Long Waves: Conceptual, Empirical and Modelling Issues

Gerald Silverberg

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MERIT – Maastricht Economic Research Institute on Innovation and Technology

PO Box 616
6200 MD Maastricht
The Netherlands
T: +31 43 3883875
F: +31 43 3884905

http://www.merit.unimaas.nl
e-mail:secr-merit@merit.unimaas.nl

International Institute of Infonomics

c/o Maastricht University
PO Box 616
6200 MD Maastricht
The Netherlands
T: +31 43 388 3875
F: +31 45 388 4905

http://www.infonomics.nl
e-mail: secr@infonomics.nl

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Gerald Silverberg

MERIT
Maastricht University

Email: Gerald.Silverberg@merit.unimaas.nl

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1 Introduction

The theory of long waves is exceptionally fortunate in that, while there is no general consensus that they exist or, assuming that they do, what an appropriate theory should be, due to the unstinting efforts of several researchers, we have encyclopaedic compendia of the literature (Freeman 1996, Reijnders and Louçã 1999) and a recent valiant attempt to write modern economic history from a long-wave perspective (Freeman and Louçã 2001). The purpose of this entry is to succinctly review the controversy about what long waves might mean as a phenomenon, how they might be measured and modelled, and where they might fit into an overarching theory of economic dynamics and evolution. The seminal work of Kondratieff (1925/1979) and Schumpeter (1939) of course will play a central role, but I will also draw on recent work in complex modelling, nonlinear dynamics and time-series econometrics to put the debate into a more contemporary perspective. As was frequently Schumpeter's fate, however, his name has become associated in the subsequent literature with various hypotheses that he never made in the form they were later expressed, and, to judge by what he did write, to which he almost certainly did not subscribe. Nevertheless, Schumpeter's basic ideas about the central importance of the innovation process and its disequilibrim character, the role of the entrepreneur or the large, bureaucratic R&D-based firm, creative destruction as the driving force behind structural change, and aggregate fluctuations at different time scales as inseparable features of the capitalist process of development, have all become basic tenets of the neo-Schumpeterian research paradigm in economics.

The most agnostic approach to long waves is to simply regard them as a discernable but otherwise inexplicable pattern in aggregate time series of real and price variables. By the end of the nineteenth and beginning of the twentieth centuries it was apparent, even given the inadequacy of the available data, that in addition to the long-surmised trade (Juglar) and inventory cycles (Kitchen) of two to ten year period, economies developed irregularly at even longer time scales (it was, prior to Kondratief, particularly Marxists such as Parvus, de Wolff and van Gelderen who were especially awake to such possibilities). It is probably only natural that observers would attempt to interpret this irregularity in terms of periodic or regular cycles, just as gamblers will attempt to read all sorts of regularities, including cyclical patterns, into the spin of a roulette wheel (which is not to deny that even roulette wheels may display subtle and exploitable regularities). Pattern, predictability, and causality, however, are very different things. A pattern in the past need never repeat itself in the future and need not imply that any specific mechanism is responsible for its occurrence and can be used for forecasting (think of a run of ten red 17s during an evening of roulette). Yet humans do seem to have a natural proclivity to attach deeper significance to perceived (or even) imagined patterns, a proclivity we can dignify with the name induction and perhaps even elevate to the basic urge underlying all scientific discovery. Nevertheless we must always be wary that we do no fall victim to a gambler's equally strong propensity for self-delusion, superstition, and even desire for metaphysical revelation. Only the control of statistical methodology, as inadequate as it often is, and critical reasoning can limit the excesses of this tendency. By the same token no hypothesis should be simply rejected out of hand just because it appears too neat and all-encompassing (think of the early opposition to Wegener's theory of continental drift, based as it was on the often remarked, all too neat fit of the east coast of South America into the west coast of Africa, or Kepler's theory of the Platonic solids as an explanation of the spacing of the planetary orbits). Such hypotheses, even when they prove mistaken, can often be fruitful inspirations for empirical and theoretical research. It is in this spirit that I will treat the long-wave hypothesis as a source of a number of useful conjectures and, even if untenable or untestable in its original formulation, as amenable to a modern interpretation with important empirical implications.

Kondratief was the first modern econometrician to attempt to identify long waves from the data. Kondratief, however, did not content himself with just this numerical exercise, as pathbreaking as it was, but went on to outline a general cyclical theory that is especially impressive for the range of phenomena it attempts to endogenize. These include gold discoveries, inventions, wars, and particularly investment cycles in infrastructure. Phenomena that conventionally had been assumed exogenous to the economic system, he argued, were actually components of a larger feedback process, a process in some respect even more cogent and encompassing than the one Marx had sketched[1].

