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Technology Diffusion in the Coal-Mining Industry of the USSR
An Interim Assessment

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ABSTRACT

This article presents an analysis of technological change in the underground coal-mining industry of the USSR. It describes within a quantitative framework first the evolution of the coal-mining industry in general, based on macro-indicators of output, production intensity, and labor productivity. The article then discusses qualitatively the different historical phases of technology development inside the industry and concludes by a quantification of technological diffusion trajectories, based on standard bi- and multi-variate models of technological substitution of the Fisher-Pry and Marchetti-Nakicenovic type.

The paper not only provides insight into the dynamics of technological change in the coal-mining industry of the USSR, but also illustrates the applicability of standard technology diffusion and substitution models for the analysis of technological change in a planned economy. Although not exhaustive, the analysis presents a first step for the development of more comprehensive models of the causal forces behind the patterns of technological change identified, and for international comparisons of technology diffusion in the coal-mining sector.

Introduction

Technology diffusion in the coal-mining industry has received limited attention in the vast body of diffusion studies. [1] Whether this situation is possibly due to the fact that the coal industry as a mature industry sector with decreasing market shares in the total energy supply since 1945 has not attracted the interest of researchers, it is certainly not

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[1]Noteworthy exceptions are the studies by Mansfield [1,2] and, in the case of longwall mining, Souder and Quaddus [3] for the United States and Ray and Uhlmann [4] and Ray [5] for the United Kingdom. A good quantitative overview (however, outside of the statistical framework of classic diffusion studies) of technological developments in the hard-coal-mining industry of the Federal Republic of Germany is provided by Kundel [6, 7]. An overview of the long-term production and technology trends in the coal industry at the global level as well as in the United Kingdom and Germany is given by Grübler [8].

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warranted from the viewpoint of data availability on technical change in the sector or from the importance in terms of employment and contribution to the primary materials sector of an economy. In addition, the ***quantitative*** description of technological diffusion processes, or as it would be termed in the USSR, the quantitative aspects of ***rates and regularities of scientific and technical progress,*** is a rather recent field in the USSR and resulting studies are rather scarce.

The present study attempts to fill both gaps and to provide an interim assessment of technological change in the coal-mining industry of the USSR by analyzing some of the most important technological innovations occurring in the industry in the last 50 years against a background of a general discussion of the evolution of the industry in terms of output, production intensity, and labor productivity. The study is seen as a first step, in that the present discussion of technological trends in coal mining in the USSR. although fairly comprehensive, is by far not exhaustive and is intended to stimulate further research. The study provides a first test of the applicability of some of the standard methodological apparatus developed to analyze technology diffusion in market economies to the study of technological change in planned economies. As it turns out, the methodological instruments appear quite applicable, thus providing the basis for a subsequent cross-national analysis of technological change in the coal-mining industry. This follows earlier IIASA research on a cross-national comparison of resource requirements and the economics of the coal extraction process [9] and is intended to provide a deeper understanding of the dynamics and impacts of technological change in the coal-mining industry.

A Brief Overview of Coal-Mining Development in the USSR

THE IMPORTANCE OF EXTERNAL FACTORS IN THE DEVELOPMENT OF THE INDUSTRY

The historic development of the coal industry in the USSR has been highly influenced by a number of external factors, including the effects of the two world wars and of the October Revolution and also the effects of the discovery and subsequent development of large oil and natural gas resources, leading to a reorientation of the energy policy which had previously been entirely concentrated on coal. These external factors have to be taken into account in understanding the development of the USSR coal industry in general and of technological change in coal mining in particular.

The coal-mining industry was for a long time considered as the key branch in basic industries. The very large coal resources were basically the only base to support the ambitious plans of rapid and autonomous development of the industry of the USSR. The major role that technical advance had to play within this policy context was to support these extensive development programs. "More coal" was considered synonymous for an "improved efficiency" of the national economy. In view of the high targets to increase coal production, the predominant objective was to overcome the main limiting factor in this expansion of coal production, i.e., ***the*** fact, that coal mining was essentially a manual process with hard physical working conditions, thus impeding a dramatic intensification of coal production. This was the origin of the introduction of the first mechanization steps at coal faces, primarily through the rapid spread of the use of pneumatic picks and explosives for coal-winning operations.

Capital and labor constraints were not really limiting factors in these first mechanization steps, because the first measures of mechanization were relatively inexpensive and the coal industry was receiving high priority in the central allocation of investment funds. With increasing labor productivity and a relatively large labor force, the rapid expansion of the coal industry did not face any considerable labor supply constraints. The main drive in the development of the industry was aimed at production intensification as reflected in its most important indices like total industry output and, in particular, coal output per face and per mine. The most important technical innovations to reach this goal were introduced in the areas of face and transport operations.

With the discovery of important oil and natural gas resources, the situation with respect to coal was drastically altered. Coal demand did not decrease, however the growth rates of the coal industry slowed down considerably. Public attention and priorities in its development and capital investments were reduced. The main driving force for decision making was no longer the increase of output, but production enconomics. The social prestige of working in coal mines was also drastically lowered, particularly among the younger generation. Thus the main driving force for technological innovation in the coal-mining industry was shifted to the realization of economic (cost reduction) and social (safety and improvement of working conditions) goals. This period, which lasted from about 1955 to 1975, resulted in the introduction and rapid diffusion of a number of important technological innovations to pursue the economic and social goals and in particular to offset the effects of continuously deteriorating geological conditions at underground mines.

The time period after 1975 can again be seen as a new period in the development of the coal-mining industry in the USSR. The potential of the technological innovations introduced in the earlier period became progressively exhausted. While the returns of technical innovations decreased, ever more capital was required for further improvements of existing techniques as well as their introduction into new areas of applications. Improving social conditions, both in terms of safety and working conditions, required additional capital without resulting in a relief of the by now tight labor supply situation. The worsening of geological conditions at greater mining depths, particularly the European coal basins of the USSR, accelerated, and no principally new technologies were available for widespread introduction into the industry to compensate for these effects. Consequently the labor productivity at underground mines started to decline after 1975, and opencast mining appeared as the only main technological option available to the coal-mining industry, especially in view of the fact that labor productivity is on average ten times higher in opencast mines as in underground mines. Thus, while the output from underground mines more or less stagnated around 430 million tons since 1965, the output from opencast mines increased over this time period from 140 to 320 million tons.

SPECIFICS OF TECHNOLOGICAL INNOVATIONS IN THE COAL-MINING INDUSTRY OF THE USSR

Technological innovations in the USSR coal-mining industry are characterized by a number of rather specific features. These relate to the specific character of coal mining as an industrial process, as well as to the specific circumstances of the industrial development of the USSR at various historical time periods. Technological innovations thus have to be understood within the *technological, economic,* and *social* environments in which they are embedded.

The **technological** environment of importance to the understanding of technical change in coal mining in the USSR may be summarized as follows:

1. Coal mining in prerevolutionary Russia was essentially an entirely manual process, with mechanization largely limited to mining support functions like ven-

tilation, water drainage, and transport to the surface. Thus, the main driving force of technological change can be seen in the progressive application of mechanization to manual operations such as winning, loading, and transport, roof support, and driving of development workings.

2. Coal mines are in fact very heterogeneous, because of their differences in natural bedding conditions. Mining machinery has to be developed following the characteristics of each of these different conditions (e.g., thickness of coal seams and their inclination). Thus the life cycle of a particular innovation for a given mining operation (e.g., transport or development) appears to be rather long, as it involves a series of subsequent development cycles aiming at the progressive utilization of an innovation under a wide range of geological conditions; e.g., shearers and self-advancing roof supports were first developed for flat and medium-thickness seams, and drastically new equipment with the same name had to be developed for steep bedding and thin seams. This, however, happened much later.
3. The state of the art of coal-mining technologies at the world level does not propose a large number of radically different mining technologies (in the broad sense of the term) to result in drastically different technological solutions in different countries. Underground and opencast mining methods are used worldwide.[2] Underground mining systems can be subdivided into longwall and shortwall mining and room and pillar mining, with each of them relying on specific technologies or, as in the case of room and pillar mining, having a specific range of geological conditions where they can be applied, i.e., only in relatively shallow (above 300 meters depth) deposits. Opencast mining systems can also be subdivided into three or four subvariants. Hydraulic underground mining (winning by water jet and coal transport by gravity flow of the coal-water slurry) is listed as the third principal technological system in Soviet statistics; however, this method is used only on a very small scale even in the USSR, which made the largest efforts for its introduction. Drilling technologies, e.g., in combination with in situ coal gasification, have to date not penetrated the coal industry. Thus, on the whole, coal winning at the face is today based on the same basic physical principles as it was centuries ago. No radically new technologies for practical introduction into the sector before the year 2000 appear to be available. The historical technological development of the coal industry may thus be described as incremental rather than as having radical breakthroughs.
4. Technological innovations in the coal-mining sector have often been incomplete, especially in the development of the *integration* of the various coal-mining operations. The separate introduction of new, highly productive equipment in a number of different operations did not change the total technological chain, which remained segmented. A number of auxiliary labor-intensive operations are still unmechanized (e.g., repair and maintenance operations, and equipment installation, for which no specialized equipment has been introduced), becoming in turn new bottlenecks in the technological chain at a coal mine.

Specific **economic** characteristics of coal-mining development in the USSR may be summarized as follows:

[2] For a more detailed discussion of the various opencast and underground mining technologies used worldwide, see Astakhov and Grübler [9].

1. Availability of investment capital was no practical constraint during the first phase of mechanization, i.e., coal-winning operations. The share of face equipment in the total capital cost of an underground mine was relatively low. This situation changed drastically when (expensive) hydraulic self-advancing roof-support systems were introduced and the number of "completely mechanized" faces (i.e., with completely mechanized winning, coal-loading, transportation, and roof-support operations) grew.
2. The economic benefits of highly productive, completely mechanized faces could only be realized if all other underground operating systems were also reorganized. The total reorganization of transportation and ventilation operations turned out to be rather complicated and very capital consuming. If these reorganizations are not managed successfully, the economic benefits of the introduction of a new technology turn out to be worse than expected.
3. Mining activities develop under ever-worsening geological conditions of depth, gas content, etc. All economic and productivity indices of a particular mine and of the industry as a whole would thus deteriorate in the absence of technological advances. Technical innovations are the only way to overcome the adverse effects of progressive depletion of low-cost resources. Thus the real effects of technological advances in the area of coal mining are not adequately described by the evolution of general economic or productivity indicators, as a large share of the improvements in productivity increase and cost reduction are offset by the deterioration in the geology of the deposits mined. If in turn the rate of advance of technological improvements starts to slow down, as for instance when all high-output faces are already completely mechanized and further technological improvement is approaching a barrier, cost and productivity indices start to decline under the ever-deteriorating geology. This is apparently the case in the USSR coal industry since 1975.
4. The economic effects of mechanization show decreasing rates of return in time. At the beginning, when manual labor is substituted by machines, the economic (and social) benefits are high. In due course the capital-labor ratio starts to deteriorate even under further incremental improvements of the given technological generation. At the end of the diffusion process the new machinery penetrates into its poorest field of application, where the economics are much worse than in the initial field of application. Nevertheless, the application of a new technology even under these conditions may be justified for social (work conditions, safety) or other reasons.
5. Opencast mining is the most economic coal production method in the USSR. Production costs are 4-8 times lower than for underground mines, and labor productivity is on average ten times as high as in underground mines. The rapid further development of opencast mines will result in significant structural changes in the coal-mining industry of the USSR, including the geographical distribution of production (a move to the east). Clearly the economic advantages of opencast mining are not primarily a result of technology. They are first the result of the more advantageous and simpler bedding conditions of the deposits being mined by opencast methods. The USSR disposes of a number of large deposits with excellent geological conditions (e.g., the Ekibastuz deposit with seam thickness of up to 100 meters of high-quality coal and mines with annual capacities up to 30 million tons per year); however, these deposits are located far from the main centers of consumption (and thus entail high transportation costs) and sometimes

consist of low-grade resources (e.g., the brown coal in the Kansk Achinsk basin, which would allow from the available resource base a tremendous production level of up to 1,000 million tons per year). Still, the massive development of such giant opencast mining operations relies first on the resolution of a number of complex problems in the other sectors of the economy, including the development of appropriate transport and social infrastructure, technology developments to cope with extremely harsh climatic conditions, and finally also on a reduction of the (long) lead times for production and delivery of large-scale opencast mining equipment. Resulting environmental problems (mine reclamation, emissions from coal conversion facilities, etc.) remain also to be resolved.

