AN ALTERNATIVE, SIMPLE ECONOMIC LONG-WAVE MODEL

by

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Abstract

The simple two-sector Kondratieff model developed by John Sterman has contributed significantly to our understanding of some of the basic mechanisms underlying the economic long wave. The dynamic hypothesis of this model is that the positive feed-back associated with the so-called self-ordering of capital reinforces and prolongs the characteristic expansions and contractions of the capital sector as it adjusts its capacity to the required production. It is assumed that this feed-back can be strong enough to produce a self-sustained oscillation (a limit cycle) with a period which is about twice as long as usual capital lifetimes.

Concentrating on the ordering and production of capital, the Sterman model only depicts a relatively small fraction of our economic system. At least in its original version, the model doesn't deal with several of the basic phenomena involved in the verbal description of the economic long wave, as it is usually presented. There is no account of variations in employment, buying power or political attitudes, for instance, and changes in the rate of innovations are also outside the model boundary.

We do not think that one can presently develop a complete and satisfactory model of the economic long wave. We have therefore adopted an alternative starting point by assuming that the alternating phases of economic expansion and stagnation arrise from the succession of technical-economic cultures each characterized by its own infrastructure, leading industrial sectors, typical production methods and main products. Even the geographical location of the dominant political-economic center may shift from wave to wave. This is Mensch's process of metamorphosis.

Where the Sterman approach emphasizes the cyclic character of the wave, our model is meant to describe the qualitative changes through which one set of technologies replaces the next. In our model, the economic system has no equilibrium point to oscillate around. As long as technology develops and new discoveries are made, the potential for economic activity continues to grow. A purpose of the model is therefore to show how randomly distributed discoveries can be bunched into waves of innovations with a relatively well defined period.

Introduction

Since the industrial revolution some 200 years ago, the economic development in the Western World appears to have been characterized by alternating phases of expansion and stagnation with a period of 50-60 years[1]. This phenomenon, which is referred to as the economic long wave, was already noted by Kondratieff[2] and others in the beginning of this century as a cyclic pattern in economic variables such as interest rates, foreign trade, wages and commodity prices for some of the leading industrial countries.

Similar variations could also be observed for the production of iron, coal and lead in England, and for the consumption of coal in France. As indicators of economic activity, these variables show sharp downturns in the 1830-40's and in the 1870-80's with subsequent periods of economic recovery and relative prosperity.

Data for economic quantity variables were available only for a very restricted period of time (less than 100 years), however. Partly for this reason, and partly due to misbelief in the applied statistical methods, Kondratieff's notion of a 50-60 years economic cycle was never really accepted, even though a new dramatic downturn occured in the 1930's. Of course, the lack of a convincing theory to assert that the wave was endogenous to the economic system and not generated by random events such as wars, revolutions, gold discoveries, etc., also played a significant role for the limited interest in Kondratieff's work. Nontheless, well reputed economists such as Joseph A. Schumpeter and Walt W. Rostow have contributed significantly to the development of the long-wave idea.

Occuring precisely 50 years after the depression of the 1930's, the present economic crisis has added considerable new momentum to the study of the economic long wave, and during the last decade significant new evidence has been established, and a number of theoretical explanations proposed.

Through the development of the National Model[3], the System Dynamics Group at MIT has shown how bounded rationality in economic decission making combined with physical lags for instance in the acquisition of capital create the potential for oscillatory behaviour. By virtue of a number of self-reinforcing processes, including the acceleration and multiplication processes of ordinary Keynesian business cycle theory, the oscillatory behaviour is destablized, and the macroscopic system becomes capable of performing self-sustained oscillations with a period of 50-60 years.

John Sterman has presented the basic dynamic hypotheses of Forrester's theory in simplified form[4]. According to his treatment, an increase in demand for capital leads to further increase through capital self-ordering, i.e. by the fact that the capital sector depends on its own output to produce more capital. Combined with other positive loops, associated for instance with the locally rational inclination for capital acquisitors to order farther ahead in the face of increasing delivery delays, the system becomes unstable. Once a capital expansion gets under way, reinforcing processes sustain it until non-linear effects finally allows production to catch up with orders.

By this time, a considerable amount of excess capital has been built up, and the loops now reverse: a reduction in orders reduces the demand for investments, leading to a contraction in the capital sector and consequently also to declining employment, wages, aggregate demand, and GNP. Capital production must remain below the level required for replacements until the excess capital has been fully depreciated and room for a new expansion created. Due to the long lifetimes of capital this process may take a decade or two.

An important feature of this type of description is the assumption that the economic system oscillates around an equilibrium point[5] or, in other words, that the Kondratieff wave can be separated from secular economic growth. The economic long wave undoubtedly has a significant element of cyclic behaviour which in fact reaches far beyond the boundaries of what is usually considered the economic system:

The 20 years of economic upswing are characterized not only by massive investments, rising stock prices, increasing employment and growing prosperity, but during this period of optimism the society becomes more open and permissive, liberal political and economic ideas are adopted, women's position is improved, dicipline and parantel authority are revolted against, and people gradually tend to become less interested in professional careers and more interested in self-fulfilment.

