. According to Perez (2013), the 2007-08 crisis may mark, if accompanied by effective policies, the beginning of the high growth phase of the ICTs paradigm, based on the combination between ICTs and environmental technologies. A similar position is present in Tylecote (2019), which, nevertheless points to the combination between ICTs and biotechnologies. 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 ICTs revolution, or as the declining phase of the ICTs 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 ICTs decline, if confirmed,

should provide incentive for the emergence of a new technological revolution. Our analysis also seems to confirm that the expansive phase engendered by ICTs has been relatively short.

5. Conclusions

The study of the forces that determine long-term fluctuations in economic activity is important for better understanding and orienting the long-term pattern of economic development. In this paper, we propose a framework in which the economic system tends to generate endogenously technological revolutions, structural change and growth waves. This tendency is explained through a process of co-evolution between investments in innovation and demand, based on multiplier and accelerator feedback effects: the productivity gains generated by investments in innovation over the technological cycle produce a surplus income that drives demand growth, while adaptive expectations on demand growth push investments in innovation. These feedback effects generate a succession of cumulative upward and downward spirals that would allow explaining why radically new technologies and associated industries recurrently emerge and dramatically transform the economy. In the upward spiral, technological change positively acts on firms' profit expectations and confidence, stabilizing investment. In the downward spiral, technological change undermines business confidence, destabilizing investment in predominant technologies and providing incentive, for a minority of new firms, to invest in radically new technologies and sectors, which will eventually generate a new growth wave. In this perspective, the economic system would tend to grow in a cyclical way. However, we also propose that a variety of exogenous factors, including random historical events (e.g., wars, financial crisis, international factors, demographic dynamics, etc.), technical factors, socio-institutional variables and public policies, have a major impact upon this cyclical behavior by influencing the length and amplitude of fluctuations, that is, the duration and intensity of expansive and recessive phases.

The proposed framework provides the following contributions to long waves literature (Schumpeter 1939, Mensch 1979, Clark et al. 1981, Freeman and Perez 1988, Perez 2010, Perez 2013). First, to our knowledge, it represents the first attempt to integrate in the same framework endogenous and exogenous factors. In this context, technological revolutions, structural change and growth waves are endogenous, and therefore recurrent, but exogenous factors play an important role in determining their timing, as well as their economic and social impact. This implies that 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 periods of slow growth may be long-lasting. The role assigned to exogenous factors would also allow explaining why growth waves do not display fixed length and amplitude, that is, why technological revolutions and growth waves are not regular.

Second, following recent studies (Dosi et al. 2010, Saviotti and Pyka 2012, 2013, Caiani et al. 2014), we combine Schumpeterian analyses of innovation dynamics with the multiplier and accelerator effects coming from Keynesian theories. This allows taking into account, in a long waves perspective, both the impact of demand on innovation and vice versa. 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. In this context, the co-evolution between innovation and

demand is the main endogenous mechanism that generates not only structural change and long-run economic development, but also technological revolutions and long-run fluctuations of growth.

Third, 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 co-evolutionary process between innovation and demand, the behavior of this minority of firms may create a new technological ferment and stimulate a new growth wave. This represents a microfounded endogenous mechanism that would explain technological revolutions, structural change and growth waves on the basis of firms' decision to invest in radical versus established technologies, a decision that has received little attention by the recent literature. This mechanism also contributes to explain how small gradual changes (the technological ferment introduced by a minority of firms) become radical aggregate changes as time goes by and why technological revolutions involve at first the erosion of incumbents' advantage and, later on, their replacement by new actors.

In order to provide a preliminary empirical evidence supporting the proposed framework, we have fitted the ICTs cycle and the economic cycle to patent and productivity data, respectively. Although the results of this analysis should be taken with caution (see section 4), they provide evidence for the existence of a cyclical (S-shaped) development pattern of ICTs and for associated fluctuations of productivity. 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. The results of the empirical analysis also indicate that the growth rate of innovative investment in ICTs has slackened since the early 2000s, before the 2008 crisis. This suggests that the growth potential of ICTs may be declining, as already highlighted by other studies (Gordon 2012, 2013, Cettè 2014, Bergeaud et al. 2016), although, because of the limitations of our methodology, we cannot exclude a second wave of ICTs-related innovations. According to our framework, the ICTs decline, if confirmed, should provide incentive for the emergence of a new cluster of radical technologies and its associated growth wave. In fact, as mentioned in section 1, there is some evidence that a number of potential radical technologies are emerging (Schwab 2017, OECD 2017) and some studies have highlighted an increased dynamism of new firms after the 2008 crisis (Archibugi et al. 2013a, 2013b).