The social criteria for the long-term technology development in the coal-mining industry of the USSR are important determinants for the decision making in coal-mining activities. Despite the fact that the criteria, as well as their relative roles have been changing over time, it is still possible to summarize that the main role of technical development is to ease the hard physical labor of the people working underground, to make working conditions more comfortable and safer, and in general to minimize the number of underground jobs as much as possible. This was and continues to be the major social objective pursued in the mechanization process at coal mines.

A GENERAL PERIODIZATION OF THE LONG-TERM EVOLUTION OF COAL MINING IN THE USSR

The time period from 1913 to 1986,[3] considered in our analysis of the long-term development of the USSR coal-mining industry, can be characterized by a number of changing global situations, not only within the coal-mining industry itself, but within the evolution of the national economy of the USSR as a whole. Among the historical events inducing major structural changes are the October Revolution and the effects of the two world wars. These structural change periods implied a starting point to define new objectives as well as to open new development possibilities for the coal-mining industry of the country. Exploration opened up new coal basins for production, new mining technologies were developed and were successively introduced into the industry. These various "turning points" in the long-term evolution can be clearly seen in all macro-indicators of the development of the industry. It is thus useful to differentiate in the dynamic analysis of the development of the industry between a number of historical phases of development, within which the evolution of the general situation of the industry, of the economics of coal mining, and of technical change should be discussed.

The starting point of our analysis period, 1913, was the last peace year of old Russia. The effect of World War I, the October Revolution, and the following civil war resulted in a drastic reduction of the coal production levels to less than one-third of the prewar period. The phase of reconstruction of the coal-mining industry lasted until around 1928, when the coal production level exceeded for the first time tht prewar level of around 30 million tons per year. The next development phase was characterized by rapid and stable growth that lasted until 194 1. Coal production levels rose from 35.5 to 165.9 million tons per year (i.e., at a rate close to 14% per year) with new coal basins such as the Kuznetsk and the Karaganda being brought into production. However, the Donbass (Donetsk basin) remained the dominant coal production area, accounting for close to 60% of the total coal production of the USSR.

[3]For statistics on the general evolution of the coal-mining industry during this time period, see the data appendix.

In mid-1941, World War II spread over the Soviet Union. The mines in the Donbass and in the Podmoskovny basin were totally destroyed. The resulting production gap was compensated to a large extent by the rapid development of eastern coal basins, whose output increased from around 70 million tons in 1940 to 110 million tons in 1945. After the liberation of the occupied territories, a rapid restoration of the mines in the Donbass and Podmoskovny basins started. By 1950, the coal production in the Donbass had again reached the 1940 level of 95 million tons, while the production of other basins continued to increase to a level of around 170 million tons.

The following period, 1950-1975, was characterized by a stable growth of the total coal industry, whose output rose from 260 to 270 million tons (i.e., at an annual growth rate of 4%). Nearly half of this growth came from increasing output of opencast mines, whose share in the total production increased from 10% to 32% between 1950 and 1975.

After 1975, the growth in output of underground mines and in particular the production of the Donbass started to stagnate and later declined. A similar situation can be observed with the evolution of labor productivity of underground mines in this time period. Only very recently can some indicators of a certain revival be observed.

GENERAL PERIODIZATION OF TECHNOLOGICAL CHANGE IN UNDERGROUND COAL MINING IN THE USSR

The dynamics of technological change, and in particular of the mechanization in coal mining, can be described as evolving through a number of characteristic phases. During the period 1913-1928 coal mining was essentially a hard manual labor process.

Between 1928 and 1950, the use of explosives, pneumatic picks, and cutters diffused throughout the industry and these became the predominant tools for winning operations. In the early 1950s, the first coal shearers were developed and introduced into the mines; this marked the beginning of mechanization of one of the most labor-consuming operations at coal faces, i.e., coal loading.

The period 1955-1965 was characterized by an intensive rate of introduction and penetration of a large number of technological improvements at coal faces. Individual metal props replaced wooden ones for roof support. Retreating longwall faces[4] and labor-saving roof-support operations through self-advancing hydraulic roof supports found wider application. Mechanization of coal-winning operations increased drastically: in 1955, only about 10% of the coal output was winned by shearers; ten years later, shearers accounted for more than 50% of coal output. On the whole, however, this period can be characterized as a period of partial mechanization of selected operations, which did not result in a rearrangement of face operations into a fully integrated mechanization scheme.

Such integrated face mechanization schemes consisting of high-output shearers and chain conveyors in combination with hydraulic self-advancing roof supports started to penetrate on a large scale in the period 1965-1980. The elements of these integrated mechanization schemes had been in development since the beginning of the 1950s for the specific conditions of the Podmoskovny coal basin and gradually became adopted for the geological conditions of other coal basins. At the end of the 1970s about 45% of all faces were equipped with mechanization schemes, including self-advancing roof supports. The share of these faces in total coal output was even higher, because of the larger output

[4]Recall here the main features of retreating mining schemes: the headings are driven first to the end of the mining block, thus the investment for driving the headings is concentrated prior to the start-up of mining operations. However, the uncertainty about the detailed geology (roof and floor conditions, tectonic disturbances, etc.) of the mining block is drastically reduced, resulting in more effective production planning, lower standing times, and lower production costs.

per face of these fully mechanized faces. The penetration rate has in the last ten years slowed down, due to the fact that these mechanization schemes had to be introduced gradually into faces with more complex geology, which hinders the full application of complete mechanization schemes.

In contrast to coal-mining operations, where the first mechanization measures were taking place in the 1930s, all *driving operations* were practically manual until the end of World War II. Loading machines and scrapers started to be introduced immediately after the end of the war, and their share in the total driving work at mines increased to a peak of around 45% in the period 1970-1975. After this period their share decreases, as they are replaced by driving combines, which are presently the most important technology for driving operations.

About 70% of *transport operations* at underground horizontal main roads were performed by manual labor and horses in the 1930s. Only by the mid-1950s had their use, together with rope assets, disappeared for transport operations. The share of locomotives in transport operations increased from 12% in 1930 to over 90% in the 1950s. Since this time they in turn are being replaced by conveyors, which presently account for around 45% of the coal transported underground.

Mechanization of the underground mining operations discussed above took place against the background of the rapid growth of coal production until the mid-1970s. Each mechanization technology introduced resulted in the lowering of the labor requirements at the appropriate operation. The new technologies were also more productive, i.e., they helped to intensify production in raising the coal output per face and per mine. Thus the increasing labor productivity was not only the result of the introduction of new technologies, but was also influenced by increasing economies of scale, which became possible through the application of new technologies. The labor (and cost) productivity increase due to the concentration of production in large output mines is a result of the reduction of general expenditures through the sharing of infrastructures, surface operations, etc. Another predominant feature of the development of mechanization technologies was their gradual *integration* into a complete mechanization scheme. By the integration of the individual mechanization measures at coal-winning, loading, roof support, and underground transport operations, additional benefits in terms of labor productivity increases were obtained, which exceeded the gains from the mechanization of the individual mining operation taken separately.

The economic effects of the technological developments discussed above cannot be exactly evaluated in cost terms, because of resource depletion, inflation, and other factors. The best simple proxy variable to quantify the effects of technology diffusion in coal mining is labor productivity (recall here that typically over 50% of the production costs at underground coal mines are labor costs).

Labor productivity in the period 1913-1928 was extremely low, less than 600 kg (raw) coal per shift.[5] This figure increased by a factor of 2 in the interwar industrialization period, decreased during the World War II period, and after 195 1 reached again its prewar value of around 1,400 kg/shift. The average labor productivity at underground mines rose as a result of mechanization until 1975 to a figure of around 2,800 kg/shift.

Since 1975 labor productivity decreased, to around 2,250 kg/shift in 1986. There are a number of reasons for this decrease in labor productivity. First, deconcentration factors should be mentioned; the average output of an underground mine, which had risen

[5]See also Tables 5-7 in the data appendix.

to 2,120 tons per day (see Table 4 in the data appendix), fell to around, 2000 tons/day. Thus a higher share of the production was coming from smaller mines and negative economies of scale, especially at the back-end (surface) operations of mining, exerted an influence. Second, after 1975 one can observe a slowdown from the previously observed diffusion rates of mechanization technologies. Thus it was no longer possible to compensate through mechanization for the effects of continuously deteriorating geological conditions. This slowdown of past diffusion rates can be attributed to the difficulties of adopting certain mechanization technologies at mines with more complex geological conditions (i.e., the field of most effective application of a technology gradually was exhausted), to the lack of new technologies to overcome this difficulty, and finally to a certain lack of funds to cover the expenses of further mechanization investments. Finally, managerial problems had also an influence on this decrease of the labor productivity.

A situation similar to that for underground mines can be observed with the development of the labor productivity at opencast mines. Since 1978, the labor productivity has been decreasing, albeit from a much higher level than that in underground mines, i.e., from about 24,000 kg/shift (1978) to around 22,000 kg/shift (1985/1986).

Methodology to Describe Technological Substitution

The following quantitative analysis of a number of technological substitution processes in the USSR coal-mining industry is based on a data sample derived from official Soviet statistics. The data sample [10, 1 1] was computerized at IIASA and analyzed using standard methodologies of the analysis of technological diffusion and substitution processes. This included in particular the approximation of the empirical data on the adoption rates of new innovations by S-shaped curves in order to determine the underlying parameters to describe the substitution process, in terms of the growth rate and the parameter to locate the process in time.[6] In case a single diffusion (substitution) process is analyzed, the theoretical curve to approximate the process is assumed to be of a logistic type. However, the reality of technology development in the coal-mining sector (as in other sectors) suggests that at any given point in time there are more than just two technologies competing, thus the technology substitution process has to be analyzed as a *multiple competition* case. In such a case the replacement or introduction of new technologies is described by a set of coupled logistic equations, with a nonlogistic transition function being introduced to describe the pattern of saturation of a particular technology, linking its phase of (logistic) growth and (logistic) decline or replacement by newer technologies. This transition function is calculated as a residual (to the total market of 100%) for the oldest of all growing technologies after calculation of the logistic substitution pattern for the remaining growing or declining technologies.

The details of the methodology as well as the algorithms used for parameter estimation are described elsewhere [12–14] and will not be repeated here. In the figures we report the empirical data together with the theoretical curves used to approximate the substitution process. Note that the solid lines of these curves are plotted for the time interval of the empirical observations used to estimate the parameters of the theoretical model;'

[6]The third parameter of the logistic equation, the saturation level, is in the present case known, i.e., the market share of any particular technology cannot exceed 100%.

'In some examples the whole empirical data base was not used to determine the parameters of the model, only a subperiod. The period of the empirical data used for the parameter estimation is reported in the statistical appendix; however, in the particular graphic presentation described above it can be read off directly from the figures.

the dashed lines represent the model's back- and forecasts of the substitution process.