At the end of the upswing, the society appears over-capitalized, inflation and interest rates are usually high, and a general unsecurity develops with respect to the goals to be persued both at the national and the personal level. For the majority of people, the first years of stagnation are relatively good. The prosperity is high, and some of the tensions of the previous decade of rapid growth have disappeared. However, with the significant lay-offs and capacity reductions in many sectors of the economy, the unsecurity develops into a fear of the future.

During the following years of economic recession and high unemployment, excess capital is gradually depreciated, inflation is brought to a halt, the class struggle is intensified while at the same time the society turns more conservative and introvert. Women are forced back to their pots, skirts are lowered, and moral standards reinstalled.

This description only captures part of the picture, however. Each upswing is usually characterized by its own infrastructure, leading industrial sectors, typical production methods and main commodities. New transport systems and energy sources are taken into use, and even the geographical location of the dominant political-economic center may shift from wave to wave. In fact, the present society is quite different from the society of the 1930's: the material wealth has increased immensely, women's participation in the work force is much higher, social security has improved, international trade relations have changed, and so have our means of coping with the crisis.

A purely cyclic description neglects the significant qualitative changes which take place from upswing to upswing, and it fails to view the Kondratieff wave as an integrated part of the evolution of our society. For these reasons, we have attempted to

construct an alternative, simple model in which the alternating phases of expansion and stagnation arrise from the succession of technical-economic cultures. The difficulty with this kind of model, at least if it has to be general enough to deal with several stages in the evolution, is that the variables are much less well defined. Nontheless, we believe that such a model can add to our understanding of the economic growth process and its interaction with the Kondratieff cycle.

A Theory of Technical-Economic Succession

Partly based on earlier work by Kuznets and others, Mensch[6] has described how the development of the industrialized world can be pictured as a succession of technical-economic cultures.

In this account, the first Kondratieff upswing exploited the potential generated through the introduction of cotton textiles and steam power. This took place between 1783 and about 1803, and the wave is generally referred to as the 'Industrial Revolution Kondratieff'. The upswing of the subsequent wave, the 'Bourgeois Kondratieff' from 1843 to about 1857 represents the economic growth made possible through the introduction of wood-powered locomotives, telegraphy, Bessemer steel and Portland cement. The upswing of the 'neo-Mercantilist Kondratieff' from 1893 to about 1913 is associated with the introduction of coal powered railroads, steam ships, automobiles, electricity, and tungsten filament lamps. Finally the fourth upswing from 1949 to about 1967 is associated with motorization, air traffic, electric-arc steel, computers, and a varity of durable goods such as TV-sets, refrigerators and washing machines.

Graham and Senge[7] suggest that each Kondratieff wave can be associated with a particular type of primary energy source. The use of wood as a fuel appears to have peaked at the end of the first Kondratieff upswing. The significance of wind and water power reached saturation at the end of the second Kondratieff upswing, application of coal reached a relative maximum at about 1910, and the significance of oil presumable peaked around 1970, or just at the end of the fourth Kondratieff upswing.

In accordance with the National Model, Graham and Senge see the periodic shifts in technology and the associated wave-like variation in the rate of innovation as a consequence of the 50-60 years oscillation generated by self-ordering in the capital sector. Each burst of capital build-up allows a new set of technologies to be utilized. However, as the build-up proceeds beyond its initial phases, opportunities for applying new inventions rapidly deteriorate. The society locks itself onto a particular mix of technologies, rapid expansion of the dominant industrial sectors reduces the incentives for investments in new and less tried techniques, commitment to a particular type of infrastructure makes it difficulty to apply other forms of transport or communication systems, engineers are taught to use the adopted technologies, and bureaucrates learn to trust them. In this period, the society greatly favours improvements of existing technologies over introduction of basically new technologies.

During the subsequent downturn phase, innovation opportunities gradually improve as existing capital becomes increasingly

obsolescent, and large and strong institutions are brought to fall. Near the bottom of the wave, where old capital is depreciated and the technologies of the previous expansion completely outdated, the possibilities for introducing basic new innovations reach a maximum.

We certainly subscribe to most of these ideas. However, we would like to give the qualitative changes associated with the technological development a more pronounced role, and we would like to see the potential of a given ensemple of techniques and the switch from basic to improvement innovations explicity represented in the model. In addition, we do not see the existence of capital per se as a hindrance to the introduction of new techniques: If a completely new type of industries has to develop, we do not think that it necessarily has to await the depreciation of old capital. If the geographical location of the dominant political economic center is going to shift (as it has done between some of the previous waves), we do not think that the next upswing has to await the depreciation of infrastructure in the existing center[8].