This tendency to imbue the at first sight purely numerical observation of long-term fluctuations in some time series with systemic significance is characteristic on the one hand, in a more limited domain, of Schumpeter's conceptual scheme (singling out innovations for pride of place in a more strictly economic context) and, on the other, of a number of scholars coming from a political science background. The latter have attempted to wed political and economic considerations into a world systems-level theory of hegemonic or leadership cycles (Modelski 1987, Goldstein 1988, Modelski and Thompson 1996) in which warfare and patterns of international trade and capital flows play the crucial role[2], or have focussed on long-term changes in the distribution of income and the nature of collective bargaining in a theory of the 'social structures of accumulation' or 'regulation' (Gordon 1989, Boyer 1988). While these 'non-Schumpeterian' long-wave theories will not be examined further here, they do highlight the need to embed purely economic considerations into a wider social, political, and even cultural context. This is one of the themes of Freeman and Louçã (2001), drawing on the work of Perez (1983) and Freeman and Perez (1988), who argue that the diffusion of new technologies is conditioned on a proper match between the new techno-economic system and appropriate institutions, legal frameworks, labour relations, and cultural attitudes, and that these might only adapt with considerable delay and in a somewhat discontinuous manner.[3] Nevertheless one has the impression that this interplay between the social and the technoeconomic is almost always decided in favour of the latter, with the social merely serving as a passive retarding factor which periodically breaks down in the face of the technological onslaught and ultimately adjusts to the inevitable.

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[1] Kondratief himself was not a Marxist and confronted intense criticism from Trotsky and Oparin for what they took to be a fatal ideological challenge to Marx' theory of the inevitable final crisis of capitalism His incarceration and execution under Stalin, it is now believed, is due less to his theory of long waves than his advocacy of the priority of agriculture and a market framework in Soviet economic planning.

[2] But see Kindleberger (1999) for a more sceptical view of the plausibility of these theories, despite the impressive array of disparate phenomena these authors have combined in their arguments.

[3] In some sense Perez's theory of social mismatch is reminiscent in the small of Marx' opposition of material substructure (residing primarily in technology) and socio-political superstructure, requiring revolution to reconcile the two at a higher historical stage of development. Having long waves accomplish this rematching makes the process both less revolutionary and more frequent.

Freeman and Louçã find the evidence for their vision of long waves in both the econometric and the modelling literature unsatisfactory and resort to a version of long waves somewhat between a mere dating scheme (comparable to the anthropologist's classification of human cultural evolution based on old and new stone ages, bronze age, iron age, etc.) and Angus Maddison's (1991), a pronounced sceptic on the subject of long waves, individual reading of phases of capitalist development in terms of historical factors unique to each phase. They differ from Maddison in their emphasis on the recurrent character of these phases (thus attributing to them the property of cycles or waves) based on the same underlying mechanism, even if the phases are by no means strictly regular or periodic (or at least cannot be shown to be so given the current state of the art).[4] While their attempt to integrate the Perez mismatch theory is original, in other respects their narrative of capitalist economic history, aside from being brought up to date, does not differ significantly from that of Schumpeter (in fact, the latter is in many respects much more detailed). What stands out, however, in the Schumpeterian tradition is the endeavour to provide a fully causal explanation of long-term economic fluctuations that synthesizes historically significant stochastic elements (dateable Schumpeterian innovations, as opposed to the unidentified random 'innovations' of conventional econometric modelling) with deterministic ones, in a nontrivial way.

2 The Identification of Long Waves: Theory-Free Econometrics?

The question of our ability to discern long-run patterns in the record of aggregate economic time series turns out to be more fraught with technical difficulties than one would at first imagine. This line of research was initiated by Kondratief (1925/1935/1979), who was one of the first to apply modern methods of trend elimination and residual analysis to a large number of price and output series. As we shall see, even with the enormous advance of econometric methods since his day, this problem still cannot be satisfactorily resolved, quite aside from the question of the quality of the data and the shortness of the series.

The main reason for the difficulty is the fact that most long-period time series, such as for GDP, GDP per capita, and even for prices, are not stationary, as is obviously the case for any growth process. An alternative would be to use series that do not a priori contain a trend, such as unemployment rates, income shares, and possibly profit rates (although the Marxist prior on the latter is for a falling trend). Unfortunately, it is even more difficult to consistently define and compile these variables over such long periods than the usual ones, so very little serious work has been done with them. Trend variables must first have the trend removed in the Kondratief approach before looking for cyclical patterns in the residuals. But without a convincing argument for a particular trend form, one can produce almost any long-period cycle one wishes by using, e.g., higher-order polynomial trends. This critique was already levelled at Kondratief by Frickey 1942 among others.