All technological substitution processes are described by measuring the "market share" F, i.e., the fractional share a particular technology accounts for in the total output of the particular mining process being analyzed. The shares of technologies are calculated whenever available on the basis of (raw coal) output figures, but sometimes the primary data refer to other measures, e.g., number of faces equipped with a particular technology or the amount of work performed, expressed with a physical indicator (e.g., the amount of driving work in meters).

In an ideal case of analysis of the longer-term tendencies of technology development one would analyze the technological substitution pattern using a multidimensional approach. Thus the share of a particular technology would be analyzed considering, for instance, the number of mines and faces at which the technology is applied, share in total output, etc. In addition, main performance indicators (e.g., output per face, labor productivity, and so on) would also be analyzed dynamically to identify the main driving forces and impacts of technological change.

In the present interim assessment this multidimensional approach could be followed only to a limited degree, as the availability of the primary data determined the particular dimension in which the share of any technology was calculated. In a further analysis these measures would have to be complemented in order to overcome some of the shortcomings of simple measures like counting the number of faces at which a particular technology is applied, thus ignoring the different production intensity (output per face) resulting from the application of different technologies. In using different measures for determining the market share of a particular technology, a higher analytical resolution of the timing and the dynamics of technological change in the coal-mining industry could be achieved. For the time being, however, one has to postpone such a multidimensional approach to a later date, once more detailed statistics become available.

The figures depict the technological changes and the various estimated parameters are discussed in the next section and summarized in the statistical appendix. The figures are presented both in linear form and in the logarithmic transformation log $[F/(1-F)]$ (i.e., market share a particular technology accounts for divided by the market share of all other remaining technologies and presented on logarithmic scale) as used in the classic work of Fisher and Pry [15], converting the logistic substitution curve into a straight line. This presentation is given in order to make the (normally turbulent) early/late phases of the substitution process (e.g., below 10% or above 90% market share) more visible, as well as to clearly exhibit the phases of logistic growth/decline (appearing as straight lines on the figures) from the nonlogistic transition function, characteristic for the saturation phase of a particular technology or any deviations of the empirical data from the assumed logistic substitution paths.

Before turning to the more complex discussion of technological change in the coal mining industry of the USSR, which involves normally the case of multiple technological substitution, let us illustrate the methodology applied on basis of a simple technological substitution pattern. Figure la and b present a case of technological substitution of an important market outlet of the coal industry, i.e., in the transport sector.

Here we analyze the evolution of the market share of (coal-powered) steam locomotive against the market share of diesel and electric-powered locomotives. This particular example was adapted from Kruglikov [16]. The market share of steam and diesel/electric locomotives is calculated by their respective share in the total ton-km freight turnover. The data cover the period 1950-1980; however, only the period 1953-1972 was taken

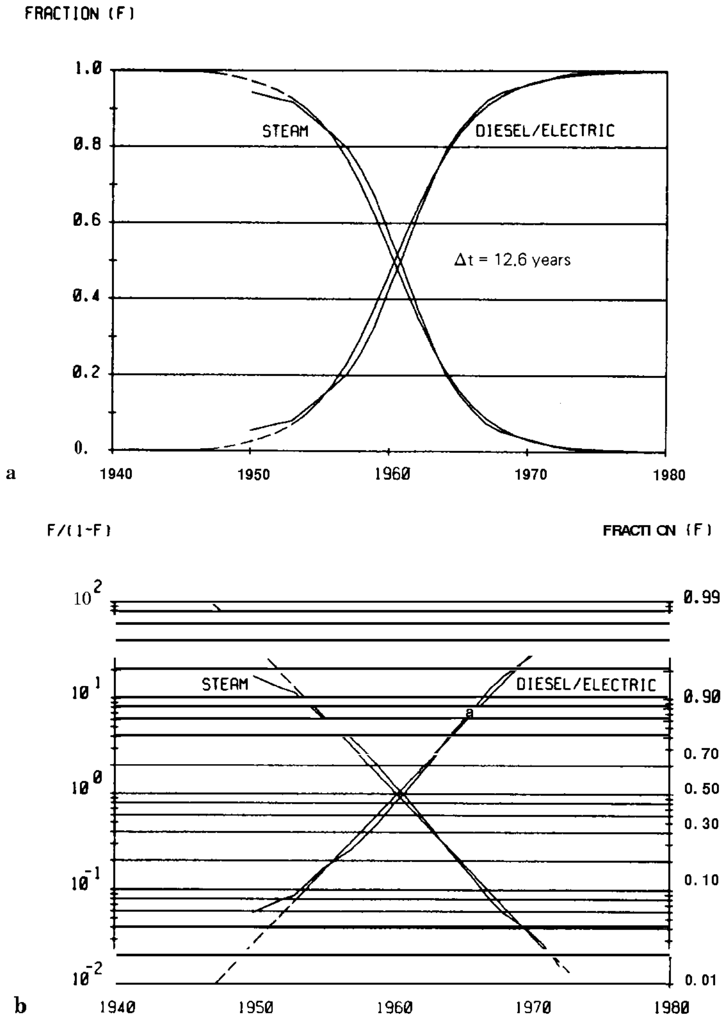


Fig. 1. Replacement of steam **locomotives** by diesel/electric locomotives, **in** fractional share of **ton-km** transported **in** the USSR (a: linear scale; b: logarithmic transformation). Adapted from **Kruglikov [16].**

into account to calculate the parameters of the logistic substitution model.' The parameters are estimated using ordinary least squares regression of the transform log $[F/(1-F)]$ (*see* Figure 1b). Two parameters with the following physical interpretation are estimated in the model.

The first parameter, α, is the rate of growth or the substitution rate of an old

[8] The cutoff points for the model calculations are by default 1% and 99% market share, respectively. Thus if data fall below or above these cutoff points (as in this example for the share of steam locomotives after 1972), they are not considered in the model parameter estimation and are not presented in the figures. In this particular example the period 1950-1953 also was excluded in the model parameter estimation.

technology by a new one. This parameter is denoted as At in the subsequent text and is defined as the time period in years it takes a technology to increase its market share from 10% to 90% or to decrease from 90% to **10%**, respectively. As the assumed substitution function is symmetric, the total substitution time to go from 1% to 99% (or vice versa) is two times At. Note here also that the At presented in the case of multiple substitution refers only to the time period of the logistic growth/decline. It is thus a measure of the "steepness" of the logistic substitution path appearing as straight line in the log $[F/(1-F)]$ transformation. In case a technology starts saturating (due to the logistic growth of a newer competitor) and starts deviating from the logistic pattern, the At measure does not apply any longer until the point when a logistic decline pattern is reassumed, with eventually a different At.

The second parameter, denoted as t_0, locates the substitution curve in time. It is defined as the point of inflection (year 1960 in Figure la and b), where 50% market share is reached. The growth rate of the substitution process (first derivative of the logistic substitution function) reaches by definition its maximum at t_0.

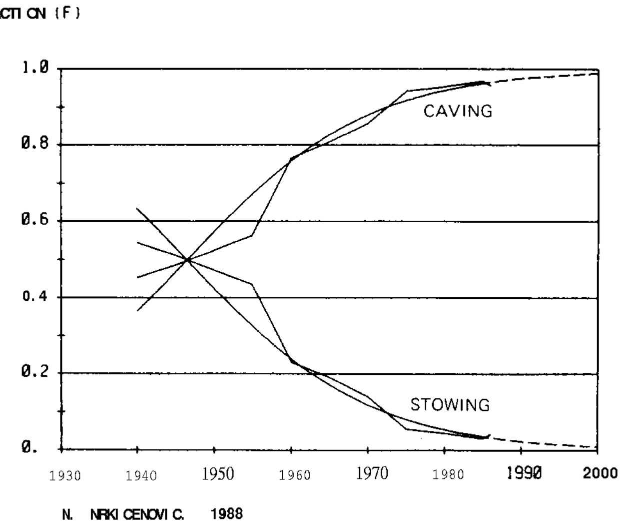
Technology Diffusion in the Coal-Mining Industry of the USSR

In this section, we present the results of the analysis of technological change in the coal-mining industry of the USSR. Whenever possible, we tried to be as comprehensive as possible with respect to the geographical coverage, i.e., an effort was made to analyze the technological development for the whole industry in the USSR. For some examples, however, data availability or significant differences in the geology of the different coal basins restricted the analysis to a smaller sample, e.g., underground mines in the Donbass, the most important coal basin of the USSR.

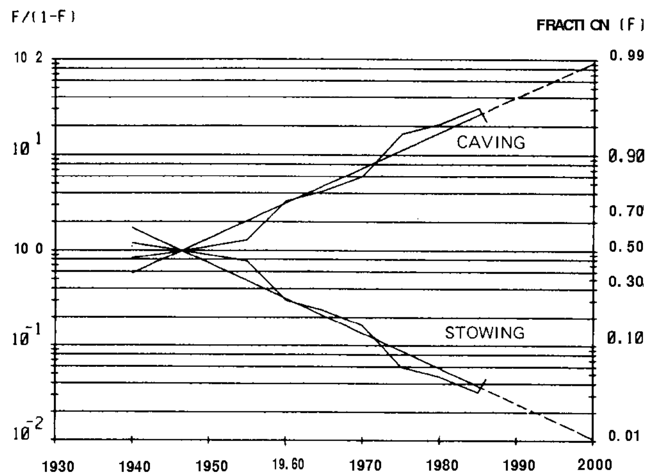
Our analysis begins with a discussion of technological change at underground mines. First, face operations are analyzed. This is followed by a discussion of the technological trends in driving and transport operations. Finally, an analysis of the long-term trends in the share of opencast vs underground mining as well as a preliminary simple model of the underlying driving force of this structural change is presented.

Three main types of operations were analyzed for coal faces: roof-control, winning, and roof-support operations. Each of these operations depends highly on the specific geological conditions prevailing at the coal face, which in turn are highly diverse in the different coal basins of the USSR. Practically no single technique can be applied to all possible ranges of geological conditions, and technology development in the coal industry is always aimed at developing differentiated models to respond to this range of different coal beddings. Thus it should not be surprising that technological substitution patterns are not always regular and complete, as the introduction of a particular technology into different geological conditions may not be always feasible and/or the diffusion pattern may proceed under these conditions at a slower rate than that observed historically.

For an analysis of the roof-control technologies, data for the Donbass, the most important coal basin of the USSR, with 200 million tons of coal produced each year, were analyzed for the period 1940-1986. The two main groups of competing technologies are stowage (as a rule, partial stowage) and artificial roof collapse, i.e., controlled caving of the roof. Stowing was the predecessor technology to caving and resulted in high labor requirements. For a long time the use of stowing was practically unavoidable as caving could not manage with the hard roof conditions typical for a large number of faces. This situation changed when new types of special metal supports were introduced in the late 1960s. Thus, caving became possible also under these conditions, and as a result the share of coal output coming from faces with caving as roof control increased along the



a



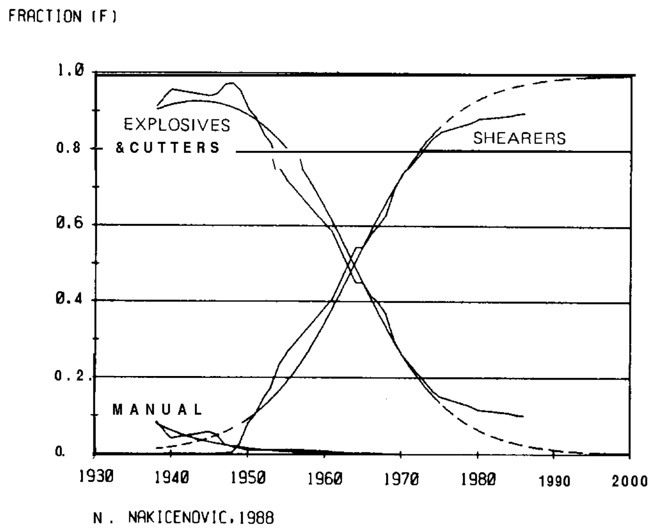
b

Fig. 2. Evolution of coal output in the Donbass by two main types of roof control (a: linear scale; b: logarithmic transformation).

logistic substitution pattern shown in Figure 2a and b to the present dominance of around 95%.