As an alternative and presumably more general view on the mechanisms behind the economic long wave, we have therefore turned to the metamorphosis model developed by Mensch[6]. Figure 1 illustrates the main ideas of this model: Fundamental scientific discoveries are considered to reflect spontaneous processes, and basic new inventions are therefore assumed to be made randomly over time. For an invention to acquire economic significance, however, it must be turned into a basic innovation from which new industries can grow. This transformation, i.e. the introduction

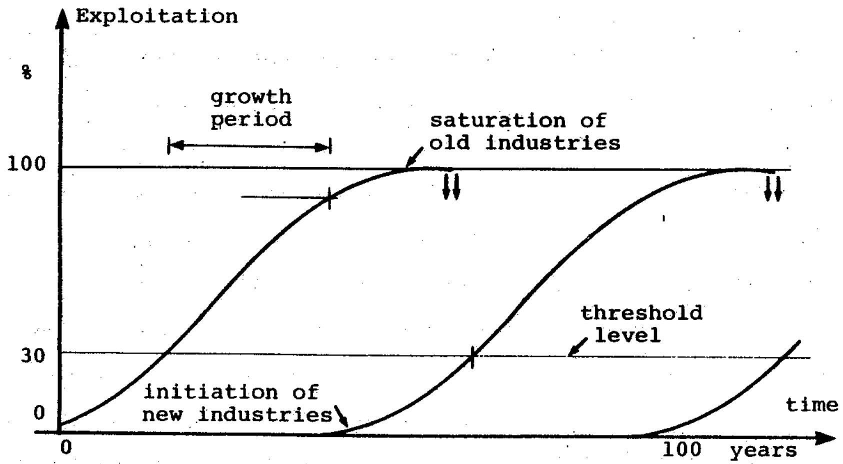

Figure 1. The metamorphosis model developed by G. Mensch.

of basically new techniques is conditioned by the state of the economy and particularly by the expectations to the already adopted techniques. Time must be right, which means that exploitation of the present ensemble of techniques must be approaching saturation.

Under such favourable conditions, many of the inventions accumulated since the last economic upswing may be turned into practical application within a relatively short period of time, and together they lay the seeds for a coming upswing. Completely new industries develop, and the most viable of these start a rapid (exponential) growth. In the beginning, as long as the new industries are economically insignificant, the competition for capital, labour and other production factors is weak, and the growth process is practically without constraints from the surroundings. However, as the new industries start to become significant, the competition increases, some of the less promising die

out, and the incentive to introduce further new innovations fades out. In this way, the society locks itself onto a particular set of technologies, and the interest shifts to improvement innovations.

This phase of rapid initial growth of new industries after the saturation of the former complex of leading sectors is actually the phase of economic stagnation. The economically significant industries have stopped to grow, and the new rapidly growing industries have not yet reached macroeconomic significance. In particular, the new industries can not yet absorp the workforce layed-off from the old industries.

In this picture, the stagnation period is not determined by the time it takes old capital to depreciate, but by the time it takes new industries to grow from virtually nothing to a leading position in the economy[9]. The stagnation period can thus be expressed by[10]

$$P_{st} = \frac{1}{\alpha} \ln \frac{q_{th}}{q_n}$$

where α is the (linear) growth constant for the new industries, q_{th} the threshold economic weight factor at which the new industries become macroeconomically significant, and q_n the initial weight factor for these industries. Inserting $q_n = 1\%$, $q_{th} = 30\%$ and $P_{st} = 20$ years, we obtain $\alpha = 17\%$/year. This we consider a reasonable estimate of the maximum growth rate for a complex of new industries.

The following years are the years of prosperity and economic growth. The new industries have attained their leading position and are still rapidly growing. As this expansion proceeds, however, the industries gradually approach the point at which the potential of the adopted technologies is fully exploited. The exponential growth may then turn into logistic growth as described by

$$\frac{dN}{dt} = kN(N_o - N)$$

N_o is here the total potential of the adopted technologies, N is the exploited part of this potential, and $k \sim a/N_o$ is a constant which characterizes the rate of exploitation.

Identifying the period of economic growth P_{gr} as the period it takes for the new industries to grow from the threshold of economic significance N_1 ($\approx$ 30% of the total potential) to near saturation N_2 (say approximately 90% of the total potential), we have

$$P_{gr} = \frac{1}{kN_o} \ln \frac{N_2(N_o-N_1)}{N_1(N_o-N_2)} \approx 17 \text{ years}$$

It may also be worthwhile to express the total potential of scientific discoveries N_o available for a given Kondratieff upswing as the product

$$N_o = f_{disc} \cdot p_{disc} \cdot T_K$$

where f_{disc} is the frequency of discoveries, p_{disc} the average

potential of the individual discovery, and T_K = 60 years is the wave period.

The simple logistic growth curve may be somewhat simplified because, as we have indicated, improvement innovations during the growth process will expand the potential of the adopted technologies. As a first approach we may describe this process by

$$\frac{dN_o}{dt} = k_i \, N(N_o - N)$$

where as before N denotes the exploited and N_o the presently available potential for the adopted technologies. The constant k_i describes the rate at which improvements are made.

The set of equations of motion

$$\frac{dN}{dt} = kN(N_o - N)$$

$$\frac{dN_o}{dt} = k_i \, N(N_o - N)$$

has the characteristic feature that if $k_i \geq k$, the saturation level recedes faster than exploitation develops. Under these conditions, a new downturn will never occur. We should thus promote a relatively slow rate of exploitation so that sufficient improvement innovations can be made along the road. This conclusion is somewhat at variance with a conclusion which can be drawn from the capital self-ordering model. Because, according to that model, if capital is allowed to expand quickly enough, the positive feed-backs in the economic system will overwin the built-in nonlinear mechanisms, and a downturn can be avoided.