Periodogram or spectral analysis, whose application in economics dates back to at least Beveridge (1922) and with which Schumpeter was thoroughly familiar and not

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[4] In this they accord with other modern works in the Kondratief revival, such as van Duijn (1983), Berry (1991), Tylecote (1992, 1994). While Berry falls victim to the moving average's well-known ability to generate cycles of arbitrary period by repeated application (the Slutzky effect), Tylecote displays extreme virtuosity in explaining departures from the a priori scheme with ad hoc reasoning.

even unsympathetic despite negative results[5], unfortunately did not belong to Kondratief's toolbox. But it is the main tool for detecting cycles in time-series statistics. Unfortunately it is only really defined for stationary series (see Brockwell and Davis 1987) and does not lend itself to statistical hypothesis testing with well-defined confidence intervals. When applied to nonstationary series, the trend will show up in the low-frequency region and be inseparable from any low-frequency (i.e., long-period) cycles. Thus one is again forced to use a detrending or other procedure to make the series stationary. One method intrinsically related to spectral analysis is to use a digital filer (see Metz 1987, 1992) to eliminate frequencies below those of interest without distorting the rest of the spectral signature. While this method finesses the question of defining a trend, the trend, however defined, may also induce spectral energy in the relevant range and thus contaminate the result. And in fact the method has not proven robust to changes in the range of the data used or to the setting of the cutoffs.

Another standard method for making economic series stationary is to take first differences (usually of the log of the series, thus approximating the growth rate). What was originally a completely 'agnostic' numerical method to make a series stationary has acquired an exaggerated statistical meaning since the so-called unit root debate arose about the fundamental distinction between trend and difference stationarity (Nelson and Plosser 1982) as fundamentally different macroeconomic paradigms in (mostly short-period) business cycle econometrics. While the knife-edge sharpness of this distinction has proven to be less clear-cut in finite datasets than originally thought, first differencing sidesteps the spurious cycle problem of trend-elimination exercises and has become standard in time-series econometrics.

Modern spectral studies of long waves include Ewijk (1982), Haustein and Neuwirth (1982), Metz (1987, 1992), and Reijnders (1990), but as noted above, the technique was already current in Schumpeter's day. An alternative method has recently been proposed by Goldstein (1999), who has applied structural time series modelling to combine deterministic and stochastic trends and, much like Schumpeter, cycles of three different periods, to a multicountry panel to argue for the existence and synchrony of long waves. Whether this methodology will stand the test of time remains to be seen.

However, spectral analysis has not provided very convincing evidence of long waves (or any other distinctive cyclical period for that matter) until now. Partly of course this is due to the fact that the data must span at least one complete cycle, or better several, so that the identification of 50-year cycles requires at least 100-200 years of annual data. But partly this may be the result of a phenomenon already noted by Granger (1966): the spectra of economic time series display a typical more or less smooth shape, declining from low to high frequencies without any pronounced peaks. Spectra with this distributed shape without evidence of individual characteristic frequencies imply that the time series display cycles of all periods and cannot be thought of as strictly periodic or the sum of a small number of individual frequencies[6].

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[5] Schumpeter (1939, p. 166fn) on periodograms: "The result of the experiment [Ayres 1934] was ... negative and presents many discouraging features ... for instance, considerable differences between the shapes of the periodogram for various subperiods and between each of them and the periodogram for the entire period. ... It might, therefore, be asked why the writer, thinking thus and, moreover, entirely unwilling to abide by the results the analysis gives, nevertheless attaches importance to periodograms. The answer is simply that they render service in exploring the material, even if results are negative or untrustworthy: some of our problems might be stated in terms of the periodograms we get."

[6] Perhaps surprisingly, this does not at all contradict Schumpeter's own expectations, despite the received interpretation of his work. Thus: "...there is nothing in the working of our model to point to

Finite time series of this type subject to random noise will display some individual peaks around the distributed envelop, but these may simply be random epiphenomenon not reproducible from other data and not due to any robust underlying mechanism. Since spectral analysis does not provide any means of hypothesis testing, only peaks standing out by an order of magnitude or more, and invariant to standard methods of detrending (such as removal of an exponential trend or first differencing) can really be taken seriously as indications of periodic components. One can conjecture that reported confirmations of Kondratief and Kuznets cycles have only been overinterpretations of the noise component of continuously distributed spectra. Thus the project of classical time-series analysis may fail in this case, but the door opens to a much wider class of interesting mechanisms which has formed the object of attention since the 1960s, such as long memory, fractional Brownian motion, chaos, Levy walks and the like[7]. The key difference between these time-series models and classical ones is the existence of long fluctuations at any scale, with no privileged time unit. It may be that only the limits of our data impose a long wave model of 50-year or any other length. Presumably, if we had significantly longer data series (on the assumption that the underlying mechanism remained unchanged for such long periods of time) we would find long waves of arbitrarily long period, or at least longer than 50-years, the upper limit of our current resolving power. The hegemony cycle literature even posits a 150-year cycle. Thus the historical obsession with finding a 50-year cycle may be blinding researchers to a much richer range of phenomenon of equal or even superior theoretical interest.