The speed of this substitution process is estimated by the model to have a At of around 52 years. The fit of the model of the empirical data appears reasonable, with an R^2 of .962, especially after the period starting in 1960. For the period before 1960, however, the model fit is not particularly good. This time period was not a very homogeneous phase, as it includes the time period of World War II and the subsequent reconstruction of the mines in the Donbass. The growth of caving in the period 1940-1955 was actually not based on new techniques of roof control; consequently, the diffusion rate is slower than in the period thereafter, when the substitution process was primarily driven by the availability of new technology.

Based on the theoretical approximation of the substitution process provided by the



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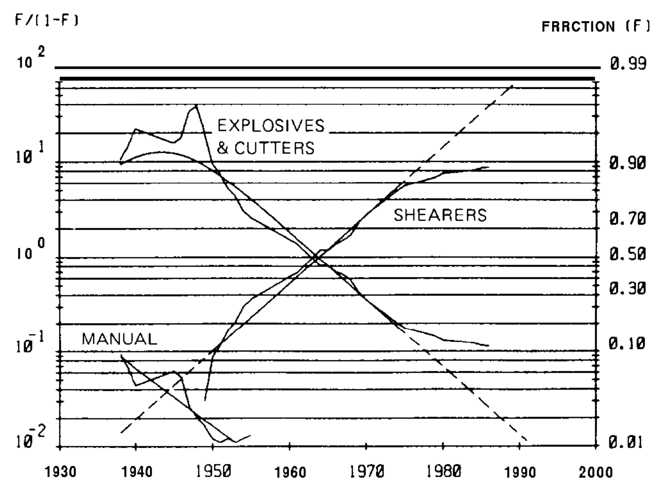


b

Fig. 3. Evolution of coal output by three technologies of coal winning at coal faces in the underground coal-mining industry of the USSR (a: linear scale; b: logarithmic transformation).

model, we can make some tentative forecasts of the future possible development of roof-control techniques. If no radically new technology becomes available, (partial) stowing techniques may eventually be totally replaced by caving techniques by the year 2000 in the Donbass.

Figure 3a and b present the results of the analysis of the mechanization of coal-winning operations for the underground coal-mining industry of the USSR. Manual operations for breaking the coal from the face wall were substituted first by the use of explosives and picks and later by cutters. However, loading of the broken coal onto conveyors remained a manual process until the introduction of shearers in the beginning of the 1950s. The model fit to the empirical data appears satisfactory, with the very first phase of the introduction of shearers (up to 10% of total coal output) proceeding somewhat faster than suggested by the model. In addition, a considerable slowdown in the diffusion rate of shearers since 1975 can be observed. Whether this is a technological problem due to the fact that (conventional) shearer technology has already penetrated into all areas of its most effective application and penetrations into other areas is more difficult, or whether this may be the result of capital shortages for new investments and thus an indicator of a certain stagnation in the industry, cannot be resolved here. The resulting model forecasts, while realistic in the general direction, are thus rather uncertain with respect to the continuation of the long-term diffusion rate of the introduction of shearers and it may well be possible that shearers will not at all, or only at a later date than suggested by the model, penetrate into the last 10% market niche of coal-winning mechanization.

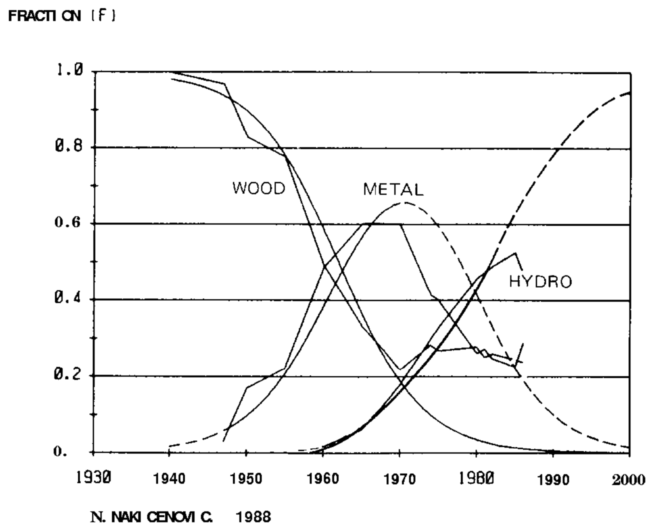
Technical advance in **roof-support** operations is reported in Figure 4a and b for the underground coal-mining industry of the USSR. The data refer to the number of faces equipped with wooden or metallic individual roof supports and self-advancing hydraulic roof-support systems. Unfortunately no data on the share of different roof-support systems in the total output were available, thus the data do not account for the different production intensity achieved in highly productive, completely mechanized faces with self-advancing hydraulic roof supports compared with the lower output at faces with individual wooden or metallic roof supports.

Roof-support technologies are of the highest importance because they reflect a whole complex of interrelated face operations and thus constitute a proxy for the development of other face operations. The substitution of wooden props by metal ones was a necessary first step in conjunction with the introduction of shearers. The integration of different types of metallic props and supports into an integrated system enabled the development of completely mechanized face operation schemes.

The fit of a technological diffusion model to the empirical data allows for two conclusions. First, the fit of the model to the diffusion and substitution of wooden and metallic individual roof supports over the period 1940-1970 is quite satisfactory. Second, the model captures the introduction of hydraulic self-advancing roof supports and their growth up to a 50% share of the total number of faces, i.e., the period 1960-1980. However, this particular example demonstrates also that relatively regular diffusion patterns might not persist over the whole life cycle of a particular technology. Particularly noteworthy is the deviation in the share of faces equipped with wooden props, which since 1970 continued to stay at around 25%. Wooden props were thus not further replaced as indicated by the historical substitution process between 1940 and 1970. Noteworthy also is the slowdown of the diffusion of hydraulic roof supports after 1980 and especially the trend reversal (i.e., decline of the share of hydraulic roof supports) between 1985 and 1986.

it is at present difficult to explain this somewhat atypical deviation from the historical diffusion pattern. The measurement problem, mentioned above, i.e., that the data do not take into account the different production intensities at the different faces by considering only their share in the total number of faces, is probably the most important cause of this deviation. In considering the higher output from completely mechanized faces, the market share of hydraulic roof-support faces should be considerably higher and the diffusion pattern more regular. By the same token, faces equipped with wooden props, although they still account for one quarter of all faces, will account for a significantly smaller share in the output of the industry. One would have to analyze the same substitution process measuring the market share of different technologies in terms of output before reaching a definitive conclusion on the deviation from long-term technological substitution patterns and speculating possible causes (like lack of investment funds, etc.).

Before turning to the discussion of the technological trends of driving operations,



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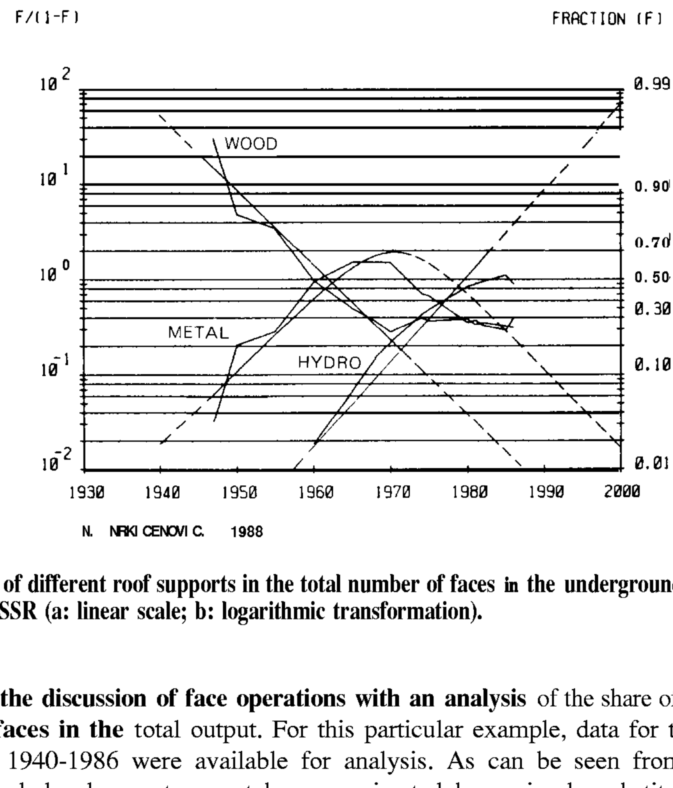
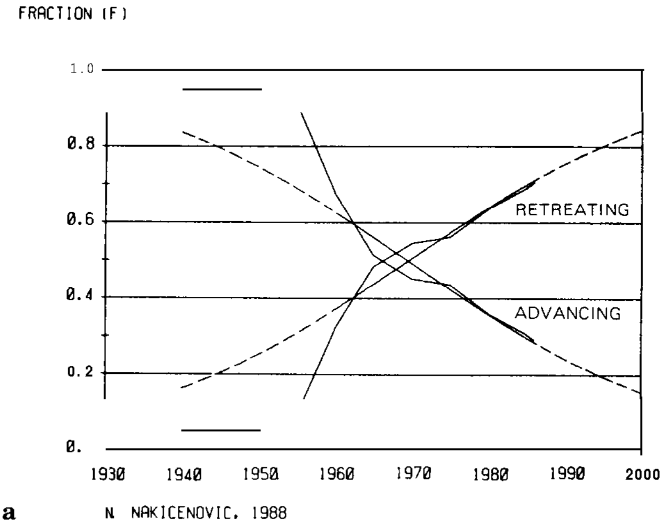


b

Fig. 4. Share of different roof supports in the total number of faces in the underground coal-mining industry of the USSR (a: linear scale; b: logarithmic transformation).

let us conclude the discussion of face operations with an analysis of the share of advancing vs retreating faces in the total output. For this particular example, data for the Donbass for the period 1940-1986 were available for analysis. As can be seen from Figure 5a and b, the actual development cannot be approximated by a simple substitution model over the whole time horizon under study.

Retreating face operation schemes are advantageous as they enable one to obtain beforehand (i. e., by driving the headings) better information on the geology (e. g., tectonic disturbances) of the mining block to be developed and thus enable more flexible and faster production. In principle, retreating face operation schemes can be applied within



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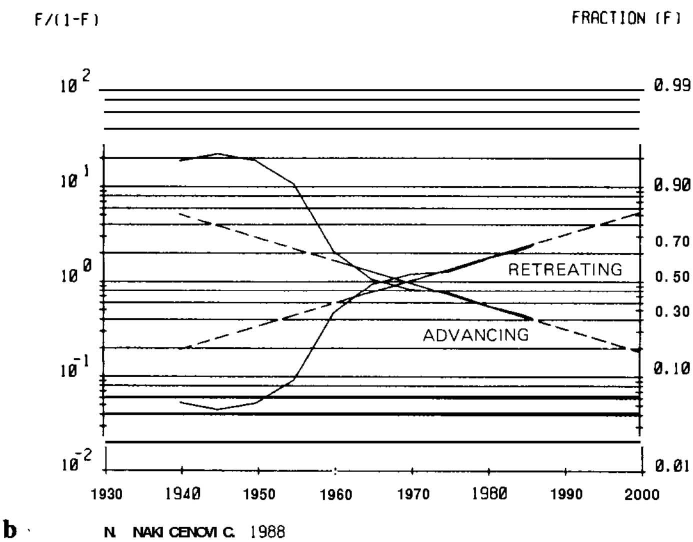

b

Fig. 5. Share of advancing vs retreating longwall faces in coal output in the Donbass (a: linear scale; b: logarithmic transformation).

the whole range of advancing systems applications. However, the preparation of a given face for a retreating operating system takes much time and concentrates investments up front, i.e., prior to production start-up.