There is one more point we would like to make before turning our attention towards our System Dynamics model: Exponential (or logistic) growth can not start from nothing. For a growth process to initiate, we must have a source term. In real life this is provided through persistent, random attempts to use new technologies. Most of these attempts will be abortive, and only under the right circumstances will a new industry develop. We are thus dealing with a typical self-organizing process[11] in which increasingly effective technical-economic complexes in a far-from-equilibrium system grow out of random noise.

We are also dealing with a self-organizing process in the sence that the economic system generates relatively coherent 50-60 years waves from an input of randomly distributed discoveries.

A System Dynamics Formulation

According to the assumptions we have made, each Kondratieff wave is qualitatively different both from previous and from subsequent waves. Each wave has its own characteristic infrastructure, leading industrial sectors, and typical production methods. Since qualitative differences can only be handled through disaggregation, each wave must be described by means of its own rate and level variables. In a more detailed model, several of these variables will be expressive of typical economic quantities such as investment rates, capital stocks, market potentials, and resource amounts. In our simplified model, only the potential of a particular technology, and the degree to which this potential is exploited are represented.

Figure 2 shows the SD-flowdiagram for a single module in our model of succeeding technical-economic cultures. Each module represents a particular Kondratieff wave. The three rate variables BND, ROA and ROE represent the processes of discovery, adoption and exploitation of a particular set of technologies. These variables may also be thought of as measuring the rates of inventions, innovations and investments, respectively. The level variable UP represents the amount of basic scientific knowledge which has not yet been turned into practical applications, PUE represent the potential for economic activities created through new innovations, and EP is the fraction of this potential which is already exploited.

As basic discoveries we consider significant scientific breakthroughs such as Maxwell's theory of electromagnetism and Pasteur's discovery of microorganisms. New inventions (the steam engine, the combustion motor, the telephone, the air plane, etc.) are also included, and so are discoveries of new primary energy sources, new types of raw materials, and new production methods. Ideas which can lead to fundamental social and political changes (land reforms and parlamentarism) also belong to this category.

In our model, basic new discoveries are generated as a Poisson process[12], i.e. we assume that they occur randomly distributed in time. For simplicity we consider only two kinds of discoveries: small discoveries with a potential PSD (= potential of small discoveries) = 600, and large discoveries with a potential PLD = 4000. Small discoveries are assumed to occur with a probability per unit time FSD (= frequency of small discoveries) = 0.3/year, and large discoveries are assumed to occur with a

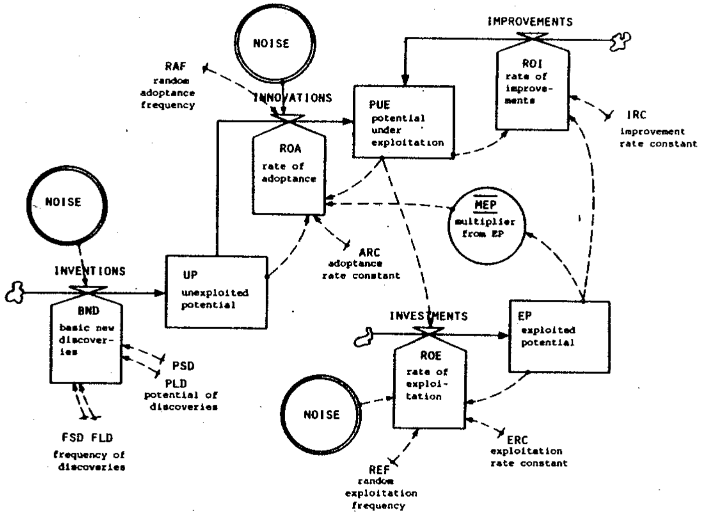

Figure 2. Module for the adoptance and exploitation of a particular set of technologies.

frequency FLD = 0.03/year. The DYNAMO-equation for the rate of new discoveries hereafter reads

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BND.KL = PSD*CLIP(1/SDT,0,FSD*DT,NOISE()+.5)
         + PLD*CLIP(1/DT,0,FLD*DT,NOISE()+.5)
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Each discovery is measured by its potential for generating economic activity. This is certainly not an easy measure to quantify, and we don't even know what the proper units should be. For the moment, one may think of it as the amount of production factors required at full exploitation of the discovery.

Scientific discoveries are usually not applied at once but often preceed their practical use by 20-80 years. The basic discovery behind the locomotive, for instance, was made by Watt in 1769, but it was not until 1824 that Stephenson build his

first locomotive plant[13]. In our model, basic new discoveries are accumulated as ideas and basic knowledge in the level of unexploited possibilities UP until, when times are right, they are turned into practical applications in the form of innovations. As basic new innovations we consider the first pratical application of new techniques, the introduction of new agricultural production methods, the introduction of new types of consumer goods, the establishment of significant trade agreements, the first succesful formation of labour unions, etc., recognizing that technological change in the present context must be given a very broad definition.

