CHAPTER 8

Technology Diffusion in a Long-Wave Context: The Case of the Steel and Coal Industries

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"La société, c'est l'imitation, et l'imitation c'est une espèce de somnambulisme."
G. Tarde, Les lois de l'imitation, 1895

8.1. Introduction

This paper is intended to illustrate, with the aid of selected examples from the steel and coal industries, the intimate relationship (or rather the *causality*) between technological change and *Wechsellagen* in long-term economic development. For this purpose periods of relatively stable homogeneous growth (characterized by regular diffusion patterns of new technologies, industries, and products into the market) and periods of turbulence and stagnation in economic activity (during which a number of leading technologies and industries, which were the main driving force of the previous upswing period, reach saturation in their market niches) will be differentiated. During these saturation phases new important technological innovations are often (although not always) introduced into the market.

It is my contention that during periods of depression leading technologies and products (in terms of their contribution to previous economic growth) are saturating. This saturation can be observed in either one or a combination of the following indicators: total output, market share, further cost reduction potential along the learning curve of a technology, and productivity indicators.

It is necessary at this point to emphasize that the argument presented here does not rely on a perfect *synchronization* of the saturation of existing and/or the emergence of new technologies as causal phenomena to explain long-term economic fluctuations, although empirical evidence suggests a certain degree of clustering in the appearance of innovations (see Chapter 4 by A. Kleinknecht). Rather, the argument is based on the high degree of overlap in the main growth periods (i.e., the period needed to increase from 10 percent to 90 percent of the ultimate market potential) of a number of key sectors and technologies, which would be sufficient to result in *Wechsellagen* of economic development.

In upswing periods one can observe regular growth in output, productivity, etc., as well as regular technological diffusion patterns, all of which convert to oscillatory behavior when reaching the saturation phase of market growth and technology diffusion. However, to describe these periods of saturation and turbulence (depression) not only in dimensions of changes in output and technological diffusion, economic and social indicators (such as prices and strike rates) will also be considered to characterize periods of stable growth and turbulence in long-term economic development.

In Chapter 9 N. Nakicenovic deals with the term technology in a wider context, in that primarily the evolution of transport infrastructures and of the energy system is analyzed. Infrastructures and energy constitute to some extent higher-level aggregates of a large number of underlying technologies. In this paper this view will be complemented (arriving at similar conclusions) by zooming from the macro level down to two specific sectors and discussing in detail changes in specific technologies, in factor inputs (energy and labor), and in major market outlets in individual countries. It will be shown that periods of turbulence and depression constitute important turning points in the *structural change* of the system with regard to all indicators mentioned above. Thus, the concept of the long wave constitutes a powerful paradigm through which long-term technological change can be systematized and better understood.

8.2. Multidimensional Indicators of Technological Change

Technological change is described along two dimensions: time and a number of indicators of technological change *per se*. With regard to the time dimension, a number of different indicators will be used to identify secular periods of stable economic growth and time periods of turbulence and stagnation. The identification of these time periods is especially important as there is evidence that all indicators of technological change *per se* show that the market saturation of major technologies and products, as well as significant turning points in the structure of the technological system (appearance of new technologies, changes in factor inputs, changes in market outlets), tend to cluster during these periods of turbulence and stagnation in economic growth.

8.2.1. Indicators to identify secular periods of growth and periods of stagnation

A large number of possible methods to describe long-term fluctuation in economic development have been advanced in analyzing empirical evidence in arguing pro or con the long-wave hypothesis.[1] For the purpose of this paper a number of different indicators will be used to increase the confidence about the exact timing of the various phases of the long wave. This approach is taken, because it is considered here that the complex phenomenon of economic fluctuations can be described only by a number of different (to an extent independent) indicators. Thus, the following indicators will be considered to describe secular movements of economic activity:

Deviations from long-term trends in output, prices, social indicators, etc. Typically, long time series are analyzed with various filters. In this paper deviations from a 50-year moving average are analyzed, these deviations are then smoothed by applying a 9-year moving average to them.

Discontinuities in long-term trends. Economic upswing periods are characterized by continuous growth in output, while downswing and depression periods are characterized by stagnation and oscillatory behavior of output figures. In this context it is interesting to note that an analysis of long-term production trends often reveals an overlap of consecutive growth pulses, with production figures oscillating between the boundaries defined by the two consecutive growth pulses.

Introduction and/or saturation of technologies.

Evolution of economic and social indicators. Under this hypothesis the periods of depression and structural change are characterized by *flares* in economic (e.g., prices) and social (e.g., strike rates) indicators. One theoretical explanation of these flares would consider the saturation of existing technologies, implying that further (real-term) cost reductions along the learning curve become infeasible (law of diminishing returns of technology improvement) and thus marginal production costs of resources, commodities, and products increase substantially. This increase in costs (and prices), along with the phenomenon of market saturation, could in turn have repercussions on social relations, making the settlement of working disputes a more difficult task and flares in working disputes more common.

8.2.2. Indicators of technological change

A number of different indicators are proposed in this paper to describe technological change:

Output. Introduction of new technologies allows an intensification of production and results in significant growth in total output. A typical example of this intensification is provided in the case of the introduction of the Bessemer process, allowing mass production of steel.

(Real) production costs. A drastic reduction in (real-term) production costs is a typical indicator for the introduction and growing importance of a new technology. The introduction of the puddling process and later of the Bessemer process, for instance, resulted in a significant decrease of the nominal and real-term steel production costs and prices.

Technological substitution. Here the share of various competing technologies in the production of total output is analyzed, using a logistic substitution model (Fisher and Pry, 1971, and Marchetti and Nakicenovic, 1979).[2] This model describes the emergence of new and the replacement of old technologies in terms of their fractional market share by a set of logistic substitution functions, where the emergence date is defined as the date a new technology captures one percent market share and the saturation phase of a technology is defined by a (non-logistic) transition function linking the logistic functions describing the introduction of a technology and its replacement by a more recent one.

Changes in factor inputs of production (in particular energy and labor). This analysis considers the long-term evolution of the intensity of factor inputs (or its inverse, in the form of energy efficiency or labor productivity) and the changes in the composition of factor inputs.

Changes in market outlets and products.

The above-listed indicators of technological change represent a considerable expansion of the descriptive framework for understanding technological change, which in the past has concentrated on indicators of output growth and factor inputs. The various indicators are, of course, closely interrelated; however, if one is able to discern their synchronous development (as we attempt to show in this paper), additional evidence supporting the hypothesis that technological change is a main driving force of long swings in economic activity can be gained.

8.3. Technological Change in the Steel Industry

The importance of steel in the industrial development in the second half of the nineteenth century as well as in the post–World War II period is widely recognized. In analyzing total world crude steel output in the period 1860 to 1985 (*Figure 8.1*) one can easily discern periods of regular growth from periods of stagnation and fluctuations in world crude steel output.

The regular growth in total output can be described by two consecutive growth pulses in the form of logistic functions with regular growth periods from 1880 to 1910 and 1950 to 1970. *Figure 8.2* shows the same two consecutive

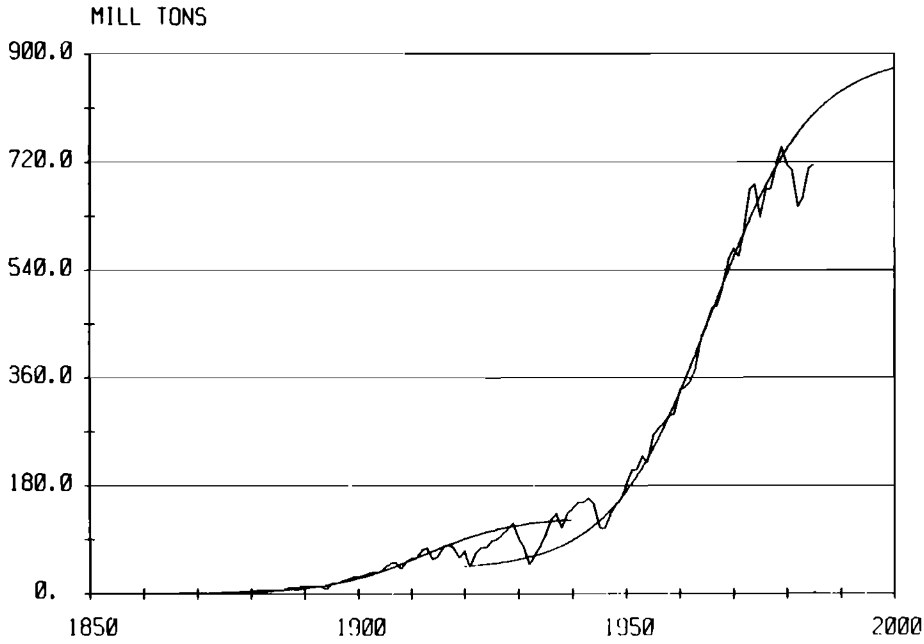


Figure 8.1. **World: growth pulses in raw steel production.**

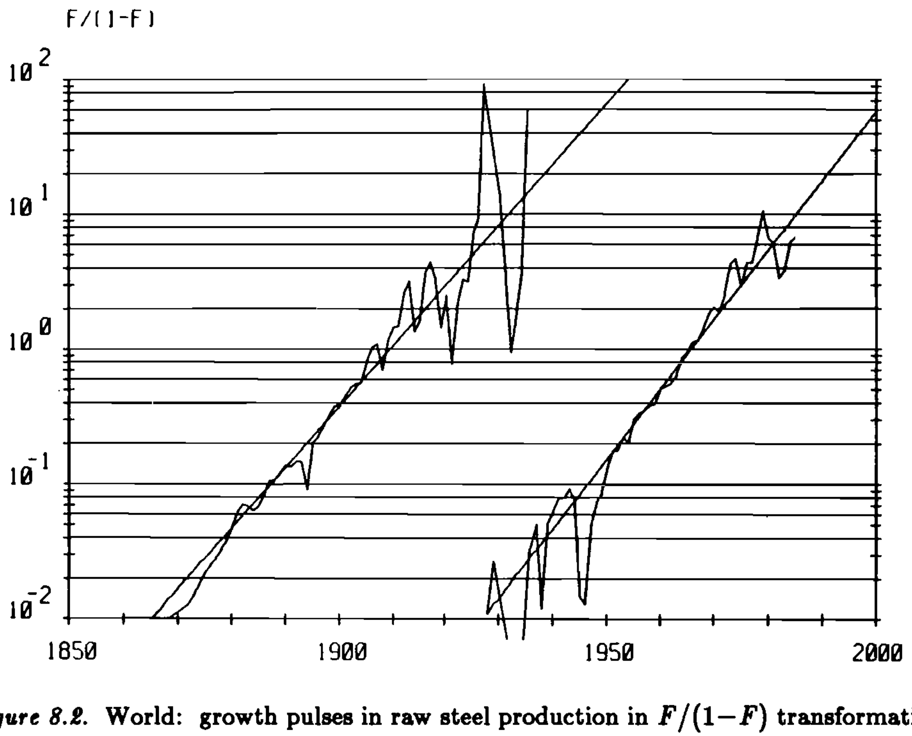


Figure 8.2. **World: growth pulses in raw steel production in $F/(1-F)$ transformation.**

pulses in the transformation $F/(1-F)$, where F represents the ratio of the world steel production in a particular year divided by the calculated saturation level of the logistic growth pulse (around 100 and 900 million tons, respectively) on a logarithmic scale. As a result, the deviations from the logistic growth trends (appearing as straight lines in *Figure 8.2*) can be more easily discerned. The two growth pulses overlap in the period 1920 to 1945, which is characterized by an oscillatory phase of turbulence, before a regular growth pattern is resumed after World War II. Since 1970, a similar deviation of total world steel production from the logistic growth pulse appears, indicating that the world steel industry is possibly facing a similar period of transition, as in the period 1920 to 1950. In *Figure 8.3* world per capita steel production is analyzed, and one can conclude that the picture is consistent with the situation illustrated in *Figures 8.1* and *8.2*.