Figure 5a and b indicate that the share of retreating face operations was remaining at around 10% of the total coal output in the Donbass for the period 1940-1955. This share then increased rapidly to over 30% up to 1960 in order to assume a regular logistic substitution pattern in the period thereafter. Consequently the model estimates of the substitution process took only the data for the time period 1960-1986 into consideration.

The reason for the deviation of the actual data with the estimated substitution model in the time period 1940-1960 is rather obvious. In the time period up to 1955, it was necessary to reestablish as quickly as possible the pre-World War II production level in the Donbass after the destruction of the mines during World War II. It was thus much simpler to expand the output by advancing systems of face development. After 1955, we can observe a rapid catch-up effect, which was made possible through the availability of loading machines and combines (speeding up driving work) and resulted in a fast replacement of advancing by retreating face development schemes. This process was completed by 1960, and only since that time can we consider the development following a standard substitution process. Our simple model of technological substitution cannot describe the historical development over the whole time horizon, as the actual development in the period following World War II was highly influenced by external factors.

Still, the fit of the substitution model after 1960 can be considered as reasonable and, assuming a continuation of the trend beyond 1986, one might expect that by the year 2000 some 80% of the coal output of the Donbass will come from retreating faces.

The above-discussed innovations introduced at coal faces have resulted in a significant improvement of the economic performance of underground mines. The daily coal output from an operating face (see Table 3 in the data appendix) increased from 106 tons in 1940 to 454 tons in 1975 (and declined to 404 tons/day in 1986) for the industry average. In the Donbass, it increased from 103 to 393 tons/day from 1940 to 1975 (and decreased to 3 16 tons in 1986). Labor productivity at the coal face (see Table 6 in the data appendix) increased from 3.92 tons/shift in 1940 to 9.7 1 in 1975 (8.62 in 1986) for the average of all underground mines in the USSR. The figures for the Donbass (see Table 7 in the data appendix) indicate an increase from 3.53 tons/shift in 1940 to 7.14 in 1975 (6.17 in 1986).

The innovations introduced thus increased the production intensity by a factor of about 4 and the labor productivity at the coal face by a factor of 2.5. One can conclude that the observed decrease in the production intensity and labor productivity since 1975 can certainly be attributed in part to the observed slowdown in the diffusion rates of the introduction of new technologies at coal faces since 1975.

Competing technologies' for **driving operations** were analyzed on basis of data for the entire underground mining industry of the USSR (Figure 6a and b).

The share of the different technologies was measured based on their share in the total meters driven in a particular year. The fit of the empirical data by the multiple substitution model can be considered as quite satisfactory, with R^2s ranging from .92 to .99. Only the early introduction phase (i.e., below 10% of market share) of combines appears to have been much faster than described by the model. Manual driving operations are being replaced with a At of around 37 years by loading machines (e.g., scrapers) and later combines. Loading machines like scrapers in turn appear to be in their long-run saturation phase, so one would expect on the basis of the model forecasts an increasing predominance of the use of combines in driving operations.

One should keep in mind when interpreting the above results that in general the type of development workings, their crosscuts, and the geological conditions of their driving are highly different, and one should not expect that these diverse conditions can be satisfied by a single type of machinery like combines. In view of this, the restricting assumption underlying our model, that any technology may eventually approach a 100% market share (not substituted in turn by a newer technology), may not hold. Thus, one ought to analyze each driving machinery separately (including a disaggregation in its most important subvariants) under a given range of (rather homogeneous) geological

[9]Note that by the term scraper we refer to loading machines in general, in absence of any further available disaggregation in our statistical data base.

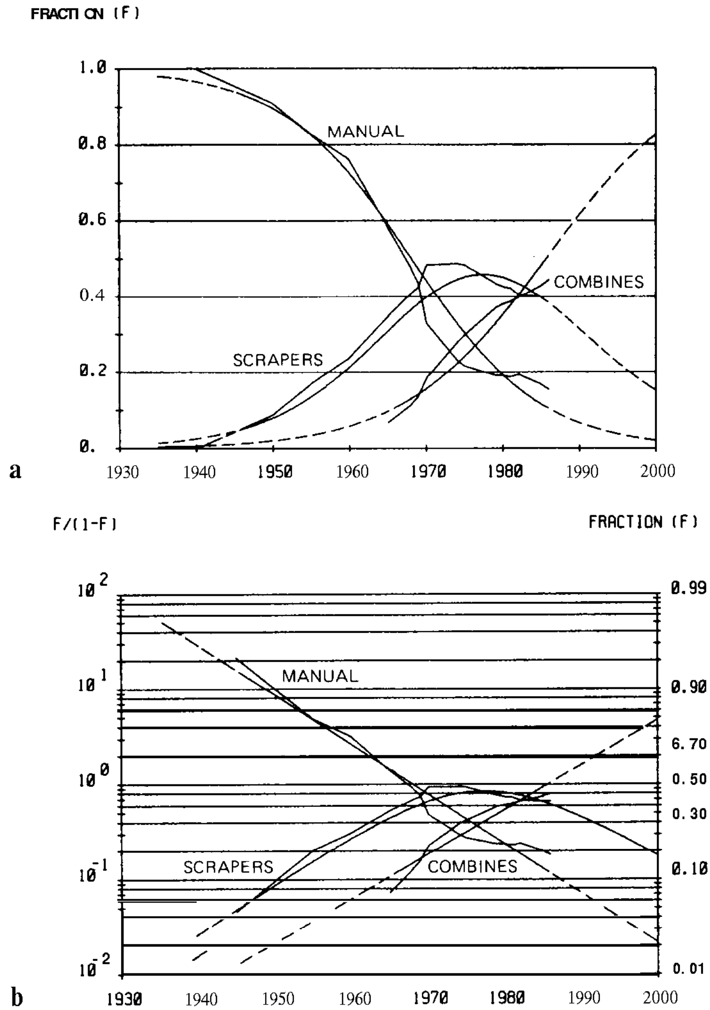

Fig. 6. Evolution of shares of different driving technologies in amount of driving work in the total underground coal-mining industry of the USSR (a: linear scale; b: logarithmic transformation).

conditions (e.g., separating flat from inclined bedding conditions) to estimate the final potential field of application of a particular technology. Similar statements can be made about other mining operations (e.g., winning), however, such a detailed analysis can only be performed at a later stage, once more detailed statistical data become available.

Underground transport operations at horizontal roads are analyzed for the entire underground coal-mining industry of the USSR in Figure 7a and b. Underground transport based on horses and manual labor had disappeared by the mid-1950s. In line with rope assets, they were substituted by locomotives, which by the beginning of the 1960s became the predominant form of underground transport, with over 90% of the tonnage transported. Later on locomotives started to be replaced by conveyor transport.

This process involved a great number of different types of locomotives and conveyors, each having their own field of effective application. But in general the trend was in favor of conveyors, which increased their market share with a At of 48 years. The model fit to the actual data can be considered quite satisfactory. Based on the model projections,

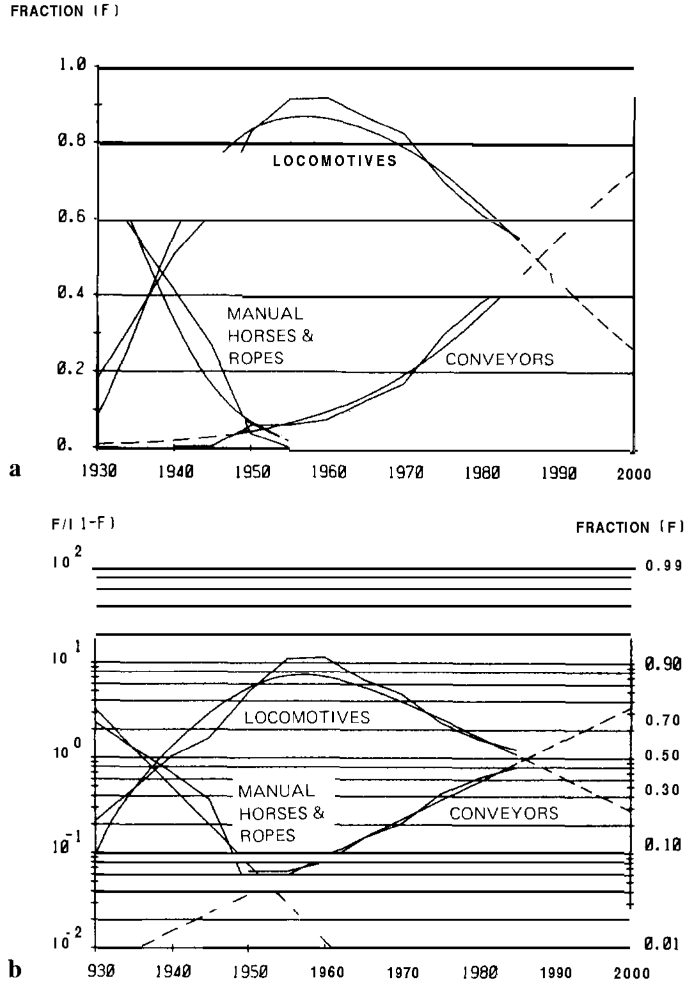

Fig. 7. Share of different transport modes at horizontal roads in the underground coal-mining industry of the USSR (a: linear scale; b: logarithmic transformation).

one might expect that, by the year 2000, over 70% of underground transport will be performed by conveyors, with locomotives accounting for the remainder.

Underground transport in inclined workings is analyzed in Figure 8a and b. The reason that transport operations were analyzed separately for flat and inclined workings is that locomotives cannot be used in inclined workings. Under these conditions special transport systems have to be used.

The rate of substitution of conveyors for rope assets was in fact faster (At of 34 years) in inclined workings than in flat workings. Although the fit of the substitution model to the empirical data is not particularly accurate, the model still captures the essential dynamics of this technological substitution process. The only uncertainty that remains at present is related to the (future) limit in the inclination where conveyors still can be applied, which will determine whether in the future the share of conveyor transport in inclined workings will increase beyond its current 90% market share.