Overall, this analysis suggests that the 2000s productivity slowdown may be a signal that the economic system needs to change its leading technologies and that we are experiencing a phase of technological ferment, which could lead to a new technological revolution. However, our study also highlights that changes of leading technologies may require a long time and periods of slow growth may prolong if favorable exogenous factors, and in particular public policies, do not intervene in this process. In fact, in the proposed framework, public policies are one of the major exogenous factors that may influence long-run fluctuations. As discussed in section 3.2, public policies are responsible for both the overall level of investment in innovation over the cycle and, most importantly, for the directions of change that investment in innovation takes. Hence, policies should take into account more explicitly the long-term pattern of economic development and should envisage different types of interventions accordingly. This is particularly important during the phases of change of leading technologies, when the technological problems and the cognitive framework of the future paradigm are defined through a complex process involving competition among different core technologies, visions, economic and political interests. The result of this process may have a profound impact on future directions of technological, economic and social change. Therefore, the current phase may represent an important and rare opportunity, for public policies and socio-institutional actors, to orient

future development toward socially desirable directions through active technology orientation policies.

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, to actively involve socio-institutional actors and to democratize the process of selection of the technologies to support. As an emerging debate on the dark side of innovation is bringing to light, there are probably some directions of technological change that should be avoided. On the other side, some socially desirable directions of change are now clear and relate to the most serious problem created by economic growth, namely environmental pollution and climate change. In that perspective, 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 a potential new revolution, again slowing down both sustainability transition and economic recovery.

To conclude, this work has tried to provide a better understanding of the forces that determine technological revolutions, structural change and growth waves. Though this study has several limitations and our conclusions are tentative, the proposed framework may represent both a basis for more sophisticated empirical analyses, and a groundwork for developing formal microfounded models that simulate the impact of endogenous and exogenous factors.

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References

- Anderson, P., Tushman, M. L., 1990. Technological discontinuities and dominant designs: a cyclical model of technological change. *Administrative Science Quarterly*, 35, 604-633.
- Archibugi, D., 2017. Blade Runner economics: Will innovation lead the economic recovery?. *Research Policy*, 46, 535–543

- Archibugi, D., Filippetti, A., Frenz, M., 2013a. The impact of the economic crisis on innovation: Evidence from Europe. *Technological Forecasting & Social Change*, 80, 1247–1260
- Archibugi, D., Filippetti, A., Frenz, M., 2013b. Economic crisis and innovation: Is destruction prevailing over accumulation?. *Research Policy*, 42, 303– 314
- Basu, S., Fernald, J. G., Shapiro M. G., 2001. Productivity growth in the 1990s: Technology, utilization, or adjustment?. *Carnegie-Rochester Conference Series on Public Policy*, 55, 117-65.
- Baxter, M., Kouparitsas, M. A., 2005. Determinants of business cycle comovement: a robust analysis. *Journal of Monetary Economics*, January, 52(1), 113-157.
- Bergeaud, A., Cette G., Lecat R., 2016. Productivity trends from 1890 to 2012 in advanced countries. *Review of Income and Wealth*, 62(3), 420–444
- Breschi, S., Malerba, F., Orsenigo, L., 2000. Technological regimes and Schumpeterian patterns of innovation. *The Economic Journal*, 110, 388–410.
- Byrne D. M., Oliner S. D., Sichel D. E., 2013. Is the information technology revolution over?. *International Productivity Monitor*, no 25, Spring, 20-36.
- Caiani A., Godin A., Lucarelli S., 2014. Innovation and finance: a stock flow consistent analysis of great surges of development. *Journal Evolutionary Economics*, 24:421–448.
- Cette G., 2014. Presidential Conference. Does ICT remain a powerful engine of growth?. *Revue d'économie politique*, 124, 473-492.
- Cette, G., Clerc C., Bresson L., 2015. Contribution of ICT Diffusion to Labour Productivity Growth: The United States, Canada, the Eurozone, and the United Kingdom, 1970-2013. *International productivity monitor*, n°28, Spring.
- Christensen, C.M., 1997. *The innovator's dilemma: when new technologies cause great firms to fail*. Harvard Business School Press, Boston, Massachusetts.
- Clark, J., Freeman, C., Soete, L., 1981. Long waves, inventions, and innovations. *Futures*, 13 (4), 308-322.
- Coffano, M., Tarasconi, G., 2014. CRIOS-Patstat Database: Sources, Contents and Access Rules (February 1, 2014). Center for Research on Innovation, Organization and Strategy, CRIOS Working Paper n.1. Available at SSRN: <http://ssrn.com/abstract=2404344>
- Crafts, N. F. R., 1995. Exogenous or Endogenous Growth? The Industrial Revolution Reconsidered. *The Journal of Economic History*, 55 (4), 745-772.
- David P., A., 1990. The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox. *The American Economic Review*, 80 (2), 355-361.
- David, P. A., 2001. Path Dependence, Its Critics and the Quest for 'Historical Economics'. In Garrouste, P., Ioannides, S., (eds.). *Evolution and Path Dependence in Economic Ideas: Past and Present*. Edward Elgar, Cheltenham.
- Dosi, G., 1982. Technological paradigms and technological trajectories. *Research Policy* 11, 147–162.