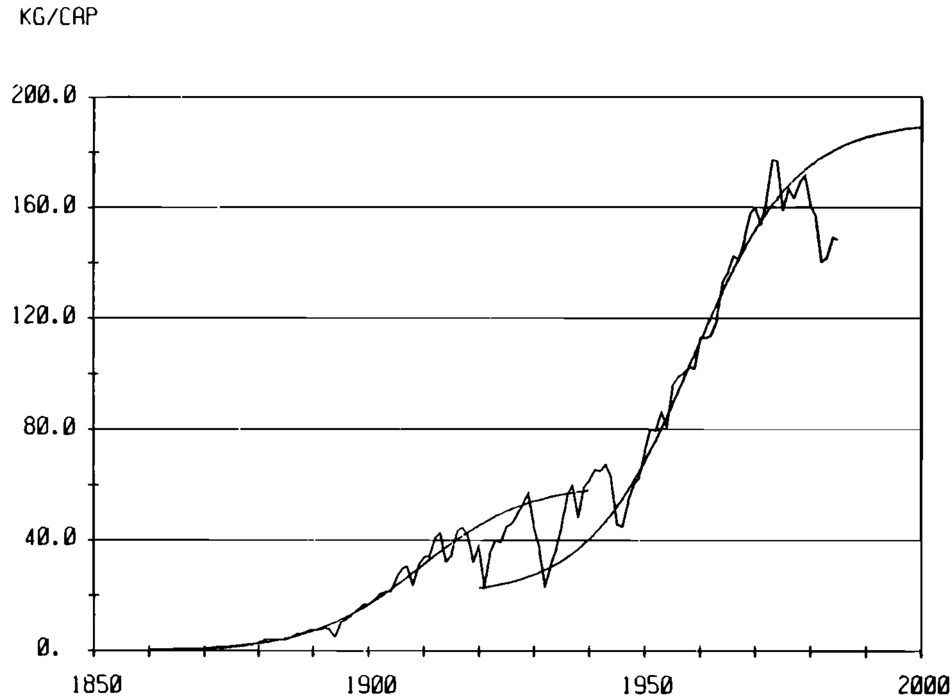


Figure 8.3. World: growth pulses in per capita raw steel production.

The reason for the rapid increase in total world steel production after 1870 can be explained by the introduction of the Bessemer steel production process in all steel-producing countries following its introduction in England in 1854. Through the Bessemer process a dramatic increase in mass production of steel became possible, compared with the production possibilities of the medieval bloomery process or the crucible and puddling processes introduced in the late eighteenth and early nineteenth centuries. The share of Bessemer steel in total steel production increased very rapidly in the period from 1860 to 1875, accounting for nearly 90 percent of total world steel production, before it was gradually replaced by the open hearth (Siemens-Martin) process.

There are two reasons for the rapid expansion of the steel production after World War II. First, in traditional steel-producing countries and regions (the UK, Europe, and the USA) new market outlets for steel products evolved, especially in the rapidly expanding automobile industry. Second, new principal producers, in particular Japan and "Newly Industrialized Countries" (NICs), appeared on the market. During this phase of expansion, we observed the rapid adoption of the basic oxygen blown furnace (BOF or LD) process and the replacement of the Bessemer and open hearth processes at the global level (see Roesch, 1979, and Chapter 9 by N. Nakicenovic).

During the same time period, one can observe a regular pattern of alternating periods of stable growth with periods of stagnation and fluctuations in output, as well as in the diffusion of new and the replacement of old steel production processes; one also observes the emergence of several new steel-producing countries and a change in the leadership of world steel production. *Figure 8.4* shows the share of principal steel-producing countries and regions (the UK, Europe including Eastern European countries, the USA and Canada, the USSR, Japan, and NICs) in total world steel production. *Figure 8.5* presents the same data transformed. The transform $F/(1\text{-}F)$ represents the share in total steel production of one country or region divided by the share of all remaining countries and is plotted on a logarithmic scale. This was done to make the data transformation underlying the logistic substitution model clearly visible.

Despite the turbulences induced by World War I, the 1930s, and World War II, one can nevertheless observe periods of significant structural change in the geographic location of steel production. These structural change periods are characterized by the emergence of new producing countries and the saturation and consequent loss of leadership (in terms of market share) of traditional producers. To better illustrate the dynamic shifts in the location of steel production, *Figure 8.5* is reconsidered by applying the multiple logistic substitution model to it (*Figure 8.6*). The transformation of the data from *Figure 8.5* compared with *Figure 8.4* makes the earlier (turbulent) phases of a particular country's market share more visible. Straight lines in *Figure 8.6* indicate logistic substitution paths of an increase and a decline in the market share. These model calculations are not intended as a method of forecast, but rather provide an instrument for data structuring that could better illustrate the dynamic geographic shifts in world steel production.

Again, periods of structural change can be distinguished from periods of regular growth and smooth transition. In periods of structural change (around 1870, 1920, and 1970 onward) new producing countries appear on the market and the long-term market share of the dominant producer(s) is reaching its saturation level in order to decline thereafter.

The period 1860–1880 is characterized by the loss of leadership in world steel production by the UK to Europe, which in turn saturated its share in total world steel production around 1870. During this time period two new producers emerged: North America (expanding very rapidly and overtaking the UK and Europe by 1890 in terms of market share) and the USSR.

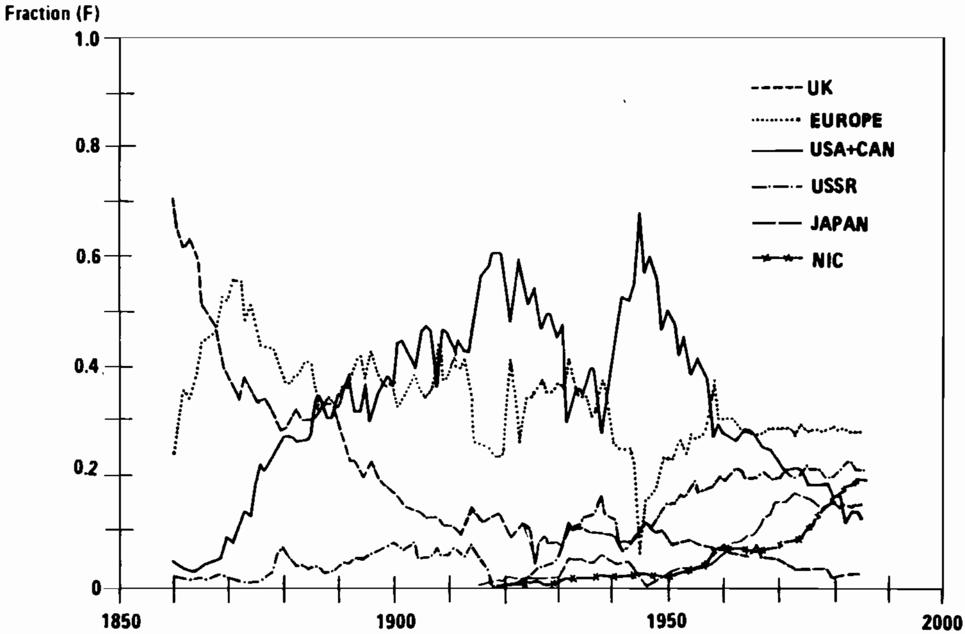


Figure 8.4. World: share of principal steel-producing countries in total crude steel production.

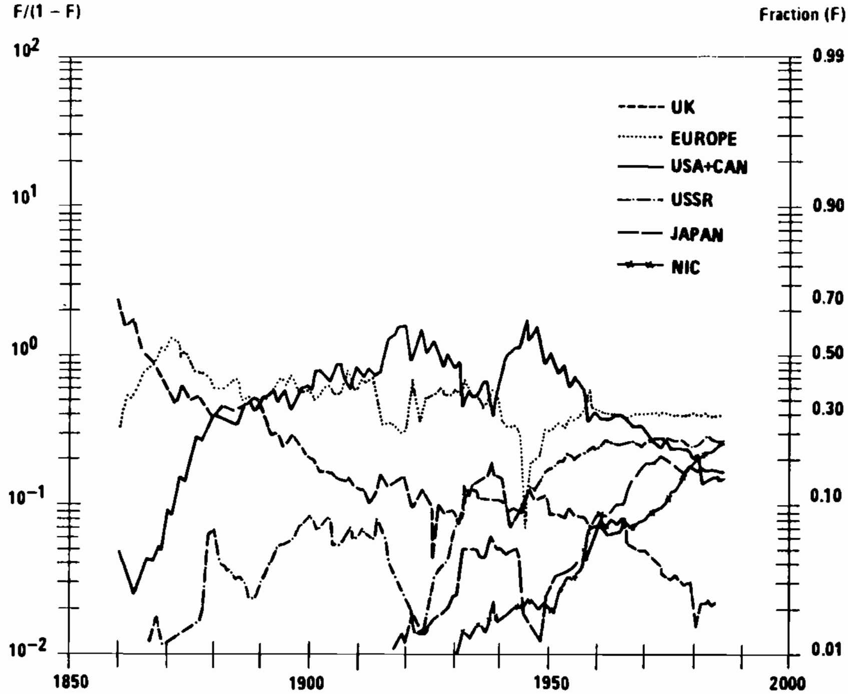


Figure 8.5. World: share of principal steel-producing countries in total crude steel production in transformation $F/(1-F)$. (Source: Nakicenovic, 1987.)

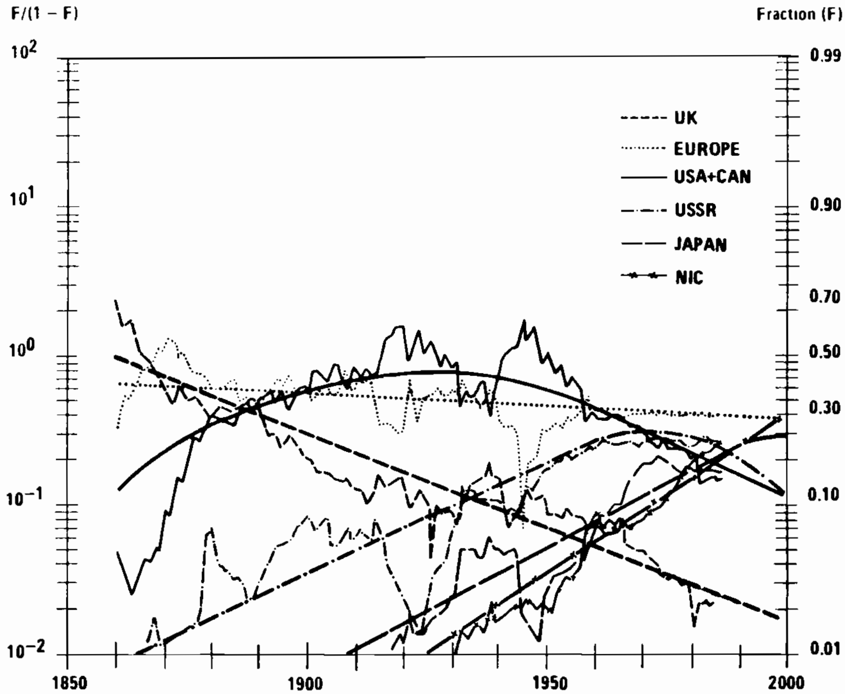


Figure 8.6. World: life cycle of principal steel-producing countries in terms of market share in total steel production $[F/(1-F)$ transformation]. (Source: Nakicenovic, 1987.)