The effects of the technological trends in underground transport operations discussed a, b

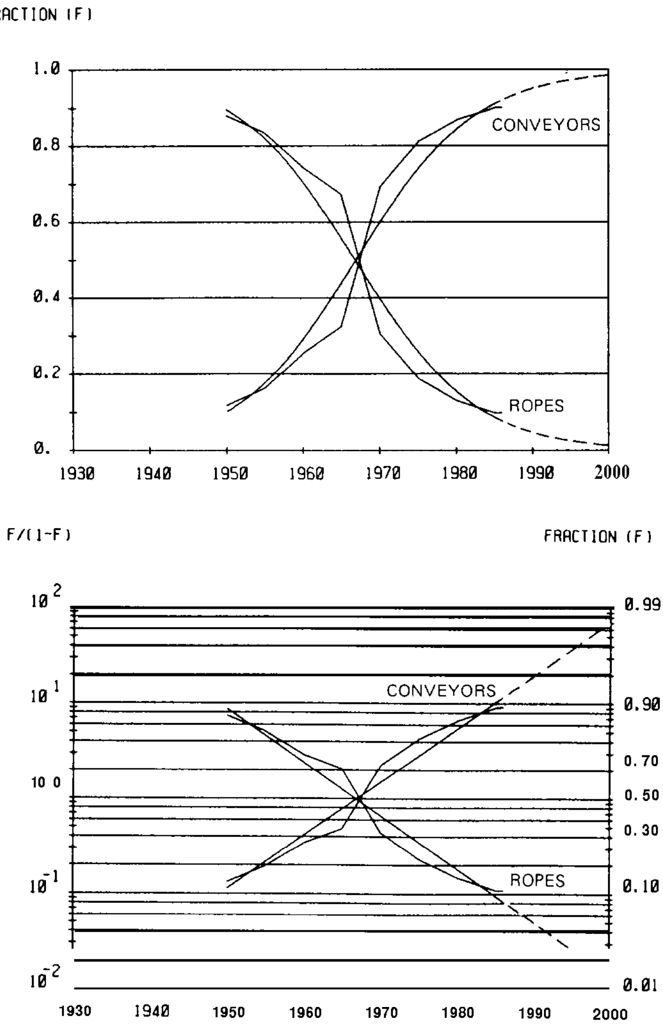

Fig. 8. **Share of rope assets and conveyors at inclined workings in the underground coal-miniig industry of the USSR (a: linear scale; b: logarithmic transformation).**

above can be seen clearly on their impact on the labor productivity for underground transport operations. Labor productivity at transport operations at all underground mines of the USSR increased from 9.3 tons/shift in 1940 to a peak of 23.8 tons/shift in 1974 (i.e., by a factor of 3). However, since 1974 it has decreased to around 17 tons/shift (see Table 6 in the data appendix). In the Donbass the productivity increased from 7.1 to 16.7 tons/shift from 1940 to 1974 (i.e., a factor of 2.4) and decreased thereafter to 11.5 tons/shift in 1986 (see Table 7 in the data appendix). Thus, we can observe a tendency toward reversal in labor productivity after 1975 for transport operations similar to that observed for face operations.

We conclude our discussion on technological trends in the coal-mining industry of the USSR by considering a technological structural change process at the highest level of aggregation of technologies, i.e., the shift in the sham of **opencast vs underground mining** in the total coal production tonnage of the USSR. The trends in the market share

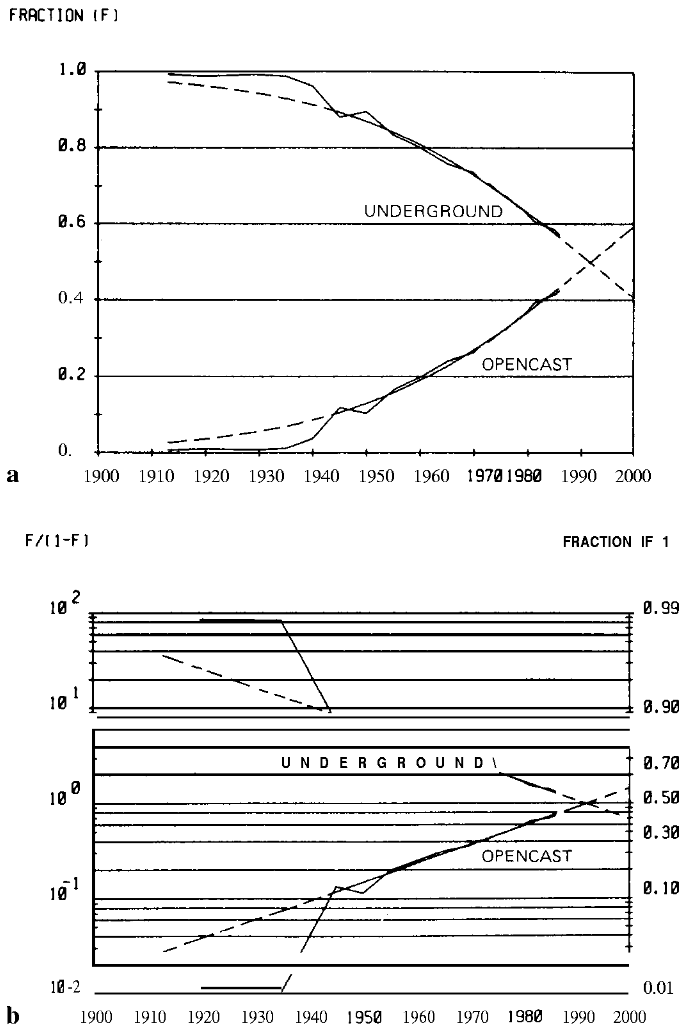

Fig. 9. **Share of underground and opencast mining in the total coal production of the USSR (a: linear scale; b: logarithmic transformation).**

accounted for by the two methods in total coal production are presented in Figure 9a and b. The success of opencast mining is evident from these figures.

Nevertheless, Figure 9b shows that a particular model cannot be applied over the whole historical range of the development for opencast mining technology. Prior to World War II opencast mining accounted for only slightly over 1% of total coal production of the USSR. An expansion of its share in total output was physically impossible in the absence of a sufficient resource base suitable for opencast mining. This situation changed only with the discovery of large resources (Kansk-Achinsk and Ekibastuz basins and some others). Once these resources had been discovered it was possible to expand production rapidly, especially during the wartime period, where the necessity arose to move production eastward to the nonoccupied part of the territory. Only after these two exogenous events happened can one consider that opencast mining entered in a technological competition with traditional underground coal mining. Consequently the substitution process was analyzed using the data from 1945 to 1986 only in order to determine the parameters of the logistic substitution model.

For this period the fit of the model appears to be excellent (R^2 of .98), and opencast mining is substituting for underground mining at a regular pace with At of 96 years. If this historical trend continues, one might expect that by 1992 opencast mines will account for half of the total coal production in the USSR. This appears not infeasible in view of the large resources available as well as by making analogies to the case of the United States, where opencast mines account for over 60% of total output.

Certainly the most effective direction of the long-term technological development in the coal-mining industry of the USSR is the substitution of underground mining by opencast mining. The principal reason for such a development was discussed above; it lies within the comparative advantage of opencast mining (i.e., in its substantially lower production costs) as a result of favorable geological bedding conditions enabling the use of giant, highly productive equipment and resulting high labor productivity. Recall here that on average the labor productivity at opencast mines is ten times higher than in underground mines (see Table 5 in the data appendix).

This enables us to formulate a simple model on the driving force underlying such a long-term technological substitution process. Briefly the hypothesis is that the level of diffusion/substitution is a function of the comparative advantage of a particular new technology over an old one.[10] In fact this comparative advantage is in reality a complex vector of a number of economic, technical, social, and other variables. For our purpose, we will concentrate on the relative economics as one (and as it appears in this particular case the principal) driving variable of the substitution process.

In the absence of detailed statistics on production costs, we consider the labor productivity as a proxy variable for the production economics of the two competing technologies. Recall here that typically over half of the production costs at underground mines are labor costs. Under our hypothesis that the comparative (economic) advantage is the main driving force of the long-term substitution of opencast mines for underground mines, we perform a regression analysis of the share of opencast mining in the total coal production over the time period 1940-1986 as a function of the comparative advantage of opencast mines expressed as the labor productivity differential between opencast and underground mines (derived from Table 5 in the data appendix). The regression yields the following result:

$$M_s = -6.027 + 4.453P_{rel},$$

where

M_S is the share of opencast mining in total coal output (%)

P_{rel} is the productivity differential expressed as a ratio between the average labor productivity at opencast mines over underground mines

$n = 37$

R^2 (adjusted for degrees of freedom) = 0.951

[10] This hypothesis is in fact very similar to the comparative advantage variable as originally formulated by Mansfield [1]. Mansfield's model relates the rate of diffusion (substitution), i.e., the At in our terminology,to the (ex post determined) expected comparative advantage differential (profitability in his case) of technologies. Mansfield's model assumes, however, that the relative (expected) comparative advantage differential between technologies remains constant over the whole diffusion period. In our case, we allow the relative productivity between opencast and underground mining to change over time and relate the achieved diffusion level (share in coal output) of opencast mining to the (changing) realized productivity differential between the two mining methods.

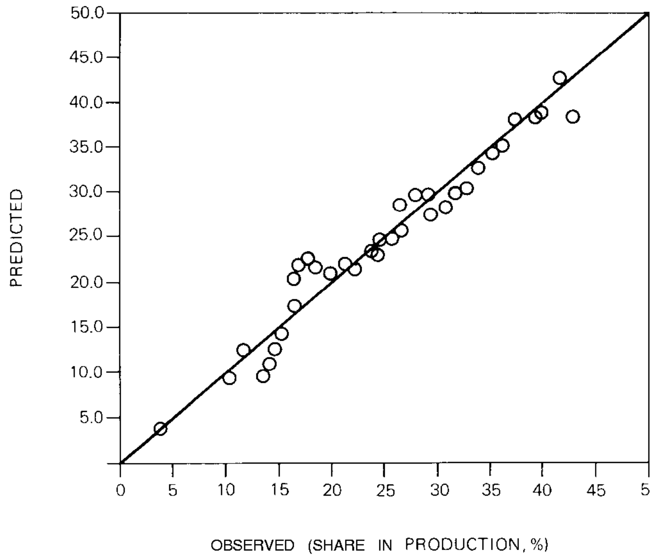

Fig. 10. Scattergram of observed versus predicted market shares of opencast mining in the total coal production of the USSR.

t value of P_{rel} = 26.5.

We can conclude that above regression explains 95% of the variance in the market share of opencast mining and that the diffusion level appears predominantly determined by the comparative (economic) advantage of opencast mining over underground mining, as expressed in the productivity differentials. Figure 10 is a scattergram of the observed vs the predicted market shares of opencast mining showing the satisfactory fit of our simple model.

The high explicative power of this simple model of the driving forces of a long-term structural shift in coal production technologies is not necessarily in contradiction to the complex set of other factors influencing the development of opencast versus underground coal mining in the USSR. Clearly, factors like high transport costs or considerations of preserving employment at underground mines were and continue to be decisive in the process of technological change in the coal mining industry of the USSR. We thus interpret the above results as a consistency check, whether the relative contribution of the two mining methods of total coal output and the evolution of their relative comparative (economic) advantage are internally consistent and are moving along a similar pace. The results of our simple model indicate they are. This however does not imply that we consider that the complex set of driving variables responsible for the long-term shift from underground to opencast mining methods can be reduced to a simple two-parameter model. Our model indicates that in the absence of a matching technological development (as reflected in the higher relative labor productivity of opencast mining) the observed historical pattern in production shift would have been very difficult if not impossible to achieve.

Finally, let us return to our discussion on the long-term prospects of opencast mining. Certainly the increasing share of opencast mining in the coal production of the USSR as suggested by Figure 9a and b will continue in the near to medium term. However, it also appears likely that this substitution trend will not continue to the extent of a complete replacement of underground mining. We can thus expect a similar discontinuity in the diffusion pattern, as already observed at the beginning of this process, where the availability of new, large resources enabled the long-term substitution process to begin. The ultimate level of the share of opencast mining will to a large degree be determined by the available resource base. The resources available for opencast mining, especially in the eastern part of the USSR, are very large. The in situ reserves alone amount to over 166 billion tons [17,18] (compared with 320 million tons produced in 1986), which would allow the current production level to be maintained for some 250 years, even when considering that only half of the reserves may eventually become recoverable. Thus, it is at present not possible to determine the ultimate limit of the share of opencast mining in the USSR. If the U.S. experience is a guide, the share of opencast mining could easily increase to over 60% (which would be the case after the year 2000 based on our model extrapolation) before stabilizing. Thus the prospects of opencast mining appear to be rather promising (in contrast to underground mining in the European part of the USSR), and further significant growth of this branch of the coal industry can be expected.