3 Schumpeter's Conceptual Framework: Clustering of Innovations

It will not be necessary to recapitulate Schumpeter's model of economic development in any detail here except to identify those features that have stimulated an active programme of research since the publication of his seminal works (Schumpeter 1919, 1939, Schumpeter 1947). As is the case with many other 'classical' authors, debates have been sparked by conjectures attributed to Schumpeter that cannot really be found in his writings and to which it is even highly unlikely he would have subscribed. Such

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periodicity in the cyclical process of economic evolution if that term is taken to mean a constant period ... All we can thus far say about the duration of the units of that process and of each of their two phases [prosperity and depression] is that it will depend on the nature of the particular innovation that carry a given cycle, the actual structure of the industrial organism that responds to them, and the financial conditions and habits prevailing in the business community in each case. But that is enough and it seems entirely unjustified to deny the existence of a phenomenon because it fails to conforms to certain arbitrary standards of regularity". (p. 143) And: "...there is a theoretically indefinite number of fluctuations present in our material at any time, the word *present* meaning that there are real factors at work to produce them and *not merely that the material may be decomposed into them by formal methods...*". (p. 168) Further: "...it cannot be emphasized too strongly that the three-cycle schema does not follow from our model - although multiplicity of cycles does." (p. 169) While this agnosticism appears to make Schumpeter a much more modern thinker than his epigones were prepared to give him credit for, it remains unclear what Schumpeter was then concretely predicting as evidence of his model, thereby making himself possibly unfalsifiable in the Popperian sense. In practice he merrily proceeded to apply the three-cycle model without compunction in the rest of his *Business Cycles* despite these disclaimers about its intrinsic irrelevance.

[7] I cannot go into any detail on this question here. Suffice it to refer to Silverberg and Lehnert (1996), Michelacci and Zafaroni (2000) and Silverberg and Verspagen (2003c) for some examples.

is the case with the ‘clustering of innovations’ hypothesis, which claims something like the statement that major innovations occur in clusters with an approximate fifty year spacing (see Silverberg and Verspagen 2003a for a number of alternative formulations of this hypothesis that are amenable to statistical testing). Schumpeter distinguishes between radical and incremental innovations (without by any means downgrading the importance of the latter – see e.g. his discussion of the motorcar industry). Radical innovations in particular may open up new industrial sectors and lead to a rapid expansion of new demand. While a radical innovation may trigger a swarm of imitators (as well as improvements and ‘collateral’ innovations) in the Schumpeterian framework, this is by no means equivalent to the statement that unrelated radical innovations tend to cluster in time, the hypothesis that has actually been tested in the literature. And for a radical innovation to trigger a long wave of economic activity (in whatever sense of the term we choose to formalize this), Schumpeter nowhere insists that it be part of a cluster of such innovations, only that it be radical enough in itself. That no innovation stands alone and in isolation historically from a web of others is a truism, but this is a different hypothesis than the clustering one. Perhaps a better formulation is that of Perez (1983), who speaks of interrelated technological systems rather than isolated innovations, as the technological substrate of long waves (e.g. the complex of AC and DC electrical innovations between the 1870s and 1900, or the electronic revolution of the late 1930s to the 1970s based on valves, transistors, and integrated circuits). Thus it is a curious fact of the sociology of science that one of the principal consequences of Schumpeter’s work is that a not insubstantial literature arose concerned with the questions of clustering per se[8].

This body of research is generally thought to have been initiated by Mensch (1975, English translation 1979), but a largely overlooked paper by Sahal (1974) both predates it and is methodologically superior to most of the work that followed (although it employed rather short time series and thus is not of much relevance to the long-wave debate). Aside from deciding what the correct hypothesis to be tested is, there are two main stumbling blocks in this literature. First, it is not as simple a matter as it seems to assemble a list of radical innovations with their dates, and the associated time series to represent the ‘intensity’ of innovative activity. There is no obvious objective way of identifying the innovations (expert opinion was mostly used), and dating is often highly controversial and ambiguous. And simply counting them on an annual basis is also not clearly the right way to weigh them. Thus Clark, Freeman and Soete (1981) and Freeman, Clark and Soete (1982) take Mensch seriously to task for relying (and then somewhat arbitrarily) on the data from Jewkes, Sawers and Stillerman (1958), which was neither meant to be a representative sample nor focuses so much on innovation as invention. Kleinknecht (1990a, b) combines several datasets with multicounting of innovations found in several sources as an implicit but rather arbitrary weighting scheme, while Silverberg and Verspagen (2003a) only count these innovations once in their combined sample and consistently use the earliest dating.