In the period 1910 to 1930 a pattern similar to that of 50 years ago can be observed. The market share of the leading region in steel production (North America) reaches its saturation phase and new producers are entering the market (Japan and NICs). Currently the steel industry again appears to be in a phase of transition: the market share of the USSR in total world steel production is saturating (around 1975) and, based on the model estimates, one would expect a similar saturation for Japan by 1990. The rapid expansion of NICs is particularly at the expense of the North American market share, with Europe, the USSR, and ultimately Japan gradually loosing market share to these countries.

Despite the turbulences induced by wars and the crudeness of representation related to such a simple model, it is interesting to note that the logistic substitution model captures quite accurately the dynamic behavior, especially of the oldest and latest competitors. The UK has been loosing its market share since 1870 along the logistic path, which appears as a straight line in *Figure 8.6*. In a similar way the emergence of newly industrialized countries can quite accurately be captured by a logistic market share growth function, suggesting that the historically observed trend will continue into the future and will leave NICs as the only winners in the game.

After having established a framework of periods of change, turbulence, and saturation (around 1870, 1930, and since 1970) and of periods of smooth growth and transition at the macro level, the analysis will now zoom down to the national level to consider economic indicators and to analyze whether technological change coincides with the periods of turbulence and saturation identified above. The examples of a number of different countries point out, that the periods of fluctuation and depression coincide with the saturation of major technologies, in terms of both their market share and their performance (energy and labor efficiency). This indicates a close causal relationship between technological change and *Wechsellagen* of economic development.

Figure 8.7 shows the evolution of the per capita steel production in Germany (Federal Republic of Germany after 1945) and of the steel intensity per unit of GNP. One can observe a regular growth pattern of the two indicators up to 1910, with a stagnation period between 1870 and 1875. After 1910 a drastic slump in the steel intensity per capita and per unit of GNP can be observed as a result of the two world wars. Particularly visible is the effect of the depression of the 1930s. After 1945 the two indicators increase in line with the economic reconstruction of the Federal Republic of Germany and reach their saturation (for steel intensity around 1960 and for per capita steel production around 1970) and consequently started to decline, pointing to the fact that the material intensity of the German economy is decreasing.

Figure 8.8 presents the evolution of nominal and real-term (in 1913 Deutsche marks) steel prices since 1850. Although the data series available to date are still incomplete in order to analyze with regard to cyclic fluctuations (in particular, the time period of the 1880s, the period after World War I, and the time period of hyperinflation in the 1920s are lacking), they nevertheless provide a first-order picture on the evolution of real-term prices. Of particular interest is the dramatic decline of nominal and real steel prices between 1860 and 1875 as a result of the rapid diffusion of the Bessemer process. It is also interesting to note that the real-term steel prices have remained rather stable during the periods of stable economic growth (1890–1910 and 1950–1975).

On the basis of *Figures 8.7* and *8.8* one can conclude that the time periods with important changes and fluctuations to be analyzed in a technological change context are the periods from 1860 to 1875 (rapid fall of nominal and real steel prices), 1910 to 1935 (decrease of per capita steel production and steel intensity), and the period since 1970, where the shift away from a material (steel) intensive economy for the Federal Republic of Germany is particularly apparent. Let us now consider how technological change in terms of the principal steel production processes integrates into this picture.

Figure 8.9 shows the evolution of the share of different steel production processes in Germany. The evolution of the technological system can be described by a regular succession of growth, saturation, and replacement of different technologies in the production of steel. This regular pattern is quite remarkable in view of the territorial changes of Germany throughout this period and in particular between the German Reich before World War II and the Federal Republic of Germany thereafter.

The most important technological shifts in German steel production technologies start with the substitution of the medieval bloomery process by the puddling process, which saturates its market share in the period from 1855 to 1865

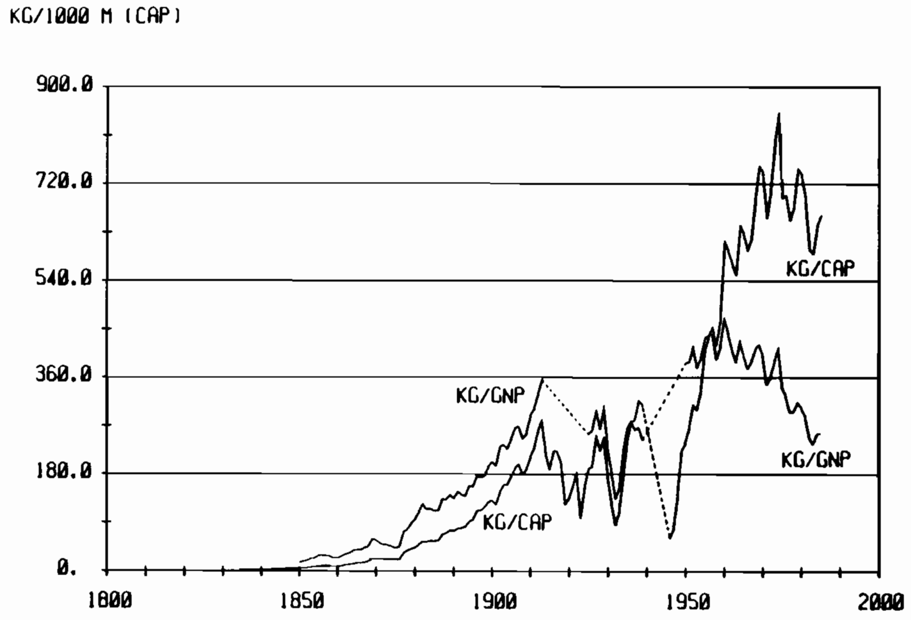


Figure 8.7. Germany (Federal Republic of Germany after 1945): steel production per capita and per unit of GNP.

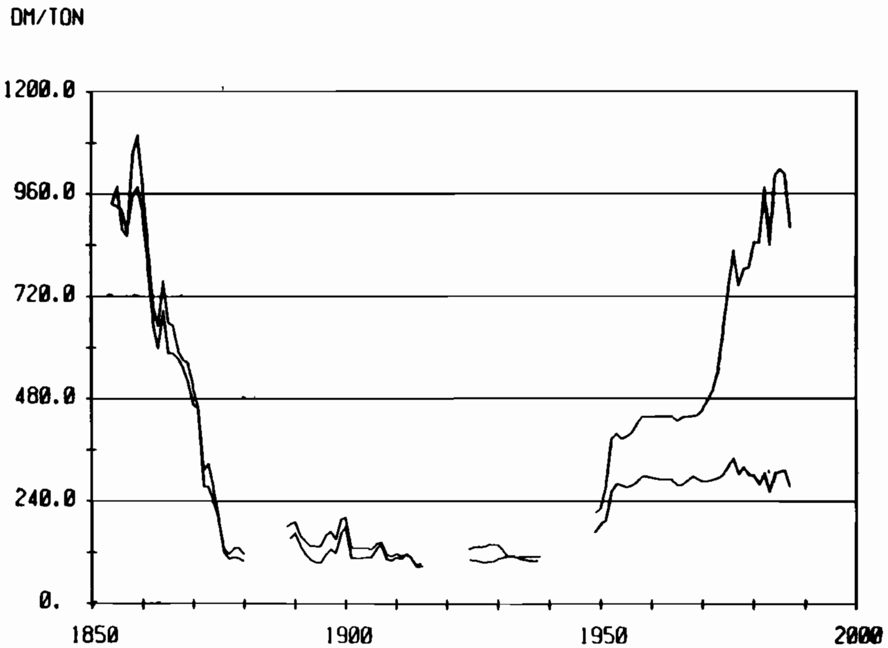


Figure 8.8. Germany (Federal Republic of Germany after 1945): nominal and constant steel prices.

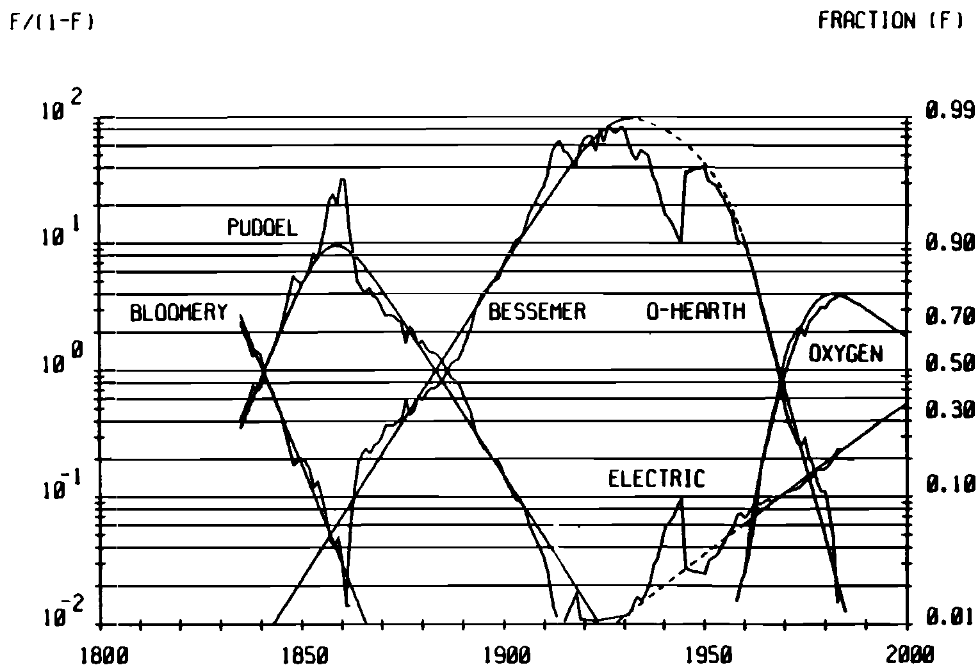


Figure 8.9. Germany (Federal Republic of Germany after 1945): substitution of steel production processes.

(period of introduction of the Bessemer process) and then is consequently replaced by the Bessemer and later by the open hearth processes.[3] The diffusion of the last two technologies follows a regular logistic path in the period from 1875 to around 1910, when the two technologies enter their phase of saturation. After 1910 the electric arc process emerges, which after some turbulence (the share of recycled scrap in total steel production increased dramatically during the wars) resumes a regular diffusion pattern in the second half of the twentieth century.

At the beginning of the 1960s one observes the appearance and fast adoption of another technology, i.e., the basic oxygen blown furnace (BOF or LD process). The emergence of a major technological innovation during a period of steady growth is in contrast to what we have observed in the past, when new technologies appeared during the phase of saturation of the predominant technology (coinciding to some extent with periods of economic fluctuation and depression). Still, it is interesting to note that, despite the appearance of the BOF technology falls outside the observed historical pattern, the diffusion of the BOF process enters its phase of saturation around 1973 and appears in the long term to be replaced by the electric arc process.