Innovation and introduction of new techniques create an increasing potential for economic activities. Exploitation of this potential involves the build up of new industries, the build up of new infrastructures, the cultivation of new land, the production of new types of consumer goods, etc. It is not until this stage that significant amounts of production factors (labour and capital) become involved, and it is therefore the exploitation of economic possibilities which controls the overall economic development: periods in which the rate of exploitation is high are economic growth periods, and periods in which relatively few new possibilties are exploited are stagnation periods.

Both the rate of adoptance ROA and the rate of exploitation ROE are modeled as logistic learning or market penetration curves[13]. Adoptance of new techniques is assumed to be proportional both to the unexploited potential of scientific knowledge UP, and to the amount of innovations already successfully introduced

PUE. The second factor gives a rapid initial growth in ROA, while the first factor provides a saturation mechanism when the available basic discoveries are fully adopted. Similarly, the rate of exploitation is controlled by the potential under exploitation PUE as well as by the already exploited potential EP.

Our model is more profound than usual market penetration models, however, because it describes both how the logistic growth processes become possible as instabilities arise in shifting parts of the system, and how the growth processes initiate in the background noise of random attempts to adopt or exploit new techniques. There will always be attempts, for instance, to apply existing scientific knowledge in practice, and the rate of adoptance therefore contains a random noise-term of the form

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UP.K*RAF*(NOISE()+.5)
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where the constant RAF measures the intensity or frequency of these random attempts.

Under normal circumstances, the economic system is fully occupied exploiting already adopted techniques, and attempts to introduce basic new technologies seldom succeed. However, if an existing set of technologies approaches saturation, the suppressing forces weaken, the system becomes susceptible to new ideas, and through an unstable transition it yields to a wave of new innovations. This produces a potential of new economic possibilities in the face of which the economic system becomes unstable, and a wave of exploitation unfolds.

The flow diagram of figure 2 also shows how a given poten-

tial PUE under its exploitation can increase through improvement innovations. This is modeled through the rate ROI, which in agreement with our discussion in the last section is taken to depend both on the potential under exploitation and on the already exploited potential.

Figure 3 illustrates how the instabilities are directed through the system from one module to the next. The first module is unstable from the very beginning since it is assumed that a number of unexploited scientific discoveries have accumulated, and since the model is initiated in a state where the society is susceptible to new innovations.

After a certain incubation time which depends both on the noise level (i.e. the intensity of random attempts to turn the accumulated knowledge into new innovations), and on the gain factor (i.e. on the rate constant ARC), a macroscopically significant potential for new economic activities develop. This innovation wave is assumed to last for about 10 years, or about 1/5 of the total wave period.

By creating a potential for economic activities, a new instability is generated, and an exponential growth in exploited potential is initiated. After a new incubation period which again depends both on the exploitation frequency (REF) and on the gain factor (the exploitation rate constant), the exploited possibilities reach macroscopic significance. The society now engages itself fully in the exploitation of already adopted technologies, and the rate of adoptance falls to 0. In the model this is obtained through the multiplier from exploited potential MEPA.

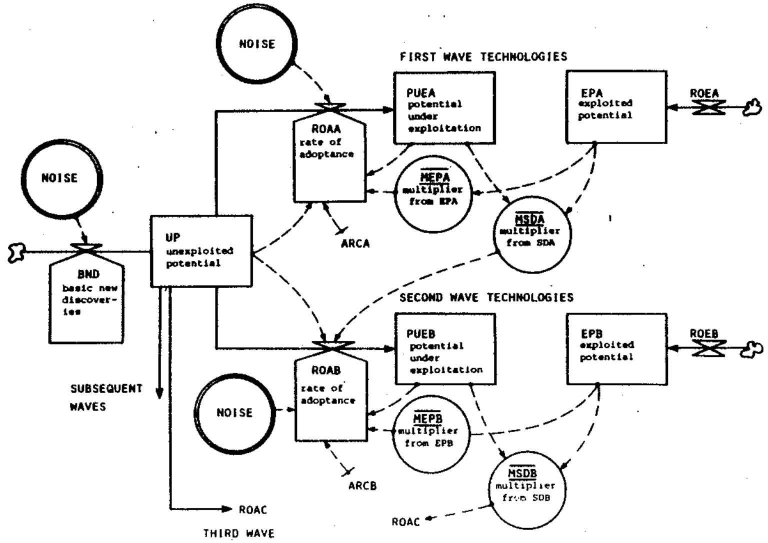

Figure 3. Overview of the coupling of subsequent modules.

MEPA is a non-linear function which, starting at 1 for small values of the exploited potential, approaches 0 as EP reaches macroscopic levels.

As exploitation of first wave technologies continues, a point of saturation is approached. The rate of economic growth then declines, and the society gradually becomes ready to accept a new set of technologies based upon scientific discoveries which have accumulated since the first innovation wave. To describe this phenomenon, we have introduced the non-linear function MSDA which is a function of the degree of saturation with first wave technologies SDA = EPA/PUEA. MSDA is 0 as long as SDA $\leq$ .7 but rises to 1 as SDA approaches 1. MSDA hereby opens for the adoption of second-wave technologies. Hereafter follows exploitation of second wave technologies, adoption of third wave technologies, etc.