Conclusions

As this article is (to the author's knowledge) the first attempt to analyze technological diffusion and substitution processes in an industry sector of a planned economy based on standard models of technological diffusion/substitution developed for market economies, a number of conclusions can be drawn from such an exercise. These conclusions deal first with the applicability and the limitations of the methodological apparatus used. Second, the usefulness of the information gained by technological diffusion and substitution analysis will be discussed. Third, some conclusions on the general state of the industry with respect to technology diffusion and future prospects will be sketched out. And finally, some ideas on future extensions and a deepening of this type of analysis will be presented, which the authors consider worthwhile in view of the initial results achieved in this interim assessment.

The first conclusion of the present study deals with the applicability of the formal analysis instruments used in an industry sector of a planned economy. The answer is that, despite the shortcomings of a relatively simple model, discussed in more depth below, the model worked surprisingly well. This is noteworthy insofar as the present study constituted an initial attempt to deploy models of technological change outside the framework of market economies, in which they were originally developed.

Technological evolution and substitution appears, in principle, to follow a similar technological life cycle pattern in planned economies, as amply documented for market economies. The present study has shown that it is not only possible to model the pattern of technological change, but also to propose and test successfully a (although simple and preliminary) model of the driving forces of technological substitution processes in a planned economy. Comparative (economic) advantage appears to be at work also in planned economies, driving the diffusion of new technologies and the replacement of old technologies. The study has also shown, that for other (external) factors, e.g., related to the (geological) specifics of coal mining operations or other factors, planning may result in a strong discontinuity in diffusion and substitution patterns (discussed in the example of roof-support technologies), thus putting the preponderance of comparative technological and economic advantages in the long-term changes in the technology base at coal mines in the USSR into perspective.

The study revealed a number of shortcomings and limitations in the applicability of the proposed single and multiple logistic substitution models. The examples analyzed have shown that technological substitution patterns can show deviant behavior from the assumed logistic pattern. Whereas it is not surprising that the early phase of introduction of a technology (i.e., below 10% market share) can sometimes proceed faster than that suggested by the model in reflecting a kind of catch-up effect due to adoption externalities (documented often for market economies), a number of cases remain where the examples analyzed show that a particular model of technology diffusion and substitution may only be applicable during a certain time period of the life cycle of a given technology.

There are two reasons for this. First is the importance of external events, which has already been mentioned. Among those discussed, we recall the effect of World War II and the consequent rapid reconstruction of mines, which in some cases slowed down the diffusion of more recent (and more expensive) technology, and the discovery of important opencast mining resources, which enabled opencast mining methods to enter a phase of (logistic) substitution with underground mining. Second, the specifics of coal mining as an industrial process, i.e., the technology employed is first of all a result of the natural bedding conditions of the deposit mined, have to be considered. The impact of central planning and its different market-clearing mechanism should also be considered; this study has shown that its influence on deviations from the basic pattern of technological change (e.g., when compared to market economies) appears to be relatively small, at least in the industry sector discussed herein.

The areas of application of a particular mining technology are extremely heterogeneous, much more than in other industrial sectors. This explains why not all technologies can be applied in 100% of the deposits mined and why a deviation from the historically observed logistic substitution pattern toward the end of the life cycle of a particular mining technology (when it enters its most difficult and least advantageous areas of applications) can sometimes be observed.

The limits of applicability of our simple model encountered in the analysis are to a large extent the result of a certain shortcoming of the data base available for analysis. In this study, we dealt with rather high-level aggregates. In reality, however, each technology consists of a large number of subvariants, specifically designed to correspond to the geological conditions of the deposit mined. In addition, the available data base did not allow (except in one case) differentiation between different ranges of geological conditions at underground mines. Clustering of applications of particular technologies under a range of comparable conditions was therefore not possible, but is considered to be a necessary step in a further analysis. It is our contention that much of the deviant behavior of technological substitution processes observed in our analysis could be better understood and is in fact not a deficiency of the model applied, but rather the result of too high a level of aggregation of the available data. In the absence of a more detailed data base, however, this contention cannot be confirmed for the time being.

Related to this limitation imposed by the available data, we would like to point to two further areas of improvement of our analysis. First, data referring to technological change in opencast mining should be assembled, as the results of our analysis have confirmed the trend of growing importance of opencast mining in the USSR. Second, more detailed data are needed to use a multiattribute approach and to describe technological change using various measures. The analysis of roof-support technologies has clearly shown, for instance, the difficulties in describing technological change simply by analyzing the number of faces where a particular technology is applied, and not also analyzing physical output, considering the different production intensities resulting from different technologies.

Although models of technological diffusion and substitution cannot answer questions regarding the time and rate of introduction of new technologies not in use today (such as in situ coal gasification), they can provide good quantitative insight into the technology dynamics of a particular industry branch, which is useful, for planning purposes, in learning from past experience. In this context it is worthwhile to note that technological change in the coal-mining industry is a rather slow process. Typically it takes a number of decades for a new technology to grow from 10% to 90% market share. The analysis has also shown that the diffusion rate is a function of the aggregation of analysis, i.e., technologies at a high level of aggregation (e.g., opencast vs underground mines) have Δts in the order of 100 years, whereas penetration of technologies into smaller (sub)markets proceeds substantially faster.

The analysis presented here and its quantitative results can therefore yield better insights into the lead and diffusion times required for the introduction and implementation of new technological systems, be it at the national or industry level. It provides a good guidance framework for the long-term planning and assessment of the prospects and impacts of technologies proposed to be introduced into the industry. Finally, as many of the technologies are closely interrelated (for instance, shearers, hydraulic roof supports, and conveyor transport), diffusion/substitution analysis can provide a consistency check on the penetration of these technologies. As can be seen from the statistical appendix, the diffusion rates and time-location parameters of the technologies are, even though they are closely interrelated, far from synchronized or having similar time constants. This may provide useful information for planning purposes, in terms that potential bottlenecks as well as necessary prerequisites in the further development of a particular technology application can be identified.

The analysis shows that the underground coal-mining industry of the USSR can be characterized as a mature industry sector. Most new technologies have diffused beyond the 50% market share level, and no radically new technologies that could yield similar productivity gains appear to be readily available, like the ones resulting from the introduction of (complete) mechanization schemes after World War II.

The analysis has further shown that the diffusion rates of most technologies began to slow down after 197.5, compared to previous experience. Whether this is the result of the progressive exhaustion of the most effective fields of application of these technologies or whether it can be interpreted as a sign of stagnation in the technological development of the industry (or both), cannot be resolved in detail within the context of the present paper. The implications of this development are, however, straightforward. In the future, it will be even more difficult to compensate for the progressive effects of deteriorating geological conditions, due to the depletion of low-cost underground mining deposits. Consequently, all economic indicators, including labor productivity, can be expected not to improve, and may even deteriorate. As the data presented in the data appendix on the general evolution of the industry show, the signs of stagnation in the technological development of the underground mining industry are reflected in the deteriorating productivity indicators since 1975.

The only available technological option for high productivity and low-cost coal production appears to be further development of opencast mining. This will have significant implications, not only on the geographical distribution of coal production but it will also require significant investments into the infrastructure to transport additional coal quantities to the main centers of consumption. In the opinion of the authors this option appears quite feasible in view of the large coal reserves available as well as the still-existing expansion potential for opencast mining, which could in the future account for more than 50% of the coal mined in the USSR.

We conclude this paper by proposing some directions for further research, which we hope the present paper and results will help to stimulate.

One research direction would be to expand and detail the present analysis along two lines. The first would be to introduce a more detailed and multidimensional approach in the analysis of underground mining technologies in view of the conclusions presented above. Second, the analysis should address technological trends in opencast mining technologies. This would check both similarities and differences in the rates of technological advances in underground and opencast mining and would identify the opencast mining technologies that still appear to have a large growth potential.

The second research direction would follow the IIASA tradition of comparative cross-national analysis. Through the proposed uniform methodological framework, it would be possible to assess technological change in the coal mining industry of different countries, to compare their structural similarities, and to single out differences and specifics of technological change in different countries. Preliminary analyses performed for the United States, and United Kingdom, and the Federal Republic of Germany (see, e.g., Marchetti and Nakicenovic [12] and Grübler [8] show encouraging results and could be used in conjunction with the present analysis of the USSR coal-mining industry.

Finally, the driving forces and impacts of mechanization in coal mining could be assessed. Provided sufficient data became available, this could yield a detailed model of the underlying driving forces of technological diffusion and substitution in coal mining. This research direction is especially challenging as one would have to integrate a model of resource depletion to assess the benefits of mechanization. All general industry indicators, while showing impressively the impact of mechanization, in fact underestimate the impacts and benefits from this technological diffusion process, as part of the benefits are counterbalanced by the deteriorating geology of the deposits mined.

It is only through technological change that the coal-mining industry can hope to face the challenge of deteriorating geology in striving for economic and safe production of coal, the fossil resource so vital in the historical development of industrialized countries.

References

1. Mansfield, E., Technical Change and the Rate of Imitation, Econometrica 29(4), 741-766 (1961).
2. Mansfield, E., *Industrial Research and Technological Innovation, An Econometric Analysis,* W. W. Norton, New York, 1968.
3. Souder, W. E., and Quaddus, A., A Decision-Modeling Approach to Forecasting the Diffusion of Longwall Mining Technologies, *Technological Forecasting and Social Change 21, 1-14 (1979).*
4. Ray, G., and Uhlmarm, L. *The Innovation Process in the Energy Industries,* Cambridge University Press, Cambridge, 1979.
5. Ray, G., Energy, in *Technological Trends and Employment: 2 Basic Process Industries. J.* Clark, ed., Gower House, Aldershot, UK, 1985, pp. 1-69.
6. Kundel, H., Die Srebetechnii im deutschen Steinkohlenbergbau, *Glückauf* 115(15), 748-758 (1979).
7. Kundel, H., Face Technology in Germany's Coal Mines in 1984, in *German Longwall Mining.* R. H. Bachstroem, ed., Verlag Glilckauf, Essen, 1985, pp. 9-21.
8. Grilbler, A., Technology of Diffusion in a Long Wave Context: The Case of the Steel and Coal Industries, in *Life Cycle and Long Waves.* T. Vasko, R. Ayres, and L. Fontvielle, eds., Lecture Notes in Economics and Mathematical Systems no. 340, Springer, Berlin, 1990, pp. 117–146.
9. Astakhov, A., and Grilbler, A., Resource Requirements and Economics of the Coal-Mining Process: A Comparative Analysis of Mines in Selected Countries, RR-84-13, IIASA, Laxenburg, Austria, 1984.
10. Astakhov, A., and Mookhin, A., Technological Development of Individual Processes in the USSR Coal Mining Industry: Analysis of Some Retrospections, IIASA, Laxenburg, Austria, 1987 (mimeo).
11. Astakhov, A., and Mookhm, A., Technological Development of Individual Processes in the USSR Coal Mining Industry: Data and Industry Statistics, IIASA, Laxenburg, Austria, 1988 (mimeo).
12. Marchetti, C., and Nakicenovic, N., The Dynamics of Energy Systems and the Logistic Substitution Model, RR-79-13, IIASA, Laxenburg, Austria, 1979.
13. Nakicenovic, N., Software Package for the Logistic Substitution Model, RR-79-12, IIASA, Laxenburg, Austria. 1979.