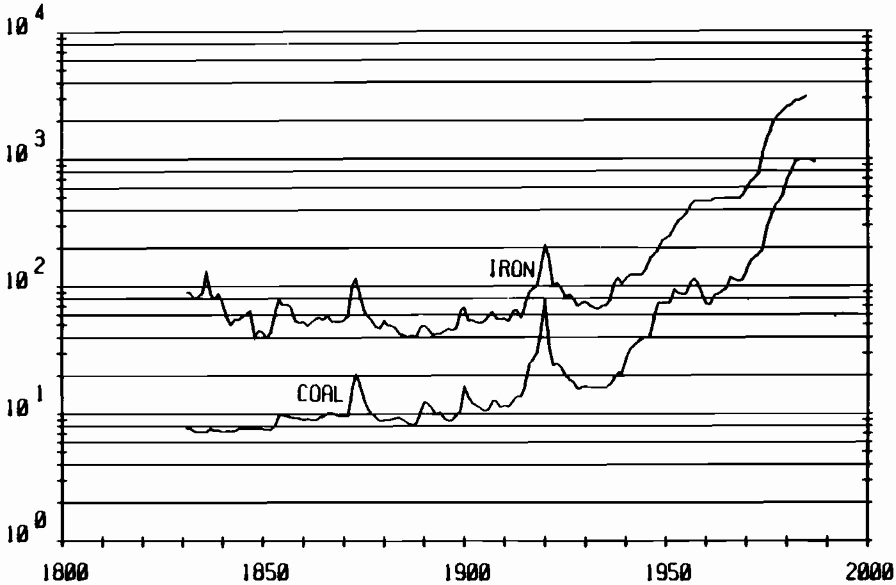
The case of steel production technologies in Germany supports thus the earlier statements in this paper that new technologies follow a regular diffusion pattern during phases of stable economic growth and approach their saturation stage during those periods defined as downswing and depression phases in the long-wave literature.

Figure 8.10 presents a time series for nominal and real prices of coal and pig iron (raw steel since 1965) for the United Kingdom. This example serves primarily to point at distinct price flares in the long-term evolution of coal and iron prices, whereas the cyclic nature of price fluctuations will not be further discussed on the basis of this particular example. *Figure 8.10* draws our attention in particular to the three distinct flares in nominal and real prices that occurred in 1835 (pig iron), after 1870 (coal and pig iron), and around 1920 (coal and pig iron). After 1940 nominal prices increase dramatically in line with inflation, and two flarings of real prices can be observed around 1950 (coal and pig iron) and around 1975 (raw steel) and 1980 (coal).

Under the assumption that price flares are indicators of periods of structural change in the system, we will now analyze the technology changes in crude steel production in the UK (*Figure 8.11*). Contrary to the example presented of Germany, the available data (Mitchell and Deane, 1971) for steel production according to processes go back only to 1871 and refer only to ingots and castings production. Thus, detailed statistics on a very important market segment of the UK steel industry in the nineteenth century – namely, the production of high-quality tool steel (Sheffield steel) by the crucible process – are missing, but it is clear that most of the steel production prior to the invention of the Bessemer process in the United Kingdom was in the form of crucible steel (Tweedale, 1986). Following the diffusion pattern in the USA, it took approximately 15 years for the Bessemer process to displace much of the market share of the crucible process, until the Bessemer process in turn was displaced by the open hearth process in the UK. Thus, it would be fair to assume the year 1870 (15 years after the introduction of the Bessemer process) as the approximate saturation period in the market share of the Bessemer technology. Since this question of the saturation date of the market share of the Bessemer process cannot in the absence of available statistics be resolved at present, the discussion will concentrate on the later period.

One can identify in the available data segment a regular diffusion pattern of open hearth technology versus the Bessemer process during the time period 1871 to 1920 when the open hearth process enters its phase of saturation (1920–1960). During World War I electric arc steel appears, and the market share of the various technologies shows no particularly regular pattern during the saturation phase of the open hearth and the emergence of electric arc steel. It is only with the appearance of the BOF technology around 1960 that a regular technological substitution pattern is resumed with the BOF replacing the open hearth process until it reaches its market saturation in the early 1970s. Along with this, one observes a steady decline in real steel prices which is only reversed the moment BOF technology reaches its saturation (and eventually its limit in cost reduction potential).

As a result, there exists evidence that the major turning points in the structural change of the system (especially with regard to the beginning of the saturation phase of the dominant technology and the emergence of new technologies) coincide with price flares, which are at least for 1870, 1920, and the present to (*a*) S/TON



(*b*) Index

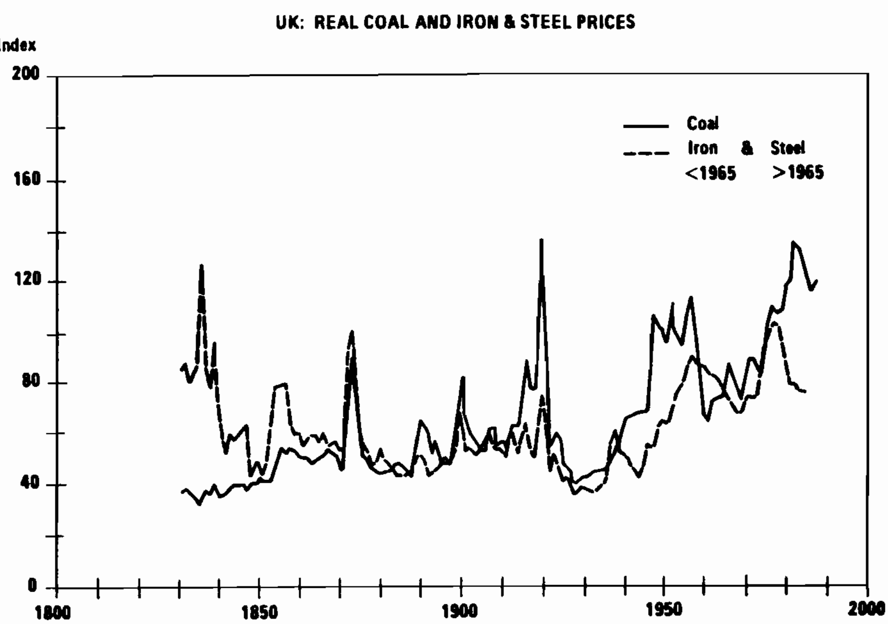


Figure 8.10. United Kingdom: nominal (*a*) and real (*b*) prices for coal, pig iron (1831–1964), and raw steel (1965–1985).

some extent consistent with phases of downswing or depression in a long-wave context.

Figure 8.12 shows the substitution of different steel production technologies in the USA. As already discussed in the examples of Germany and the UK, a strong correlation between major structural changes and turning points in technological change with the periods of downswing and depression in a long-wave context can be observed. This is illustrated by the saturation of the Bessemer process in the late 1870s, of the open hearth process at the end of the 1930s, and of the BOF process starting around 1975. During periods of stable economic growth (1890 to 1930 and 1955 to 1970), a regular pattern of technological diffusion and substitution in steel production technologies emerges from *Figure 8.12*.

Let us now consider whether these important dates of the technological change in the US steel industry can also be identified in another indicator of technological change, namely, in factor input (energy consumption).

Figure 8.13 presents the specific energy input per ton of raw steel production in the USA. Despite the fact that there is a considerable gap in the available statistics, one can still discern the historical tendencies both in energy input (specific energy consumption) and in the composition of energy input. The evolution of specific energy consumption [*Figure 8.13* (*a*)] clearly exhibits a typical learning curve, where energy efficiency of steel making dramatically increases in the period between 1850 and 1920. After this time, energy efficiency still increases, however, not in the previously exponential manner but only in a linear trend, which is illustrated well in the available statistics from 1947 onward. This trend in the learning curve of energy requirements of steel production in the USA is confirmed also by European data (see Decker, 1976).

The year 1920 represents also an important date in the structural change of the *composition* of the energy inputs *Figure 8.13* (*b*). By that time the substitution process of bituminous coal for the traditional fuels charcoal and anthracite coal is completed and the system is almost entirely based on coal as fuel. It is interesting to note that prior to 1850 a similar substitution pattern of anthracite coal for charcoal can be observed, with the market share of anthracite reaching its saturation level between 1860 and 1870 with more than 50 percent of all energy requirements in steel production. This illustrates that it takes about 50 years between the shift in the market dominance of a particular fuel.

The situation characteristic for the beginning of this century, where practically all energy requirements were provided by a single source of primary energy, is in contrast to the situation after 1950. Here the energy is provided by four different energy sources: coal, oil (with a declining market share), natural gas, and electricity (with an increasing market share). Although the available statistics do not allow linkage between the two data series directly, one can by extrapolating structural change tendencies into the past observe that the important turning point in the introduction of new fuels into the steel sector and, thus the important structural change from a system relying on a single source of energy into a system with a diversified supply, occurred in the period from 1920 to 1930.

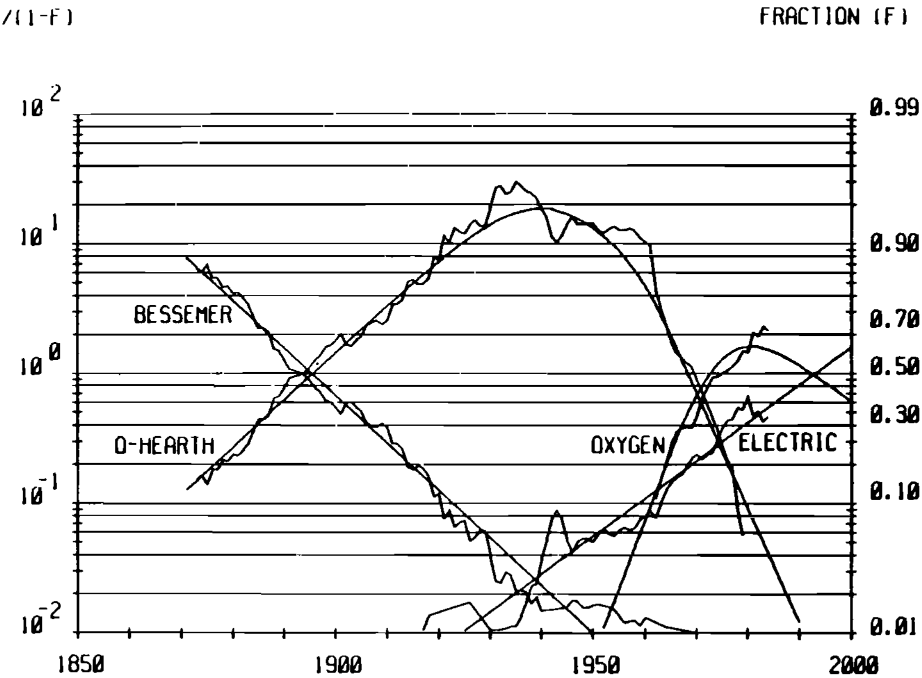


Figure 8.11. United Kingdom: substitution of steel production processes.