What many authors (with the exception of Sahal) did not explicitly realize is that the null hypothesis of a stochastic count process with no clustering is a (time-homogeneous or inhomogeneous) Poisson process. This does not mar Mensch’s work since he used a runs test of identical and independent distribution, but it is fatal to the methodology of Kleinknecht and Solomou (1986), who used *t*- und *z*-tests of

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[8] This is quite parallel to that other great ‘Schumpeterian’ conjecture concerning the supposed positive relationship between concentration, size and R&D intensity implied in Schumpeter (1947). See Cohen and Levin (1989).

normality. Moreover, the very apparent time trend must also be taken into account, which will seriously affect all of the longer data series. Finally, the procedure of decomposing the time series into subperiods (usually based on some dating of long waves with a lag) also employed by Kleinknecht and Solomou further invalidates their work since it may implicitly be selecting for random periods of above and below-average activity, as Silverberg and Lehnert (1993) argue. An alternative is represented by the nonparametric Poisson tests proposed by the latter authors, who show that an exponential time trend of the Poisson arrival rate is highly significant, with a growth rate of between ½ and 1% p.a., depending on the series. But even after conditioning on the trend with an appropriate detrending method, the series are still characterized by significant if much lower overdispersion (variance higher than the mean), indicating some form of residual clustering.

To investigate this issue further Silverberg and Verspagen (2003a) employ Poisson regression techniques, which allow both the fitting of more complicated deterministic trends and accounting for the overdispersion by making use of a negative binomial model. This model allows for clustering, but due to a purely random mechanism superimposed on the original Poisson model. They show that a second-order polynomial, negative binomial model is significantly preferred to a pure Poisson model of the same or higher order, indicating that both the trend is more complex and that real clustering occurs. Further tests of periodicity of the clustering and clustering persistence were all negative, indicating that while clustering certainly occurs, it seems to be purely random and not explicable in terms of a predictable time dependence or due to ‘knock-on’ effects. This is quite a different interpretation of the ‘Schumpeterian’ clustering hypothesis that does not conform with any of the naïve views (to the extent that they can be formalized) of how clustering occurs. Nevertheless it may be consistent with a much more ‘complex-systems’ understanding of the long-wave phenomenon, and with the empirical record, once we give up an obsession with discovering periodicities.

One interpretation of clustering in terms of purely economic considerations is Mensch’s (1975/1979) ‘depression-trigger’ hypothesis. Mensch shows that inventions are more randomly distributed than innovations, and argues that the latter are deliberately neglected in good times when entrepreneurs can continue to profitably exploit existing technologies and are only, and then perhaps even reluctantly, further developed to operational levels and adopted in bad times when falling profit rates leave them with no alternative. This would seem to fly in the face of Schmookler’s (1966) hypothesis that innovative activity seems to follow demand growth. This contradiction may perhaps be reconciled by observing that Mensch is dealing with radical innovations while Schmookler, relying on patent data, is clearly concerned with incremental ones.

The complex relationship between economic activity and innovation again came to the fore in the 1970s and 80s in the ‘productivity slowdown’ controversy initiated by Solow, who observed that the purported microelectronics and computer revolutions coincided in time with a pronounced long-term decline in productivity growth. Quite aside from such specific factors as the oil crisis, Silverberg and Lehnert (1993) show that the contemporaneous cross-correlation between a (trailing) measure of innovative activity and aggregate productivity growth is essentially zero, even though the former is an excellent predictor of the latter, but only after a time interval of 20-30 years. And causality, at least in their model, is exclusively from innovation to macroeconomics, and not vice versa. This lag should not be surprising, since innovations only impact on the economy once they have really begun to diffuse (in fact, their maximum impact is when diffusion has gone precisely halfway for a logistic process), and this can take a considerable amount of time, as diffusion research has confirmed time and again. Models that do not take diffusion realistically into account and posit a near instantaneous relationship will always miss this point. Appealing to an analogy with the economic history of electrification, David (1991) also argues that the productivity implications of computers will not show up in aggregate statistics for many years. The productivity growth revival of the 1990s has perhaps already borne this out.

One way of modelling the innovation process that seems to generate exactly this kind of result has been proposed by Silverberg (2002) and explored theoretically and empirically by Silverberg and Verspagen (2002, Silverberg and Verspagen 2003b). Invoking percolation theory to represent a multidimensional technology space, this model shows how clustering can occur naturally both in the temporal and 'technospatial' domains without any explicit recourse to a long-wave argument. Clustering is shown to increase with the 'radicality' of the innovation measure, consistent with the relative smoothness of patent indicators and the extreme jumpiness and lumpiness of radical innovation time series. It also produces the highly skewed and possibly scale-free distributions of innovation sizes and returns that can be found in the data (see e.g. Scherer, Harhoff and Kukies 2000), as well as 'technological trajectories' (Dosi 1982). Thus we are now intellectually in a position to begin to transcend the dichotomy between radical and incremental innovations and realize that innovations come in a (possibly fractal) continuum of sizes and are interdependent in complex ways. A simple growth model that directly translates this Paretian distribution of innovation sizes into fluctuating growth rates is Sornette and Zajdenweber (1999).