If the total period of the wave has to be T_K = 50-60 years, we must adjust the rate constants (ARC and ERC) as well as the noise-intensities (RAF and REF) accordingly. In the present case, we have taken the potentials and frequencies of small and large discoveries to be

PSD = 600

PLD = 4000

FSD = 0.3/year

FLD = 0.03/year,

respectively. During a wave period, the model thus in average generates scientific discoveries with a potential of

$$N_o = (PSD \cdot FSD + PLD.FLD) \cdot T_K = 15000$$

If the 30-90% exploitation of this potential should last about P_{gr} = 20 years (the period of economic growth), we must have a gain factor

$$\alpha = kN_o = \frac{1}{P_{gr}} \ln \frac{0.9 \cdot 0.7}{0.1 \cdot 0.3} \simeq 15\%/\text{year}$$

The approximate magnitude of the exploitation rate constant ERC = k = α/N_o thus becomes 10^{-5}/year. If the innovation wave is about 5 times faster than this, we may insert ARC = ERC/5. The respective noise levels can hereafter be estimated from the corresponding incubation times, which we have identified with the period of economic stagnation.

Simulation Results

Figure 4 shows a typical set of simulation results. We have here plotted the variation with time of the three level variables (the unexploited potential of basic discoveries UP, the potential under exploitation PUE and the exploited potential EP) for each of four subsequent modules. The figur shows how the curves for the potentials under exploitation and the exploited potentials all grow out of insignificant background noise. Note, how the model produces a relatively regular succession of upswings with a 50 years interval out of the external signal of random discoveries. It should also be observed how the potentials under exploitation show a double logistic growth of which the first part is associated with basic new innovations during periods of economic stagnation, while the subsequent enhancement is associated with improvement innovations during periods of economic growth.

Figure 5 shows the development in the rates of basic innovations associated with four subsequent Kondratieff waves. On this figure, we have also plotted the randomly occuring basic discoveries plus the variation of the four waves of exploitation. It can be seen, how basic innovations occur in periods with low exploitation rates.

To illustrate the significance of the random element in our model, we have run a series of simulations with different initial values for DYNAMO's NOISE-function. The results hereof are shown in figures 6 and 7 which are directly comparable to figure 4. As defined by the amplitudes of the individual waves and their precise time of occurrence, the behaviour of the model strongly depends upon the sequence of random discoveries. However, the

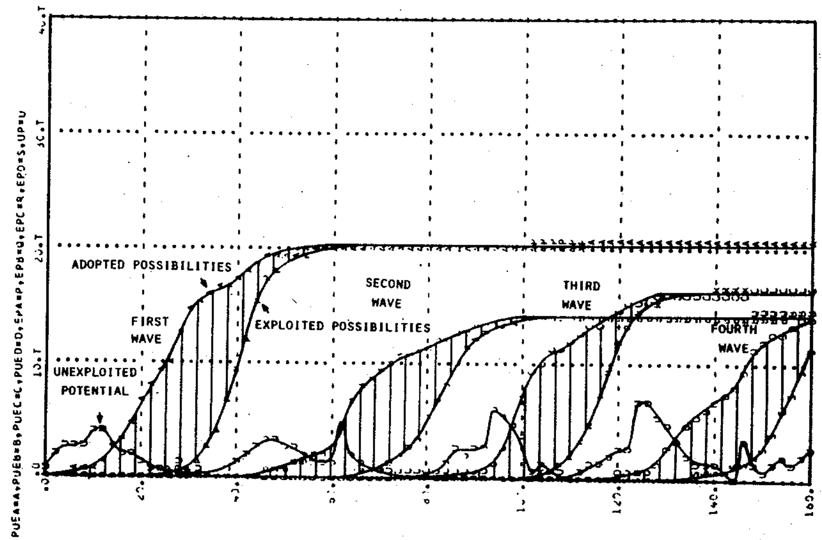

Figure 4. Development in unexploited potential, potential under exploitation and exploited potential in base case run.

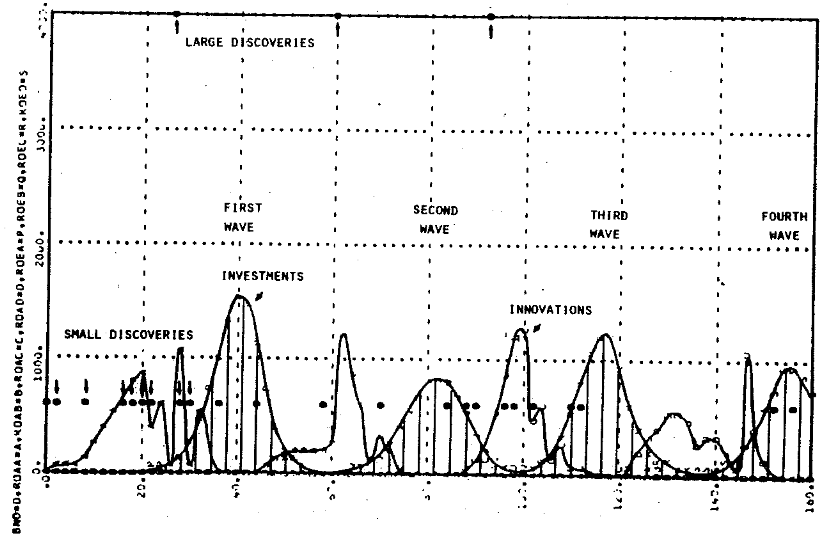

Figure 5. Development in rate of adaptance, rate of exploitation, and discovery rate in base case run.

tendency to generate 50-60 years waves out of these discoveries is maintained independent of the NOISE-sequence.