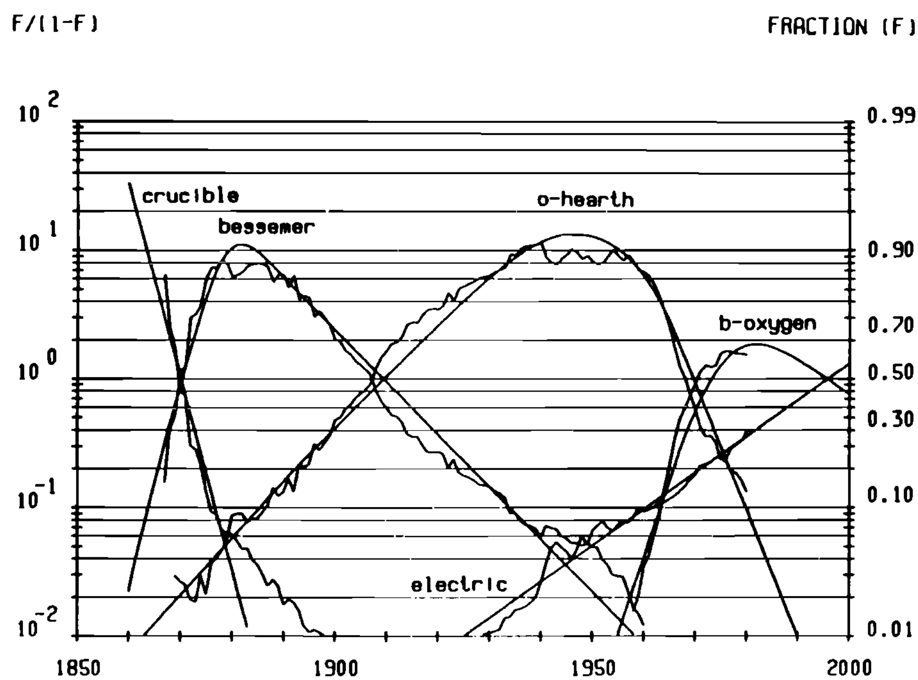


Figure 8.12. USA: substitution of steel production processes.

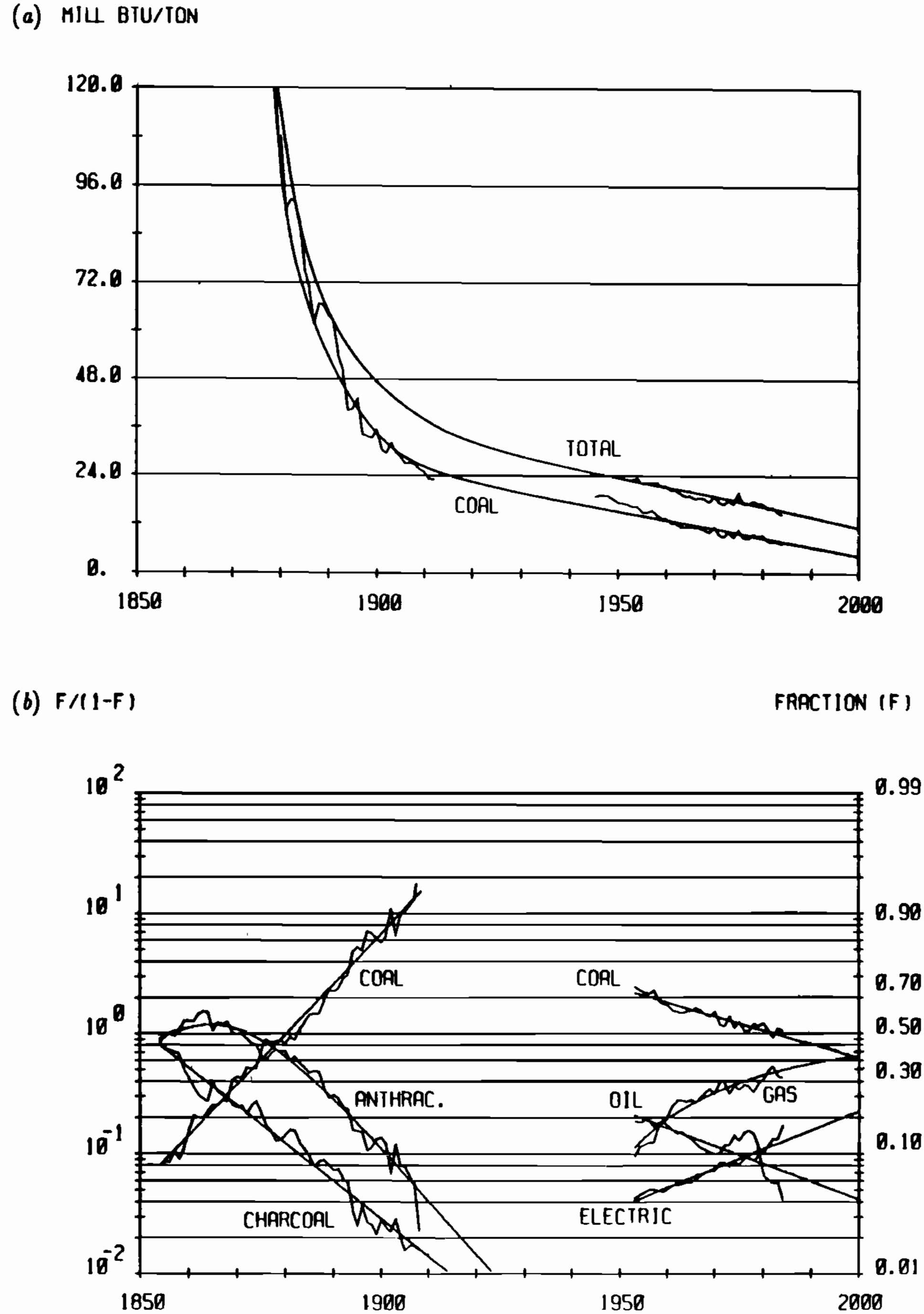


Figure 8.13. USA: specific energy consumption in raw steel production (*a*) and substitution of final energy carriers in the steel sector (*b*).

This structural change period coincides with another important date in the technological change of the system: the saturation of the open hearth process and the introduction of the electric arc process.

8.4. Technology Change in the Coal Industry (Mining and Use)

Figure 8.14 shows the evolution of world coal production from 1860 to the present. As in the case of world steel production regular periods of growth and fluctuation in world coal production can be identified. Long-term evolution can be described by a succession of two growth pulses that overlap during the period 1920 to 1945, where production oscillated between the boundaries defined by the two consecutive growth pulses.

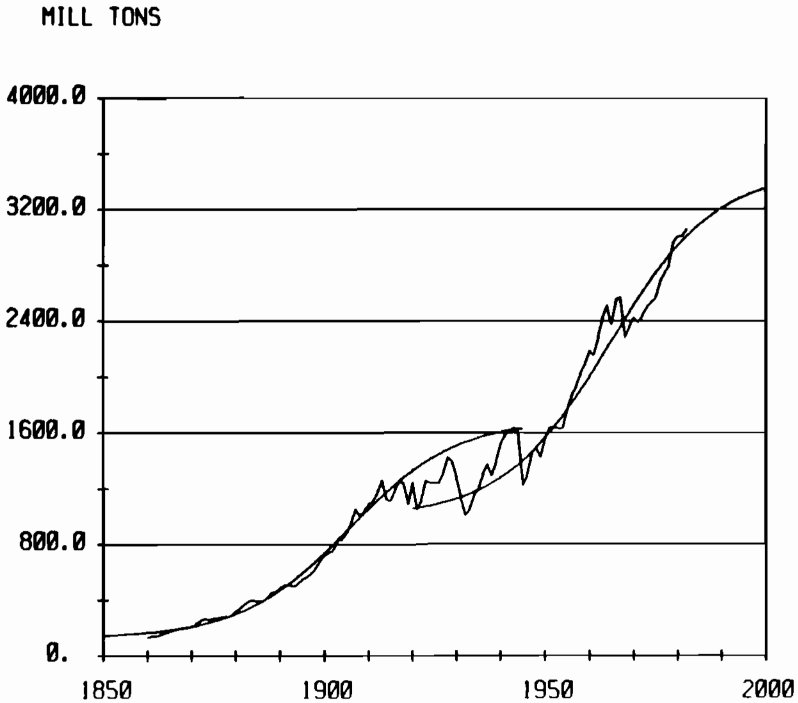


Figure 8.14. World: growth pulses in coal production.

A similar picture can be seen in the evolution of coal production and consumption figures for the UK, the country with the longest recorded history of coal production. *Figure 8.15* presents the history of coal production and consumption for the UK since 1700 and piecewise secular trends of homogeneous growth rates in the periods 1720 to 1760, 1760 to 1820, 1820 to 1870, 1870 to 1910, and then a less pronounced secular downward trend starting around 1960 becomes apparent. *Figure 8.16* illustrates these secular movements in terms of the deviation of coal consumption in the UK from a 50-year moving average.

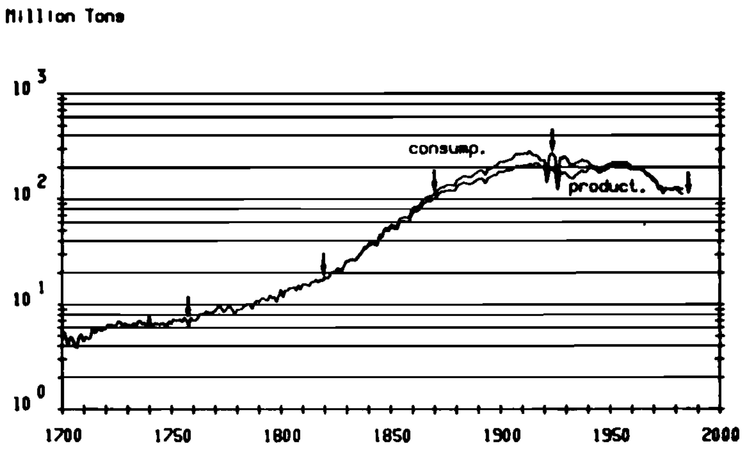


Figure 8.15. United Kingdom: coal production and consumption and periods of change in secular growth rates.

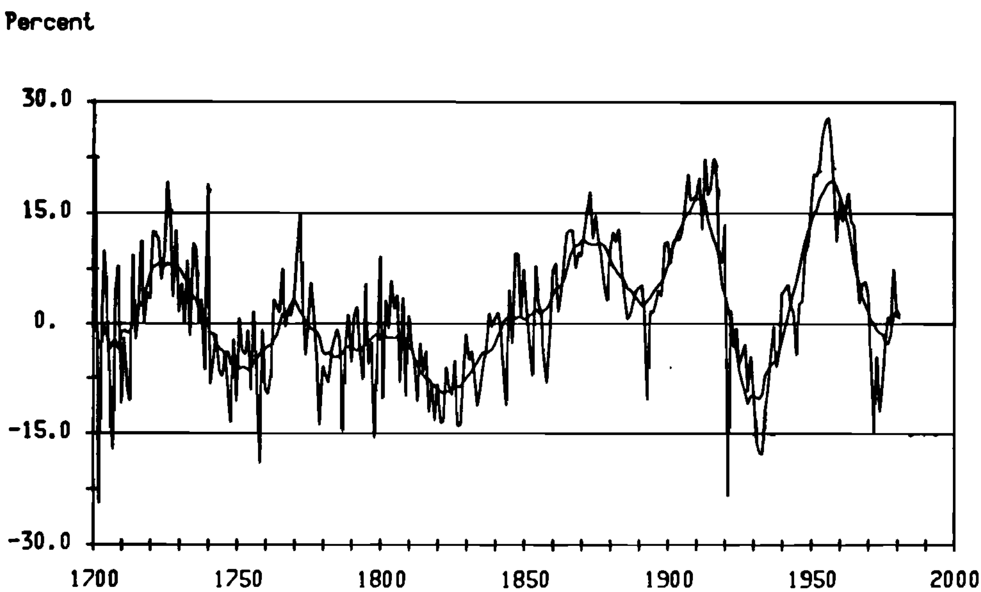


Figure 8.16. United Kingdom: long wave in coal consumption (percent deviation from 50-year moving average).