4 Schumpeter's Conceptual Framework: Leading Sectors and Creative Destruction

Schumpeter's evolutionary model is multisectoral, driven by profit disequilibria, and associated with new technology diffusion. Very few studies, either empirical or theoretical, have managed to combine all three elements. True multisectoral models have relied on input-output analysis, but it is very difficult to do so outside of an equilibrium setting either in the structural (balanced growth) or the macroeconomic (market clearing) senses. Thus Pasinetti (1981) analyses sectoral structural change (the weights of different sectors in the economy change systematically over time due to both demand and supply factors), but in such a way that full employment is always maintained and no technology diffusion or creative destruction is evident[9]. Nelson and Winter (1982) analyse a disequilibrium evolutionary model with multiple distinct (but disembodied) technologies and goods/labour market clearing, but only one final goods sector. Technologies diffuse through higher relative growth rates (due to profit rate disparities) and imitation, but nothing like aggregate long waves has been shown to emerge.

The technology diffusion literature has uncovered evidence of long-wave behaviour, particularly in the framework of the multiple replacement model (Nakicenovic 1987, Grübler 1991). Inspired by the original work of Fisher and Pry

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[9] But see Reati (1998) for an attempt to integrate major technological revolutions into the Pasinetti framework.

(1971), one can look at technology diffusion as a niche-filling exercise with successive technologies filling the (fixed) basic needs of the ‘econosphere’. By fitting logistic curves to the diffusion in market shares (or percent of saturation level attained), diffusion times and midpoints of the process for major technologies (particularly infrastructures such as transport and energy systems) can be calculated. These diffusion times are often of the order of 50 years, but particularly remarkable is the fact that the spacing between the diffusion curves is surprisingly regular and also around 50 years. This is especially true for infrastructures, while other technologies display much faster diffusion times and more irregular spacing between successive waves or generations.

Aside from the plausibility of these empirical regularities (which are reminiscent of Kondratief’s own emphasis on waves of infrastructure investment, although Kondratief did not emphasize the technological replacement aspect), this work highlights the role of investment in fixed capital and infrastructure and the corresponding creative destruction of old installed capacity in the generation of long waves. Thus in compiling a diffusion-based time series of innovation activity, Nakicenovic computes the first derivative of the diffusion curves (representing the rate of growth and replacement) rather than the date of introduction of the innovation to proxy its impact on the economy. This addresses the objection Kuznets (1940) raised to Schumpeter’s model that the stochastic nature of innovations and the widely varying rates of diffusion would obscure any long-wave pattern rather than reinforce it[10]. If some innovations, such as related to infrastructures (railroads, telephone networks, the Internet, oil and the internal combustion engine) are very widespread and pervasive, they can generate investment waves of such magnitude as to swamp the fluctuations due to other investment activity in the economy. In fact, they may even entrain synchronized waves of investment in other sectors (the motel/fast food/shopping centre/suburban tract housing complex with respect to cars, for example), a fact Schumpeter had also observed (pp. 166-7). But why these infrastructure replacement cycles should be characterized by 50-year periods is still a mystery.

For innovations to induce investment waves they need to be embodied in capital goods. While this observation seems self-evident, very few economic models have taken this seriously since a flirtation with vintage models in the 1960s (and then mostly in a steady-state growth framework). Exceptions with a disequilibrium, Schumpeterian flavour are Iwai (1984a, b, 2000), Nelson (1968), Silverberg (1984), Silverberg and Lehnert (1993, 1996), Silverberg and Verspagen (1994a, 1996), Soete and Turner (1984), Henkin and Polterovich (1991) and Franke (2001). The basic assumption of all of these models is that the rate of investment in a capital-embodied technology will be proportional to its profit rate, and thus its share in the total capital stock will obey replicator dynamics, a form of dynamical Darwinism and a natural representation of creative destruction. Additionally, when embedded in a macroeconomic framework, the induced investment effects derived from technological competition can have important multiplier effects that will influence the

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[10] Again, this is an objective Schumpeter seems to have anticipated without really refuting: "First, if innovations are at the root of cyclical fluctuations, these cannot be expected to form a single wavelike movement, because the periods of gestation and of absorption of effects by the economic system will not, in general, be equal for all innovations that are undertaken at any time. There will be innovations of relatively long span, and along with them others will be undertaken which run their course, on the back of the wave created by the former, in shorter periods. This at once suggests both multiplicity of fluctuations and the kind of interference between them which we are to expect.” (p. 166/7)

level of effective demand. Whether and what kinds of fluctuating aggregate patterns such mechanisms can produce is treated in the next section.