Besides upon the logistic rate constants, the wave period also depends upon the intensity of background noise. The more frequent the random attempts to adopt or exploit new technologies, the shorter will the wave period be. This is illustrated in figure 8, where we have increased the random adoption and exploitation frequencies for all four modules by a factor of 3. The wave period is now shortened to about 30 years, and a fifth upswing would had started, had the model contained one more module.

Figure 9 shows the effects of increasing the rate constant IRC for improvement innovations in the third Kondratieff wave from $0.6 \cdot 10^{-5}$/year to $2.4 \cdot 10^{-5}$/year. Improvement innovations can now almost keep up with the rate of exploitation with the result that the upswing of the third wave is prolonged considerably. If IRC becomes larger than the rate constant for exploitation ERC, the upswing never stops.

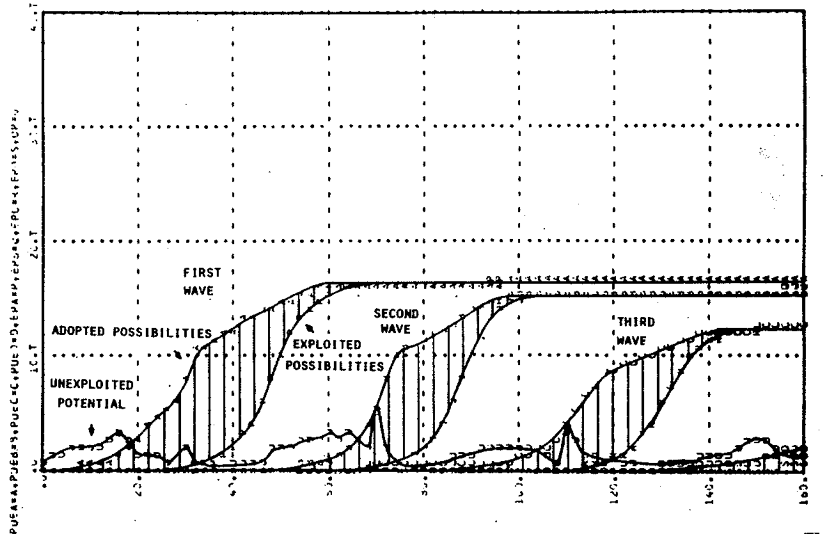

Figure 6. With a different sequence of random discoveries, a different wave picture is obtained.

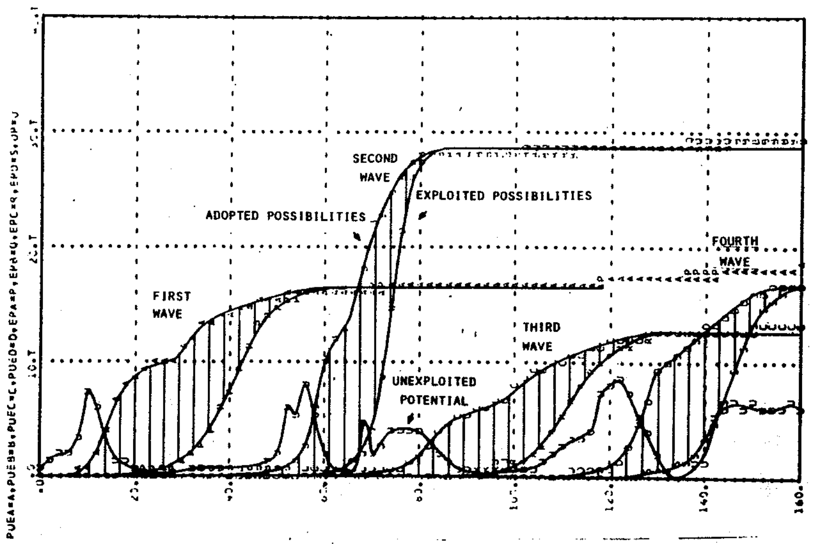

Figure 7. Same as figure 6 with new initiation of NOISE.