These deviations are smoothed by applying a 9-year moving average, with the smoothed secular deviations also being presented in *Figure 8.16.*

With regard to long-term price movements, which were already presented (in nominal and real terms) in *Figure 8.10* and which are further analyzed in *Figure 8.17* with regard to their deviations from a 50–year moving average

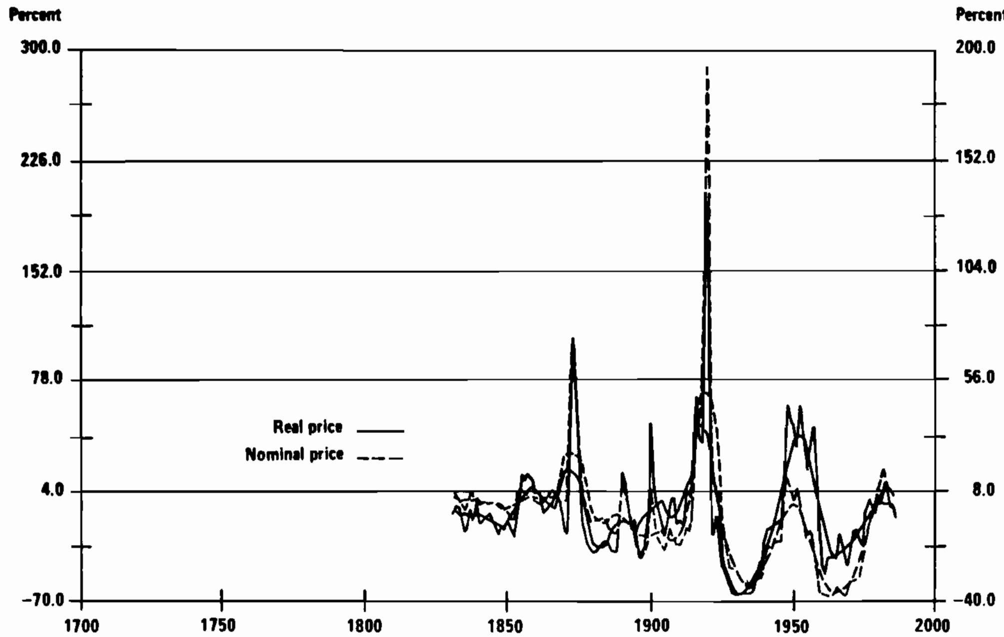


Figure 8.17. United Kingdom – long wave in nominal (left scale) and real coal prices (right scale), in percent deviation from 50–year moving average. (Source: Nakicenovic, 1987.)

(deviations are smoothed by a 9–year moving average), one observes an overlap of the secular movements in production and consumption and prices. With regard to peaks, the two secular movements harmonize for the period 1870, lag for 10 years in 1910 (consumption) and 1920 (price), and harmonize again during the 1950s. With regard to the troughs the two movements show a similar pattern only in the 1930s and a ten-year time lag between 1965 (price) and 1975 (consumption). Apparently, the frequency of the observed fluctuations has somewhat increased in the post–World War II period.

Before turning to a brief discussion on the long-term evolution of factor inputs (labor productivity) in coal production and its relation to technological change in the mining sector, another (social) indicator to determine periods of fluctuations and structural changes will be discussed. *Figure 8.18* presents the strike rates in the mining sector of the UK in the last 100 years. The original statistics refer to the number of workdays lost owing to working disputes; using this absolute measure the number of strike days in the 1980s amounts to 20 million lost workdays. This figure is not very high in comparison with the strikes in 1921 and 1926 with more than 70 million and nearly 150 million lost workdays, respectively. One has, however, to consider that the employed workforce in the coal-mining sector has drastically decreased between the 1920s and the present. Thus a relative measure, i.e., the number of strike days lost in relation to the total number of available workdays, was analyzed in *Figure 8.18*. As can be seen, the period 1912 to 1926 and the period since 1970 are particularly

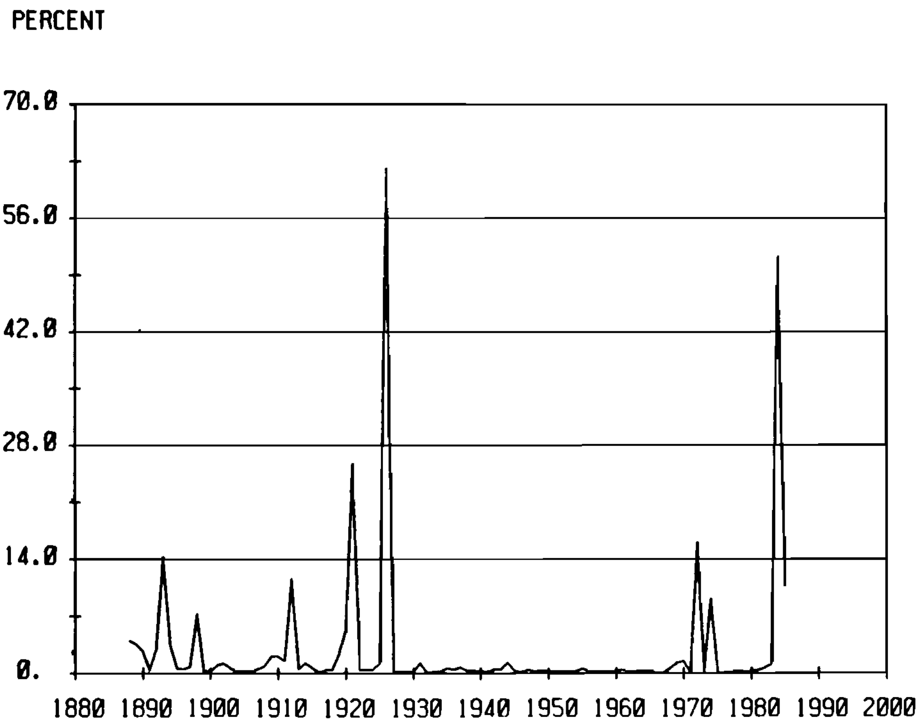
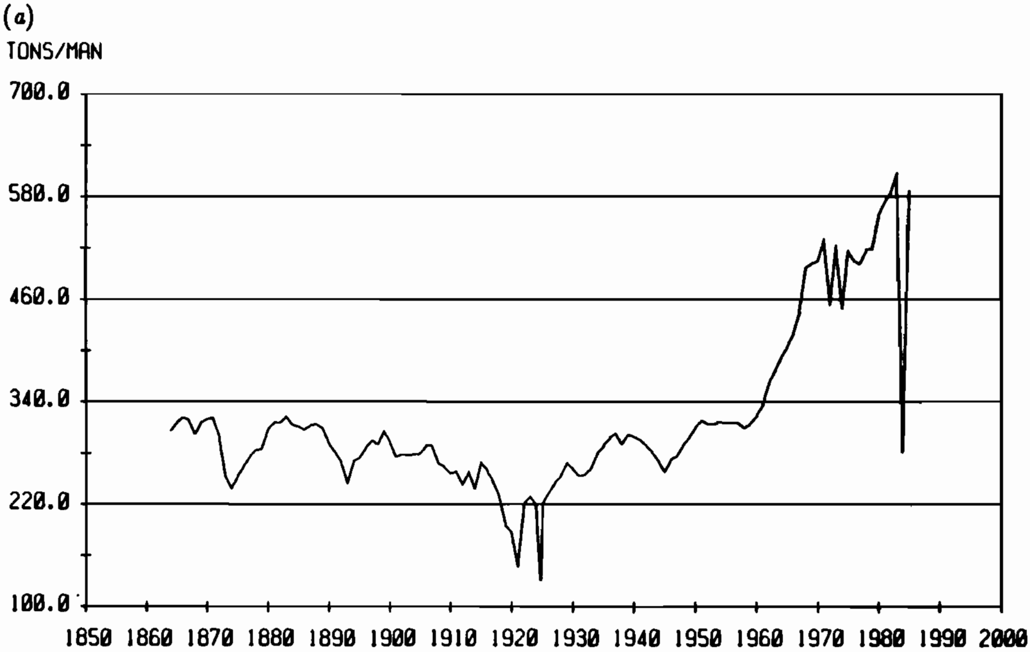


Figure 8.18. United Kingdom: percent of total workdays lost owing to strikes in mining and quarrying.

noticeable periods for intensive work disputes whereas during the period 1930 to 1970, the strike activities remained at a relatively low level. Incidentally the flares in strike activity occur at the same time as other indicators used so far to point out important turning points in the structure of the system.

Figure 8.19 shows the evolution of labor requirements (labor productivity) in UK coal mining. The productivity showed a downward trend over the period 1860 to 1925, with troughs in the productivity figures corresponding to the years of intense working disputes. This productivity decrease is primarily a consequence of resource depletion, as deeper deposits are mined, whereas the mining operation continues to be essentially a manual one.

Since 1925 labor productivity shows a reversal of the secular trend, in that 1925 productivity increased steadily (except for the wartime period 1939 to 1945) and reached a first level of saturation in 1970. This productivity increase is caused by the diffusion of mechanization technology (which will be analyzed later in more detail for the case of Germany), in terms of mechanization of winning operations (introduction of pneumatic picks and later shearers) and coal loading operations, as shown in *Figure 8.19.* Thus the massive introduction of pneumatic picks in the mid-1920s, followed by the increasing use of mechanized face operation schemes, is translated as an increase in the labor productivity, despite a continuation of the worsening in geologic conditions. Whereas the appearance



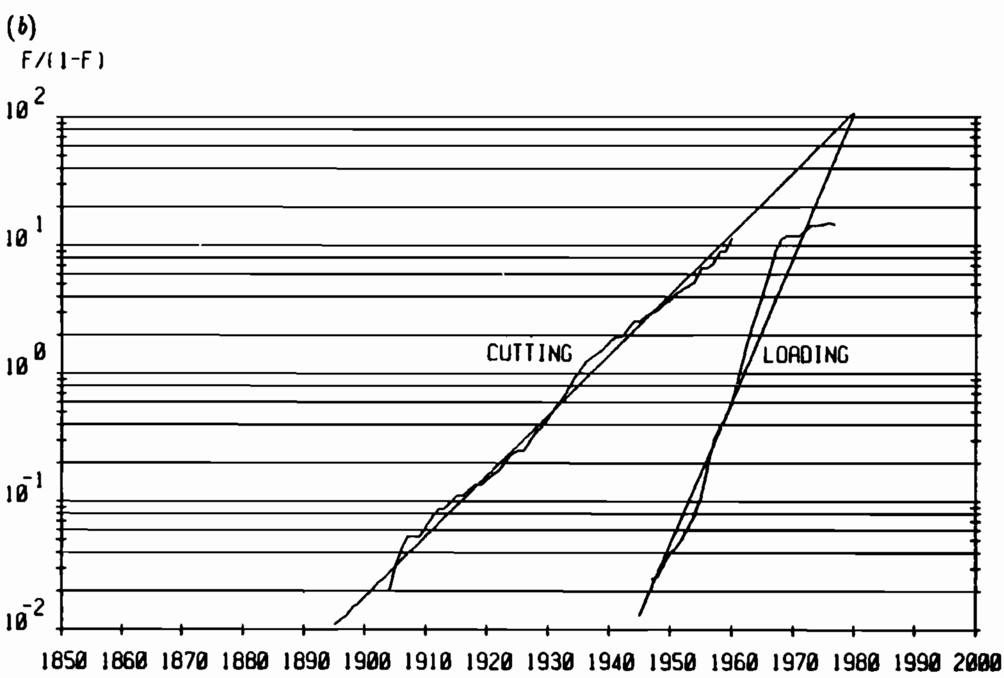


Figure 8.19. United Kingdom: labor productivity (*a*) and diffusion of mechanization (*b*) in coal mining.

of pneumatic picks and first shearers in the 1920s is consistent with earlier observations that important innovations tend to be introduced in periods of structural change and turbulence, one cannot follow a similar logic when analyzing the introduction of mechanical loading into the UK mining industry after 1945. However, it is interesting that the ultimate saturation of the two technology diffusion processes appears to be synchronized (1980). Also visible in *Figure 8.19* is the effect of the beginning saturation phase of mechanization (in passing more than 90 percent of total production) on productivity. This example would thus support the hypothesis of the importance of the simultaneous *saturation* of technology diffusion as a causal factor for economic depression periods.