- Dosi, G., Fagiolo, G., Roventini, A., 2010. Schumpeter Meeting Keynes: A Policy-Friendly Model of Endogenous Growth and Business Cycles. *Journal of Economic Dynamics and Control*, 34 (9), 1748-1767.
- Dosi, G., and Virgillito, M. E., 2019. Whither the evolution of the contemporary social fabric? New technologies and old socio-economic trends. *LEM Papers Series 2019/02*.
- Freeman, C., Perez, C., 1988. Structural Crises of Adjustment, Business Cycles and Investment Behaviour, in G., Dosi et al. (eds.), *Technical Change and Economic Theory*, Francis Pinter, London, 38-66.
- Gordon, R. J., 2012. Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds. *NBER Working Papers 18315*, National Bureau of Economic Research, Inc.
- Gordon, R. J., 2013. US productivity Growth: The Slowdown has returned after a temporary revival. *International Productivity Monitor*, Centre for the Study of Living Standards, 25, 13-19.
- Griliches, Z., 1957. Hybrid corn: an exploration in the economics of technological change. *Econometrica*, 25(4), 501-522
- Jorgenson, D., 2001. Information technology and the US economy. *The American Economic Review*, 91 (1).
- Jorgenson, D., Ho M., Stiroh K., 2006. Potential Growth of the US Economy: Will the Productivity Resurgence Continue?. *Business Economy*, January.
- Kemp, R., Schot, J., Hoogma, R., 1998. Regime shift to sustainability through process of niche formation: the approach of strategic niche management. *Technology Analysis & Strategic Management*, 10 (2), 175–195.
- Kleinknecht, A., 1990. Are there Schumpeterian waves of innovation?. *Cambridge Journal of Economics*, 14, 81–92.
- Kleinknecht, A., van der Panne, G., 2006. Who was right? Kuznets in 1930 or Schumpeter in 1939?. in T.C. Devezas (ed.), *Kondratieff waves, warfare and World security*, Amsterdam: IOS Press, 2006, 118-125.
- Kondratieff, N.D., 1935. The long waves in economic life. *Review of Economics and Statistics*, 17 (6), 105–115.
- Konstantakis, P. G., Michaelides K. N., 2017. Does technology cause business cycles in the USA? A Schumpeter-inspired approach. *Structural Change and Economic Dynamics*, 43, 15-26.
- Korotayev, A., Zinkina, J., Bogevolnov, J., 2011. Kondratieff waves in global invention activity (1900–2008). *Technological Forecasting & Social Change*, 78, 1280–1284
- Kuznets, S.S., 1930. *Secular movements in production and prices. Their nature and their bearing upon cyclical fluctuations*. Houghton Mifflin, The Riverside Press, Boston; 1967 reprint: Kelley, New York.
- Lee, M., Yun, J.J., Pyka, A., Won, D., Kodama, F., Schiuma, G., Park, H., Jeon, J., Park, K., Jung, K., Yan, M.-R., Lee, S., Zhao, X.. 2018. How to Respond to the Fourth Industrial Revolution, or the Second Information Technology Revolution? Dynamic New Combinations between Technology, Market, and Society through Open Innovation. *Journal of Open Innovation: Technology, Market and Complexity*, 4: 21.