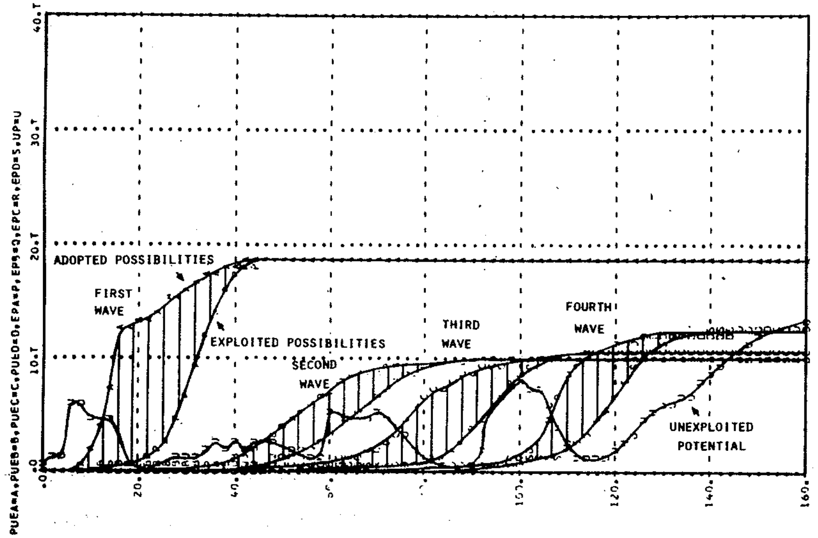

Figure 8. With increased NOISE amplitudes, the waves become shorter and smaller.

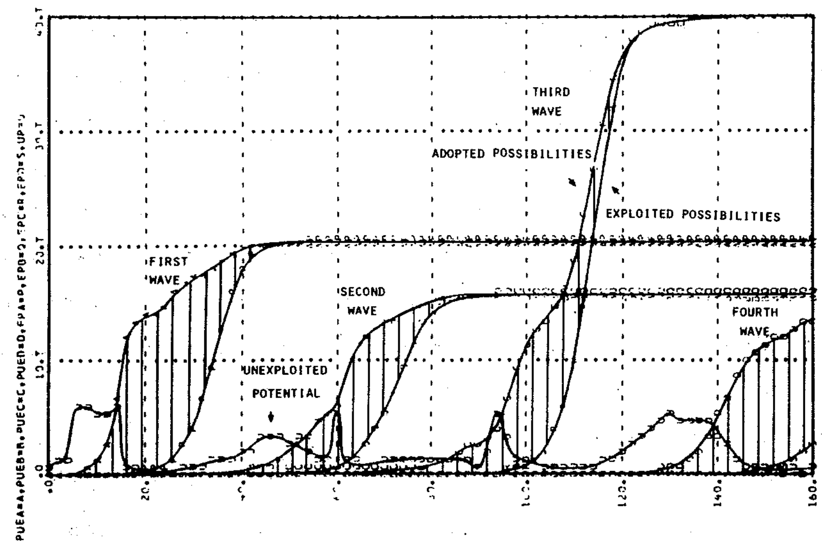

Figure 9. With a higher rate of improvements, the third wave becomes strong and long.

Conclusion

Succession is a well-known concept in ecology where it is used to describe the process by which the dominance of one species (or one composition of species) follows after another as the external or internal conditions change. To our knowledge, this process has never been modeled in a way similar to ours, and we thus consider the present work as an attempt to develop a generic model of succession.

As a model of the economic long wave, our model represents an alternative to the purely cyclic picture developed by the System Dynamics Group at MIT. In our view, the Kondratieff wave has both cyclic characteristics and characteristics of a succession process. In some way or the other, a complete description therefore involves an integration of the two approaches. Intuitively, we believe that it will be easier to start with a succession model and build on the cyclic elements than the other way around. Our model also has the advantage that overall exponential economic growth can be represented by introducing simply a positive feed back from the total of exploited possibilites to the frequencies of random discoveries.

Acknowledgments

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5. In the present case, the equilibrium point is considered to be unstable so that even the slightest disturbance of the system away from this point will trigger an expanding oscillation until the amplitude is finally limited by non-linear mechanisms.
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7. Alan K. Graham and Peter M. Senge: 'A Long-Wave Hypothesis of Innovation', Technology Forecasting and Social Change 17, 283-311 (1980).
8. We can imagine a shift in dominance from the North-Atlantic sphere to the Pacific, i.e. that Japan and other countries in the Far East in the next upswing will take over the role that European countries have had as main allies and trade partners of the US.

9. If we don't need a plant, and if we are not going to need it again, in principle at least, it can be closed from one day to the next.
10. The metamorphosis process is similar in many respects to the formation of subsequent acoustoelectric high-field domains in piezoelectric semiconductors: Erik Mosekilde: 'Linear and Non-Linear Acoustoelectric Effects in Heavily Doped GaAs Epitaxial Single Crystals', Polyteknisk Forlag, Copenhagen (1977).
11. Erik Mosekilde, Steen Rasmussen, and Torben Smith Sorensen: 'Self-Organization and Stochastic Re-Causalization in System Dynamics Models', plenary session paper, Proc. 1983 International System Dynamics Conference, Pine Manor College, p. 128, Boston. USA.
12. Erik Mosekilde and Steen Rasmussen: 'Random Processes in System Dynamics', DYNAMICA 91, 33-39 (1983).
13. Cesare Marchetti: 'Society as a Learning System: Kondratiev and the Innovation Cycles Revisited', presented at a seminar at the Banco di S. Paolo in Turin, April 18, 1980.