Figure 8.20 analyzes the development of the underground labor productivity in coal mining of Germany (Federal Republic of Germany) similar to the previous analysis for the UK. Again two distinct phases in the development of labor productivity become apparent. The productivity, which remained practically constant up to the mid-1920s, is drastically increased as a consequence of the rapid diffusion of pneumatic picks as the first technology of mechanization in coal mining. This particular diffusion process saturates in the early 1930s when practically 100 percent of the total production is won with pneumatic picks. As the diffusion of the first mechanization in coal mining is saturating, the labor productivity (which doubled compared with the period when mining was essentially a manual process) is stagnating.

After World War II a regular pattern of diffusion of semi-mechanized mining technologies (mechanization of coal winning by shearers and of transport operations by conveyors) and later of completely mechanized mining schemes (mechanization of winning, transport, and development operations by means of self-advancing hydraulic roof supports) emerges, resulting in a doubling of the prewar productivity level. With the saturation of the diffusion of complete mechanization in the mid-1980s no further significant improvements in the labor productivity are to be expected (especially in view of ever worsening geologic conditions), unless a new technology (e.g., automation) is introduced.

The saturation of the diffusion of new technologies and its impact on factor input (labor productivity) and ultimately the costs of production can consequently be considered an important contribution to the stagnation of a particular sector. The simultaneous saturation in the technology diffusion of a number of key sectors in turn could provide an explicative model of long-term economic fluctuations.

At the end of this discussion of the technological changes in the coal sector, let us briefly consider the structural changes in the market outlets. The most important utilization of coal in the nineteenth century related to supplying the energy requirements of industry and households, the conversion of coal into secondary energy forms (in particular, coke and town gas), and fueling the transport sector (steam engines). Since 1900 one observes a shift in the market outlets especially for conversion into secondary energy carriers and in the transport sector.

Whereas the conversion to coke still constitutes an important market for coal, we observe a dramatic shift in the use of coal for the production of other secondary energy carriers. The production of town gas from coal has

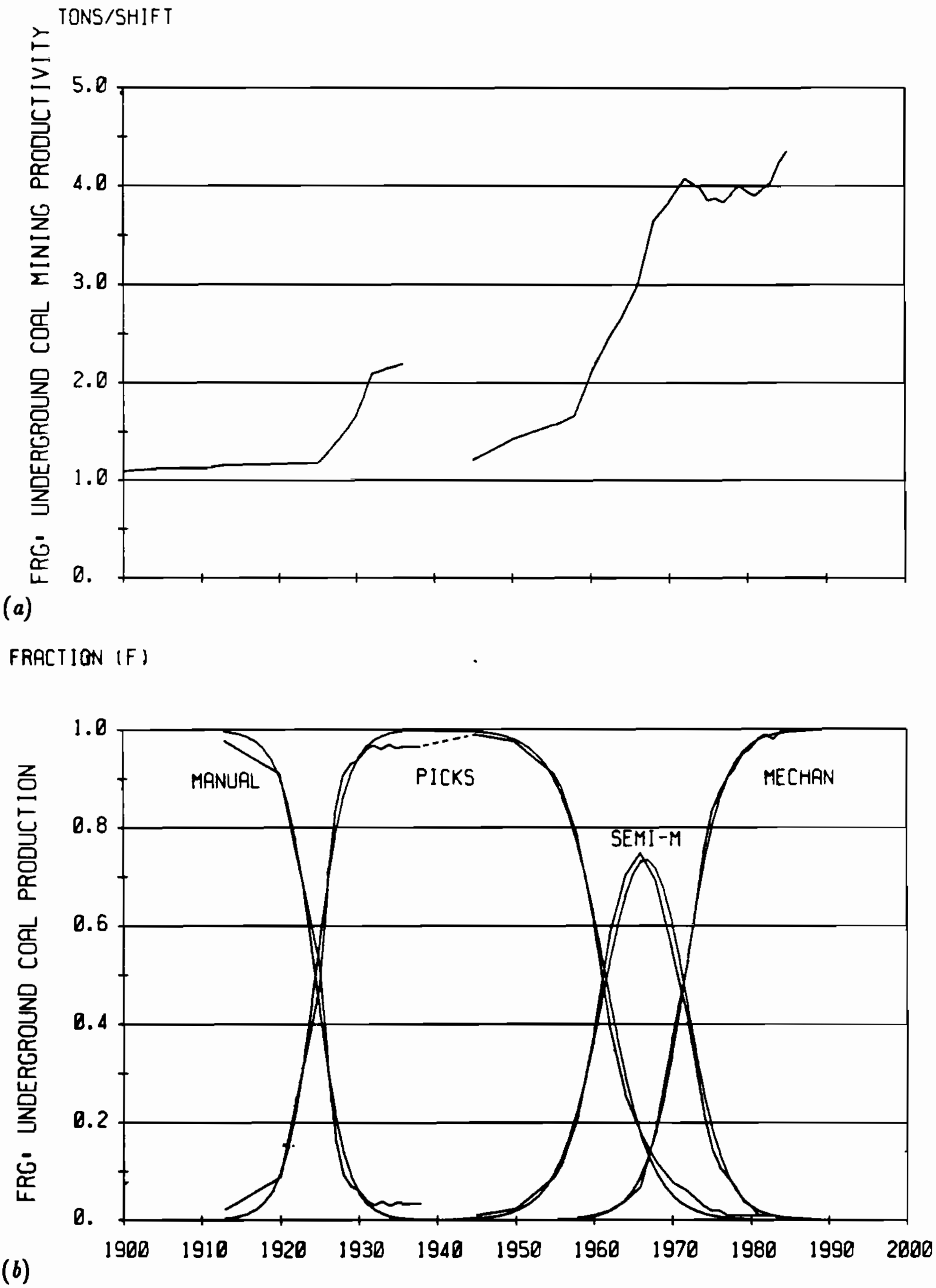


Figure 8.20. Germany (Federal Republic of Germany): underground labor productivity and substitution of mechanization technologies.

disappeared in all industrialized countries as a result of the substitution of gas for lighting purposes by electricity and by natural gas for other uses. Instead, the electricity-generating sector has in the period 1920 to present become the most important market for coal, both in absolute and in market share terms. Currently electricity production represents around 70 percent of total coal consumption in the UK and the Federal Republic of Germany, and around 80 percent in the USA.[4] The use of coal in the transport sector, which reached its peak around 1920 with more than 23 percent of total coal consumption in the USA and around 15 percent of total coal consumption in the UK, has entirely disappeared as a consequence of the substitution of the steam engine for the internal-combustion engine. This substitution occurs both in water transport (ships) and in ground transport (railways).

Figure 8.21 illustrates this substitution process of the coal-fired steam engine for the internal-combustion engine based on petroleum products in the case of the UK. In the figure the substitution process in terms of the total tonnage of ships registered in the UK fleet is presented, and a regular technological diffusion pattern emerges. Sail ships are replaced by steamships, which are introduced into the market in the mid-1820s and saturate their market share by 1920. Since that time period steamships are replaced by motor ships, resulting in the loss of the market outlet for coal for this application. For the USA a similar pattern can be observed.

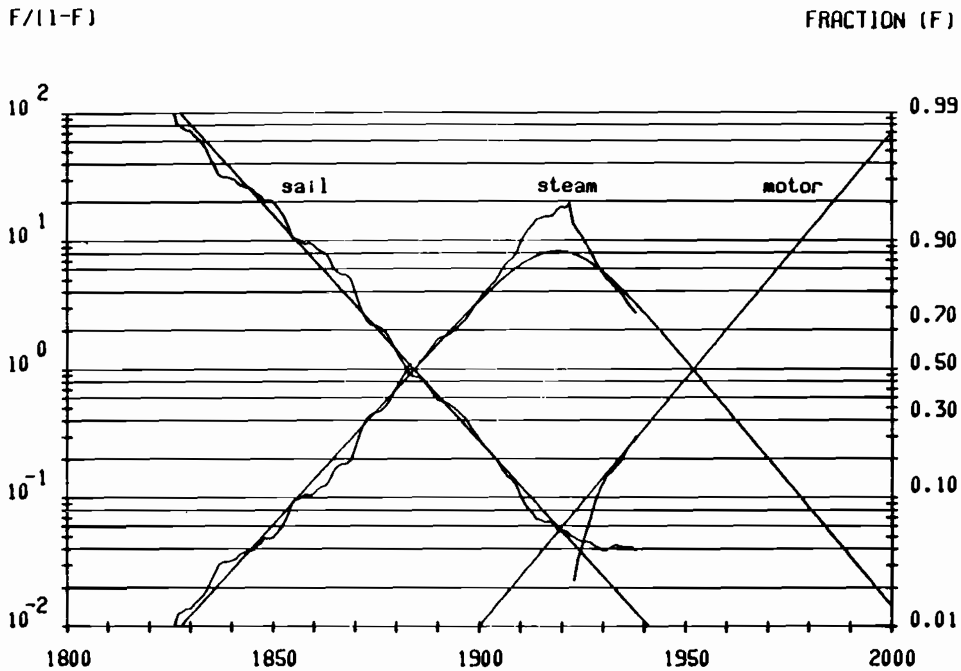


Figure 8.21. United Kingdom: substitution of propulsion in tonnage of ships registered. (Source: Nakicenovic, 1987a.)

In a similar way, coal-fired steam locomotives are replaced by diesel locomotives (illustrated in *Figure 8.22* for the USA). Since the end of the 1930s steam locomotives are replaced by diesel locomotives along a logistic substitution path. This substitution process was completed by the beginning of the 1960s and currently the entire locomotive fleet of the USA consists of diesel locomotives (contrary to Europe, electric locomotives have no practical importance in the USA). The result from these technological substitution processes in the transport sector initiated in the 1920s and 1930s was a complete disappearance of coal utilization in the transport sector and the loss of this important market outlet.

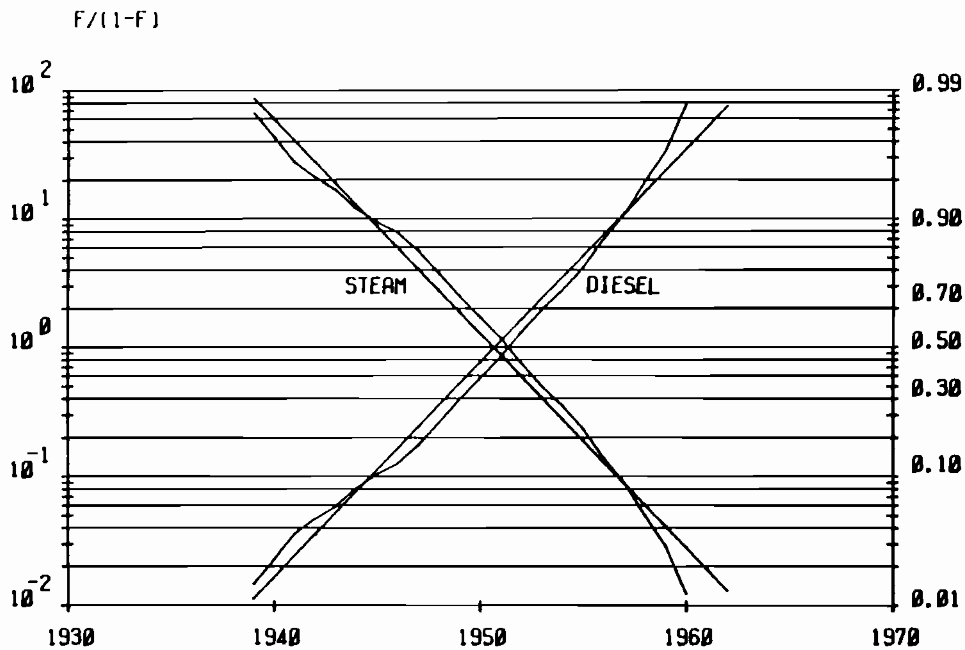


Figure 8.22. USA: substitution of steam for diesel locomotives. (Source: Nakicenovic, 1987b.)