The neoclassical endogenous growth literature has also taken up the theme of creative destruction (Aghion and Howitt 1992, Cheng and Dinopoulos 1992a, 1996) in a somewhat different stylised fashion. Technologies are regarded as intermediate goods instead of capital goods, and using patent-race like arguments, a rational expectations intertemporal equilibrium can be derived for the level of R&D investment and the (stochastic) rate of economic growth. Thus even though individual innovators attain temporary monopolistic positions and earn the associated quasi-rents, the model is as hyperrational and general equilibrium as one might desire. Whether such an approach can really be regarded as a faithful formalization of the Schumpeterian vision can be debated, to say the least. But from a neoclassical perspective this has been a very fruitful leap of paradigm.

The neoclassical embrace of a distinct category of radical innovation has taken the form of the concept of “general-purposed technologies” (GPT) (Bresnahan and Trajtenberg 1995, Helpman 1998), albeit without specific reference to Schumpeter or the theory of long waves. Nevertheless, it has been invoked to explain the same class of phenomena, even if the models make rather ad hoc modifications to make room for it: long-term fluctuations in productivity growth correlated across sectors, temporary declines in productivity due to initial learning effects, leading sectors and intersectoral spillovers. On the latter issue Carlaw and Lipsey (2002) argue that new GPTs create technological externalities that cannot be captured with conventional total factor productivity indicators. Cheng and Dinopoulos (1992a, 1996) also distinguish between breakthrough and improvement innovations in their general-equilibrium model of Schumpeterian fluctuations.

From the perspective of economic history, W.W. Rostow’s (Rostow 1960) work has most strongly emphasized the essential role of leading sectors in economic development. Thompson 1990 has attempted to quantify the role of leading sectors in a time-series analysis. What is still missing in the historical approaches is an objective method to identify the leading sectors at various times and to dynamically measure their overall effects on the economy due to input-output linkages, technological spillovers, investment multipliers and the like.

5 Schumpeter’s Conceptual Framework: Macroeconomics and Aggregate Fluctuations

A number of long-wave models exist that are both purely aggregate in character and not really Schumpeterian, particularly in the sense of not admitting distinct technological innovations. Nevertheless I include them here because they elucidate mechanisms that could play a role in more properly Schumpeterian approaches. The first class derives from Jay Forrester’s National Model of the 1970s, best elucidated in Sterman (1985). These are nonlinear multiplier-accelerator models that lead to robust limit cycle attractors based on what they call the “capital self-ordering principle”: the central capital-goods sector must order equipment from itself to build up the necessary capacity to satisfy final demand, but since it cannot distinguish between this ‘bootstrapped’ demand and optimal investment except in a centrally planned economy (and even there, with the nonlinear capacity constraint, it is not a trivial optimisation problem to solve), it can enter into an unstable autocatalytic loop. While this observation is certainly true and important, the specific simplifying assumptions of the model probably exaggerate the magnitude of the effect, which would undoubtedly be radically changed anyway by the admission of true innovations. And the time-series distinctness of their limit cycle, both in terms of amplitude and frequency, would mean that were such a mechanism really at work, econometricians could not help but be overwhelmed by it in the data, regardless of their methodology (ergo it cannot be present in this form). A modification of the model in Sterman and Mosekilde (1994) shows that entrainment between short and long-period business cycle mechanisms leads to a more complex cyclical pattern. Goodwin (1987, 1990) also develops an aggregate nonlinear dynamic model based on a 'Roman fountain' formulation of the investment accelerator function that generates chaotic dynamics instead of strictly periodic behaviour. And chaos, it should be noted, will usually also have a distributed rather than a discrete spectrum, even if it has not been detected (as difficult as that is on short data sets) in empirical data on growth until now.

The neoclassical, general equilibrium models of creative destruction have aggregate cyclical properties that have not been studied in detail. In an R&D steady state, the Aghion and Howitt (1992) model produces a Poisson jumping process for aggregate productivity, certainly nothing anyone would seriously look for in the empirical record. Under certain circumstances they show that the R&D rate can converge to a two-period cycle (each phase of which is of stochastically determined length). These results, while intriguing, are artefacts of their assumptions that at any one time only one technology is employed in the entire economy (perhaps an overinterpretation of general purposeness) and that the transition between technologies is instantaneous. Nor do innovations have any investment repercussions, since they are considered to be mere intermediate goods that can always be produced with existing productive capacity once their 'blueprints' have been discovered by R&D firms.

Cheng and Dinopoulos (1992a, 1996) also derive fluctuating aggregate behaviour from their rather similar model of Schumpeterian innovative activity, due to the interacting effects of radical and improving innovations. Li (2001) is somewhat parallel in structure but identifies a different underlying mechanism - paradigm shifts due to scientific discoveries, with subsequent technological innovations within any such scientific paradigm subject to diminishing returns. The alternation between the two produces long-wave fluctuations, but of an as yet unspecified character.