- Lundvall, B., 2017. Is there a technological fix for the current global stagnation? A response to Daniele Archibugi, *Blade Runner economics: Will innovation lead the economic recovery?*. *Research Policy*, 46, 544–549
- Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. *Research Policy*, 41, 955–967.
- Mensch, G., 1979. *Stalemate in technology – innovations overcome the depression*. Ballinger, New York.
- Mokyr, J., 1993. "Introduction: The New Economic History and the Industrial Revolution." In *The British Industrial Revolution: An Economic Perspective*, edited by Joel Mokyr, Oxford: Westview Press, 1993.
- Nelson, R. R., Winter, S. G., 1982. *An Evolutionary Theory of Economic Change*. The Belknap Press of Harvard University Press, Cambridge.
- OECD, 2015. *The Future of Productivity*. OECD Publishing, Paris.
- OECD, 2017. *The Next Production Revolution: Implications for Governments and Business*. Andersen, B., 1994. The hunt for S-shaped growth paths in technological innovation: a patent study. *Journal Evolutionary Economics*, 9 (4), 487-526.
- Perez, C., 2010. Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics*, 34, 185–202.
- Perez, C., 2013. Unleashing a golden age after the financial collapse: Drawing lessons from history. *Environmental Innovations and Societal Transitions*, 80 (1), 11–23.
- Pillai, U., 2011. Technological progress in the microprocessor industry. *Survey of Current Business*, February, 13-16.
- Rosenberg, N. and Frischtak, R., 1983. Long Waves and Economic Growth: A Critical Appraisal. *The American Economic Review*, 73 (2), 146-151.
- Saviotti, P.P. and Pyka, A., 2012. On the Co-Evolution of Innovation and Demand: Some Policy Implications. *Revue de L'OFCE / Debates and Policies*, 124, 347-388.
- Saviotti, P.P. and Pyka, A., 2013. The co-evolution of innovation, demand and growth. *Economics of Innovation and New Technology*, 22: 461-482.
- Schmookler, J., 1966. *Invention and Economic Growth*. Harvard University Press, Cambridge.
- Schumpeter, J. A., 1939. *Business Cycles. A Theoretical, Historical and Statistical Analysis of the Capitalist Process*. London: McGraw-Hill Book Co.
- Schwab, K., 2017. *The Fourth Industrial Revolution*. Crown Business, New York.
- Silverberg, G., 2002. The discrete charm of the bourgeoisie: quantum and continuous perspectives on innovation and growth. *Research Policy*, 31(8-9), 1275-1289.
- Silverberg, G., Lehnert, D., 1993. Long Waves and 'Evolutionary Chaos' in a Simple Schumpeterian Model of Embodied Technical Change. *Structural Change and Economic Dynamics*, 4, 9-37.
- Silverberg, G., Verspagen, B., 2003. Breaking the waves: a Poisson regression approach to Schumpeterian clustering of basic innovations. *Cambridge Journal of Economics*, 27, 671–693.

Solomou, S., 1986. Innovation clusters and Kondratieff long waves in economic growth. *Cambridge Journal of Economics*, 10, 101-112.

Steinmueller, W. E., 2017. Science fiction and innovation: A response. *Research Policy*, 46, 550–553

Tushman, M., Romanelli E., 1985. Organizational evolution: A metamorphosis model of convergence and reorientation. In: Cummings L.L., Barry M.S. (Eds.). *Research in Organizational Behavior*, 7: 171-222, Greenwich, JAI Press.

Tylecote, A., 2019. Biotechnology as a new techno-economic paradigm that will help drive the world economy and mitigate climate change. *Research Policy*, 48, 858–868

Utterback, J. M., Suarez, F., 1993. Innovation, competition, and industry structure. *Research Policy*, 22(1), 1-21.