8.5. Conclusion

The illustrative examples from the steel and coal sector presented in this paper provide evidence to support the hypothesis that technological change is closely related to *Wechsellagen* in long-term economic development.

A variety of different indicators has been used to illustrate that historically one can discern periods of turbulence from periods of stable economic development, where stable growth in output, regular technological diffusion patterns, and stable (real-term) prices are observed.

The regularity of growth and technological diffusion patterns during upswing phases seconds the contention that long-term economic fluctuations are to a large extent driven by the growth and the resulting saturation of technologies.[5] The regularity of technological diffusion processes (as captured quite accurately by the logistic substitution model), i.e., the *somnambulisme* in the structural change of a technological system during the phase of regular economic growth, is seen as a result of the *comparative advantage* (with regard to quality of output, economics of production, and response to societal needs) of new technologies over old ones.

Stable growth periods are followed by periods of stagnation and turbulence (depressions), during which time a high degree of *clustering of saturations* (saturation of market growth and subsequent oscillation of output levels and the saturation in market penetration and in efficiency improvements of technologies) can be observed. The *clustering of saturations* in the diffusion of different technologies is not necessarily related to the introduction date, i.e., technologies that are introduced at a later date tend to diffuse faster and reach saturation at a similar time period to technologies introduced much earlier into the system. During this *clustering of saturations* of leading technologies and markets/products, new technological innovations very often emerge and flares in nominal/real-term prices and social indicators can be observed.

Thus it is my contention that long-term fluctuations in economic activity are caused by the overlap of the main growth phases in output and technology diffusion *and* the subsequent *clustering of saturations* in markets, in output, and in the diffusion of technology, in particular, in those key sectors responsible for much of the previous economic growth.

The examples analyzed in this paper from the steel and coal industries are seconded by similar types of development patterns in the field of primary energy and transport infrastructures, which can be considered as (aggregate) "metatechnologies," and are analyzed by Nakicenovic in Chapter 9.

The *clustering of saturations* hypothesis thus draws on examples of the saturation of primary energy carriers (coal), infrastructures (railways) [6], steel technologies (open hearth processes), and mining technologies (first mechanization of coal mining with the introduction of pneumatic picks), among others, to explain, for instance, the depression of the 1930s. In that respect it is noticeable that the diffusion rates of these examples are widely different. In the case of the primary energy share of coal and the expansion of the railway network, the time constant is around 100 years; in the case of the diffusion of the open hearth process it is around 50 years; and in the case of coal mechanization the diffusion rate amounts to only 20 years. Still the dates of saturation of all these technologies fall within a relatively short time period, between 1920 to 1935.

It would be illusionary to expect from such a working hypothesis as the *clustering of saturations* a perfect synchronization with the historically observed depression dates. Consequently, similar saturation phenomena or price flares outside the 50-year pattern of Kondratieff cycles can be found. Examples for this saturation of technology diffusion and price flares *during* periods of economic growth include the saturation of the puddling process in Germany around 1860, the price flares and long-wave upswing in coal and steel prices in the UK around

1950, and the date of the trend shift in one steel intensity indicator for the Federal Republic of Germany (per capita steel production) around 1960. This, however, is not necessarily a contradiction to our working hypothesis, as the saturation dates should be considered in terms of a frequency distribution around the depression date of a Kondratieff cycle, rather than in terms of a rigid synchronization.

The regularity of growth rates, the regular technological diffusion patterns, and their overlap in time, as well as the coincidence of the (– in a larger sense – simultaneous) saturation in output and technology diffusion and the often-observed emergence of new technologies during these saturation phases would point to a Schumpeterian view of long-term economic development.

More phenomenological evidence has still to be assembled before the conclusions of this paper can decisively be confirmed and a causal model of economic *Wechsellagen* can be developed. The preliminary phenomenological cluster presented in this paper is intended to provide the basis for such a model, in which technology diffusion and growth, clustering of technology and market saturation, and a certain degree of clustering in the introduction of key technological innovations are considered as driving forces of economic development.

Notes

[1] For example, van Duijn, 1983; Freeman, 1983; Hartman and Wheeler, 1979; Kleinknecht, 1984; Kondratieff, 1926; Kuznets, 1930; Rostow, 1975; Schumpeter, 1939; Stewart, 1982.

[2] This particular model draws an analogy to the behavior of biological systems in using models of S-shaped growth patterns, like the logistic curve (Verhulst, 1838), used in biology to describe the growth and the dynamics of interaction of biological populations (Goell, Maitra, and Montroll, 1971; Lotka, 1910; Pearl, 1925). The theoretical basis for an application of such models in the technology and market area can be found in the concept of product life cycles as well as in the theories of the adoption and diffusion of new innovations, in both time (Rogers, 1962; Bass, 1969 and 1980) and space (Hägerstrand, 1967).

[3] Contrary to other countries (e.g., the UK and the USA) one cannot observe a displacement of the Bessemer process by the open hearth process in the case of Germany. The reason for the continuing importance of the Bessemer process can be found in the available iron ore resource base of continental Europe (e.g., the high phosphorous ores of the Lorraine) for which a variant of the Bessemer process, the basic Bessemer, or Thomas process was particularly suited.

[4] For a detailed overview of the historical changes of the market outlets of coal produced in the Rhur basin of the Federal Republic of Germany see Wiel, (1970).

[5] At this point it is necessary to stress the synergistic effects of the growth of a *number* of key sectors in explaining major upswings in economic development. Thus, a number of sectors would have to be studied under the "leading sector" hypothesis (Rostow, 1962; Hirschmann, 1967) in order to explain the extent of economic growth during certain time periods of intense economic development. See, for instance, Holtfrerich, 1973, and Fremdling, 1975, for an analysis of coal and railways in the economic development of Germany in the second half of the nineteenth century.

[6] For additional evidence see also Mothes, 1950.

References

Bass, F.M., 1969, A New Product Growth Model for Consumer Durables, *Management Science* **15**:215–227.

Bass, F.M., 1980, The Relationship Between Diffusion Rates, Experience Curves and Demand Elasticities for Consumer Durable Technological Innovations, *Journal of Business* **53**:51–67.

Decker, A., 1976, *Energy Accounting for Steel*, 9th International TNO Conference: The Energy Accounting of Materials, Products, Processes and Services, TNO, Applied Scientific Research Organization, Delft, The Netherlands.

van Duijn, J., 1983, *The Long Wave in Economic Life*, George Allan and Unwin, London, UK.

Fisher, J.C. and Pry, R.H., 1971, A Simple Substitution Model of Technological Change, *Technological Forecasting and Social Change* **3**:75–88.

Freeman, C., ed., 1983, *Long Waves in the World Economy*, Butterworths, London, UK.

Fremdling, R., 1975, *Eisenbahnen und deutsches Wirtschaftswachstum 1840–1879.* Gesellschaft für westfälische Wirtschaftsgeschichte, Dortmund, Germany, F.R.

Goell, N.S., Maitra, S.C., and Montroll, E.W., 1971, On the Volterra and Other Nonlinear Models of Interacting Populations, *Rev. Mod. Phys.* **43**:231–276.

Hägerstrand, T., 1967, *Innovation Diffusion as a Spatial Process*, University of Chicago Press, Chicago, IL, USA.

Hartman, R. and Wheeler, D., 1979, Schumpeterian Waves of Innovation and Infrastructure Development in Great Britain and the United States: The Kondratieff Cycle Revisited, *Research in Economic History* **4**:37–85.

Hirschmann, A.O., 1967, *Die Strategie der wirtschaftlichen Entwicklung*, Stuttgart, Germany, F.R.

Holtfrerich, C.L., 1973, *Quantitative Wirtschaftsgeschichte des Ruhrkohlenbergbaus im 19. Jahrhundert*, Gesellschaft für westfälische Wirtschaftsgeschichte, Dortmund, Germany, F.R.

Kleinknecht, A., 1984, *Innovation Patterns in Crisis and Prosperity: Schumpeter's Long Cycle Reconsidered*, Vrije Universiteit, Amsterdam, The Netherlands.

Kondratieff, N.D., 1926, Die langen Wellen in der Konjunktur, *Archiv für Sozialwissenschaft und Sozialpolitik* **56**(3):573–609.

Kuznets, S., 1930, *Secular Movements in Production and Prices*, A. M. Kelly, Fairfield, NJ, USA.

Lotka, A.J., 1910, *Journal of Physical Chemistry* **14**:271.

Marchetti, C. and Nakicenovic, N., 1979, *The Dynamics of Energy Systems and the Logistic Substitution Model*, RR-79-13, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Mitchell, B.R. and Deane, P., 1971, *Abstract of British Historical Statistics*, Cambridge University Press, Cambridge, UK.

Mothes, F., 1950, *Das Wachstum der Eisenbahnen, Zeitschrift für Ökonometrie* (1950), 1:85–104.

Nakicenovic, N., 1987a, private communication

Nakicenovic, N., 1987b, *Transportation and Energy Systems in the US*, WP-87-01. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Pearl, R., 1925, *The Biology of Population Growth*, Knopf, New York, NY, USA.

Roesch, K., 1979, *3500 Jahre Stahl, Abhandlungen und Berichte*, (1979) Vol. 2, Deutsches Museum, Munich, Germany, F.R.

Rogers, E.M., 1962, *Diffusion of Innovation*, Free Press, New York, NY, USA.

Rostow, W.W., 1962, *The Process of Economic Growth*, New York, NY, USA.

Rostow, W.W., 1975, Kondratieff, Schumpeter and Kuznets: Trend Periods Revisited, *Journal of Economic History* 35:719–753.

Schumpeter, J.A., 1939, *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process*, Vols. 1 and 2, McGraw-Hill, New York, NY, USA.

Stewart, H.B., 1982, *Technology Innovation and Business Growth*, Nutveco, San Diego, CA, USA.

Tarde, G., 1895, *Les lois de l'imitation, étude sociologique*, 2nd Ed., Germer Baillière et Cie., Paris, France.

Tweedale, G., 1986, Metallurgy and Technological Change: A Case Study of Sheffield Specialty Steel and America, 1830–1930, *Technology and Culture* 27(2):189–222.

Verhulst, P.-F., 1838, Notice sur la Loi que la Popluation suit dans son Accroissement, *Correspondence Mathématique et Physique* 10:113–121.

Wiel, P., 1970, *Wirtschaftsgeschichte des Ruhrgebietes Tatsachen und Zahlen*, Siedlungsverband Ruhrkohlenbezirk, Essen, Germany, F.R.