Silverberg and Lehnert (1993, 1996) investigate in more detail the time-series properties of their model under the assumption that the innovation rate is constant[11]. Since innovations are then generated by a time-homogeneous Poisson process, they arrive unevenly but, in a strict statistic sense, do not cluster. Nevertheless they show that the model robustly generates significant spectral density in the 'Kondratief' range of 40-60 years without being in any sense strictly periodic. They then investigate whether a classical ARMA-type stochastic model or a nonlinear model provides a better explanation of the artificially generated time series. They produce quite convincing evidence in favour of the latter based on such modern methods as false nearest neighbours, the correlation dimension, Lyapunov exponents and nonlinear predictability. In fact, the high-dimensional dynamic system that generates the data

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[11] Recall that this model assumes that innovations are capital-embodied and that the relative rates of growth of their associated capital 'vintages' is proportional to their profit rates. A Philips-curve like wage mechanism ensures that, even without assuming labour market clearing, in the long run real wages track productivity growth even though they may fluctuate, as does employment, at different time scales.

can be shown to be reducible to an underlying dynamic involving only 2-4 principal variables. These results are robust with respect to changes in parameters and some modifications of model structure, such as allowing the innovation rate to react to changes in profits.

Silverberg and Verspagen (1994, 1996) take this model one step further by allowing the R&D rate to be determined endogenously as the result of an evolutionary learning mechanism. Individual firms use boundedly rational investment rules to determine the share of R&D in their investment portfolios and can experiment with small changes and imitate each other. The competitive dynamics leads to a convergence over the long term to an evolutionary growth 'steady state', but only after passing through a succession of R&D and industrial structure stages. While long waves are not the focus of these studies, they are still present just like in the original Silverberg and Lehnert studies even under these much more dynamic conditions. Thus long waves seem to be a very robust feature of this modelling approach, which one may consider to be a much more faithful formulation of Schumpeter's original vision even if still highly stylised. Franke (2001), by combining features of the Silverberg and Lehnert model with Iwai's very similar approach, shows in numerical experiments that the length of the cycles is related to the lifetimes of the capital stocks associated with each innovation.

6 Moral and Conclusions

There can be no doubt that long-period fluctuations take place in the world economy and it is no surprising that scholars have been attempting to make sense of them for almost a century. It is also not surprising that a cyclical hypothesis was the first to be seized upon. The idea that human fate is solely the plaything of purely random forces is probably too disturbing for most to stomach, and probably also not entirely true. Furthermore, the attempt to connect such long-period fluctuations with underlying mechanisms implicated in other aspects of economic life, such as innovation, technology diffusion, financial conditions and the competitive role of entrepreneurship, has fruitfully stimulated research into understanding the economy as a systemic whole governed by complicated feedback relationships.

Nevertheless, the search for Kondratief waves has sometimes taken on the character of a religious quest or a search for a holy grail, as if the existence of such waves had crucial implications for human salvation (quite aside from its erstwhile perceived challenge to a Marxist theory of crisis). A more sober perspective has also lead to the other extreme – not only a rejection of the hypothesis on hard-nosed econometric grounds, but an abhorrence of research in this area as if it were somehow tainted with a New Age or astrological cachet. Neither of these positions is justified, and neither is fruitful. In fact, both may have obscured a very rich terrain of research in which we do not merely proof or refute things we have always yearned for or abhorred, but we actually discover relationships we neither had any vested interests in nor at first could even conceive.

My personal position is that Schumpeter's model is basically correct: there is an important, perhaps even dominant, relationship between innovation, disequilibrium forms of competition, imitation, technology diffusion, the operation of financial markets, structural change, investment multipliers, and aggregate activity. Existing models have begun to connect these pieces of the puzzle together in a dynamic way, and they indicate they we may truly be dealing with what complex systems modellers call emergent phenomena. However, these models are still in a very primitive state and our empirical knowledge is also woefully inadequate. However, it is essential that we continue to seek the connection between such models and their expression at the level of statistically testable aggregate time series effects, the original thrust of Kondratief's work. It is not enough to say that there are no discernable patterns in the data and thus no longer worth studying, or that the statistical analysis is irrelevant to the question. It certainly was the case that Kondratief, Schumpeter and other proponents of long-wave theory believed that they could be detected in the data with appropriate techniques that would also stand up to technical criticism. To turn one's back on this issue is to retreat into metaphysics or relegate long-wave analysis to a sophistic form of the very legitimate kind of historical analysis practiced by Rostow, Kindleberger, Maddison, and Landes.

But it would also be tantamount to closing one's eyes to important scientific alternatives, such as that long waves are not to be found in strict periodicity but rather in complex distributed spectra that are often the hallmarks of interesting but nontrivial complex systems. Innovations may indeed cluster, but not in any deterministic sense, and their pattern may shed light on a unified mechanism explaining a range of their properties. Aggregate economic activity, simultaneously with certain patterns of structural change, may obey certain laws that dialectically intertwine chance and necessity and produce robust patterns, but ones that do not lend themselves to any very simple forecasting. It is on this note that I hope long waves will long be with us as a field of scientific research.

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