14. Posch, M., Grübler, A., and Nakicenovic, N., Methods of Estimating S-shaped Growth Functions: Algorithms and Computer Programs, IIASA, Laxenburg, Austria, 1987.
15. Fisher, J. C., and Pry, R. H., A Simple Substitution Model of Technological Change, Technological Forecasting and Social *Change.* 3, 75-88 (1971).
16. Kruglikov, A. G., Dynamics Modeling of Technological Innovation Diffusion Processes. Paper presented at the IIASA Task Force Meeting on Dynamizing Technology October 28-29, 1985, IIASA, Laxenburg, Austria.
17. Kuznetsov, K. K., et al., Coal *Deposits for Opencast Mining,* Nedra, Moscow, 1971 [in Russian].
18. Astakhov, A., The Geological-Mining Appraisal of the Major Coal Basins in the USSR: Materials for the Coal Resources Working Group of the IIASA Energy Project, IIASA, Laxenburg, Austria 1977 (mimeo).

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TABLE A-1
Coal Output in the USSR, 1913–1986, 10^6 (metric) tons

Year	Total	Underground mines	Hydraulic mining[a,b]	Opencast mines
1913	29.2	29.0	—	0.2
1917	31.3	31.0	—	0.3
1920	8.7	8.6	—	0.1
1928	35.5	35.2	—	0.3
1930	47.8	47.4	—	0.4
1935	109.6	108.3	—	1.3
1940	165.9	159.6	—	6.3
1945	149.3	131.5	—	17.8
1950	261.1	234.0	—	27.1
1955	389.9	325.4	0.600	64.5
1960	509.6	407.6	2.600	102.0
1965	577.7	437.2	4.700	140.5
1970	624.1	457.5	6.200	166.6
1971	640.8	461.7	n.a.	179.1
1972	655.2	465.0	n.a.	190.2
1973	667.6	468.2	9.872	199.4
1974	684.5	471.8	9.075	212.7
1975	701.3	475.5	9.100	225.8
1976	711.5	479.9	n.a.	231.6
1977	722.1	478.1	n.a.	244.0
1978	723.6	469.7	n.a.	253.9
1979	718.7	459.9	n.a.	258.8
1980	716.4	445.5	8.900	270.9
1981	704.0	428.5	n.a.	275.5
1982	718.1	432.0	n.a.	286.1
1985	726.4	421.7	8.200	304.7
1986	751.1	429.9	n.a.	321.2

[a]Included in figures for underground mines.
[b]n.a., data not available.

TABLE A-2
Coal Output by Basin in the USSR, 1913–1986, 10^6 (metric) tons

Year	Total	Donbass	Kuzbass	Kraganda	Ekibastuz
1913	29.2	25.3	0.8	—	—
1917	31.3	24.8	1.3	—	—
1920	8.7	4.5	0.9	—	—
1928	35.5	27.3	2.6	—	—
1930	47.8	n.a.	n.a.	—	—
1935	109.6	n.a.	n.a.	—	—
1940	165.9	94.3	22.5	6.30	—
1945	149.3	38.4	30.0	11.50	—
1950	261.1	94.6	38.5	16.40	—
1955	389.9	139.2	56.9	25.80	2.30
1960	509.6	186.2	84.0	26.20	6.00
1965	577.7	217.4	97.3	31.30	14.30
1970	624.1	223.0	113.3	38.80	22.80
1975	701.3	225.3	137.6	46.30	45.80
1979	718.7	211.5	148.1	46.80	59.20
1980	716.4	205.6	145.0	48.60	66.50
1981	704.0	202.2	142.9	48.30	67.60
1982	718.1	203.0	145.3	48.90	69.34
1985	726.4	198.7	146.2	49.80	80.45
1986	751.1	200.6	147.4	51.19	85.73

n.a., data not available.

TABLE A-3
Daily Coal Output per Operating Face in the USSR, 1940–1986, ton/day per face

Year	Total coal-mining industry	Donbass
1940	106	103
1950	107	106
1960	197	198
1965	253	245
1966	268	261
1967	278	273
1968	301	295
1969	317	317
1970	331	313
1971	354	332
1972	384	358
1973	415	380
1974	440	390
1975	454	393
1979	421	339
1980	409	328
1981	395	312
1982	396	312
1985	389	305
1986	404	316

TABLE A-4
Daily Coal Output per Mine in the USSR, 1940–1986, tons per day

Year	Total coal-mining industry	Donbass
1940	738	702
1950	688	536
1960	1,148	923
1965	1,442	1,119
1966	1,489	1,256
1967	1,562	1,313
1968	1,646	1,387
1969	1,687	1,428
1970	1,804	1,570
1971	1,872	1,647
1972	1,933	1,695
1973	2,039	1,804
1974	2,083	1,831
1975	2,120	1,844
1976	2,170	1,884
1977	2,173	1,881
1978	2,108	1,808
1979	2,087	1,776
1980	1,996	1,742
1981	1,942	1,691
1982	1,966	1,692
1985	1,974	1,722
1986	2,014	1,753

TABLE A-5
Labor Productivity at Coal Mines in the USSR, 1913–1986

	Tons/month per person employed			Tons per shift		
Year	Total	Underground mines	Opencast mines	Total	Underground mines	Opencast mines
1913	12.8	12.8	—	0.576	0.576	—
1928	12.7	12.7	—	0.572	0.572	—
1932	16.2	16.2	—	0.729	0.729	—
1937	26.9	n.a.	n.a.	1.170	n.a.	—
1940	30.6	29.9	65.7	1.324	1.293	2.887
1945	23.8	21.6	86.9	0.968	0.874	3.557
1950	30.1	27.8	96.3	1.301	1.199	4.176
1951	32.4	29.8	105.4	1.409	1.296	4.577
1952	33.8	30.8	118.4	1.468	1.337	5.082
1953	34.8	31.1	132.3	1.517	1.357	5.666
1954	36.3	31.9	150.7	1.599	1.406	6.429
1955	37.6	32.5	174.7	1.660	1.433	7.514
1956	37.8	32.0	197.7	1.678	1.421	8.500
1957	38.7	32.5	209.0	1.739	1.462	9.164
1958	39.0	32.5	210.3	1.750	1.460	9.242
1959	39.8	33.2	209.5	1.794	1.497	9.351
1960	41.9	35.0	213.7	1.887	1.573	9.539
1961	43.3	35.7	214.5	1.952	1.609	9.776
1962	44.9	36.6	220.9	2.032	1.655	10.119
1963	46.7	37.9	230.9	2.089	1.693	10.614
1964	48.7	39.2	238.1	2.171	1.746	10.865
1965	50.2	40.0	255.8	2.240	1.781	11.676
1966	50.9	40.3	260.1	2.296	1.815	12.027
1967	52.0	41.0	264.2	2.399	1.888	13.027
1968	53.1	42.0	264.6	2.535	1.997	13.945
1969	55.8	44.0	279.9	2.636	2.067	14.872
1970	57.6	44.9	303.9	2.687	2.081	16.274
1971	61.2	47.0	324.2	2.847	2.172	17.458
1972	65.0	49.4	347.1	3.055	2.305	18.527
1973	68.5	51.6	372.7	2.516	2.642	19.907
1974	71.9	53.3	400.5	3.731	2.763	21.369
1975	73.7	53.8	425.7	3.847	2.807	22.716
1976	74.4	54.1	434.2	3.866	2.809	23.006
1977	74.7	53.3	451.3	3.855	2.746	23.958
1978	72.4	50.7	456.8	3.760	2.632	23.971
1979	70.1	48.5	447.9	3.659	2.532	23.482
1980	69.1	46.2	455.5	3.606	2.411	23.858
1981	67.0	44.0	438.7	3.494	2.293	23.078
1982	66.3	43.1	427.2	3.457	2.246	22.707
1985	65.4	41.2	417.5	3.493	2.000	21.946
1986	67.4	41.9	425.1	3.601	2.242	22.427

n.a., data not available.

TABLE A-6
Labor Productivity at Underground Coal Mines in the USSR, 1940–1986

Year	Labor productivity, tons/shift					Drivage work, m/1,000 ton production	Labor requirements for drivage, shifts
	Total	Underground	At faces	Drivage	Transport		
1940	1.292	1.672	3.922	10.753	9.259	n.a.	n.a.
1950	1.202	1.582	3.425	9.259	10.000	29.5	3.66
1953	1.366	1.786	4.115	10.417	11.236	n.a.	n.a.
1960	1.567	2.066	4.902	11.236	15.625	24.9	3.57
1965	1.779	2.283	5.556	11.765	16.129	22.8	3.73
1970	2.083	2.695	6.897	13.889	18.868	18.0	4.00
1971	2.169	2.725	7.246	14.493	19.608	17.5	3.94
1972	2.309	2.882	7.692	14.286	19.231	16.7	4.19
1973	2.632	3.289	8.621	16.393	23.810	15.7	3.89
1974	2.762	3.448	9.259	16.129	23.810	15.1	4.11
1975	2.801	3.546	9.709	17.544	23.256	14.5	3.93
1980	2.415	3.058	8.621	13.699	18.519	13.8	5.29
1981	2.294	2.899	8.197	12.987	20.000	14.7	5.24
1982	2.252	2.849	8.333	12.821	17.857	14.8	5.27
1985	2.208	2.755	8.197	11.628	16.949	14.3	6.01
1986	2.242	2.801	8.621	11.765	17.241	14.2	5.99

n.a., Data not available.

TABLE A-7
Labor Productivity at Underground Coal Mines in the Donbass, 1940–1986

Year	Labor productivity, tons/shift					Drivage work, m/1,000 ton production	Labor requirements for drivage, shifts
	Total	Underground	At faces	Drivage	Transport		
1940	1.222	1.458	3.536	10.309	7.092	19.7	4.924
1950	0.987	1.316	2.849	9.174	7.874	26.2	4.160
1953	1.090	1.486	3.509	10.638	8.130	28.6	3.287
1960	1.284	n.a.	4.237	10.870	10.000	25.0	3.680
1965	1.468	1.818	4.808	11.628	11.111	22.0	3.909
1970	1.694	2.092	5.556	13.514	12.195	17.0	4.353
1974	2.237	2.732	7.042	15.385	16.667	14.5	4.483
1975	2.157	2.725	7.143	14.925	16.393	13.8	4.855
1979	1.850	2.304	6.289	12.048	12.821	14.4	5.764
1980	1.777	2.217	6.135	11.364	12.346	14.8	5.946
1985	1.642	2.024	5.952	9.901	11.236	15.1	6.689
1986	1.672	2.066	6.173	9.901	11.494	15.0	6.733

n.a., Data not available.

TABLE A-8
Diffusion Parameters and Statistics of Goodness of Fit

Figure	Technology	t_0[a]	Δt (years)[b]	Data period used for parameter estimation	t statistic	R^2
1	Steam	1960.5	−12.3	1953–1972	69.5	.996
	Diesel/ electric	1960.5	+12.3	1953–1972	69.5	.996
2	Stowage	1946.5	−51.7	1940–1986	15.0	.962
	Caving	1946.5	+51.7	1940–1986	15.0	.962
3	Manual	1918.7	−34.2	1938–1955	7.6	.828
	Explosives and cutters	1963.9	−26.6	1938–1975	2.5	.561
	Shearers	1963.9	+26.6	1948–1975	17.8	.952
4	Wood	1962.0	−24.2	1947–1970	10.1	.945
	Metal	1961.5	+22.6	1947–1965	5.1	.897
	Hydraulic	1981.3	+27.8	1960–1985	11.8	.939
5	Advancing	1969.6	−79.4	1960–1986	8.7	.938
	Retreating	1969.6	+79.4	1960–1986	8.7	.938
6	Manual	1968.1	−36.6	1940–1986	18.9	.962
	Scrapers	1969.5	+36.4	1940–1965	14.9	.987
	Combines	1985.5	+40.7	1940–1986	10.7	.920
7	Manual, horses, and ropes	1939.2	−21.3	1930–1955	7.2	.945
	Locomotives	1940.2	+28.1	1930–1955	17.6	.990
	Conveyors	1986.2	+48.5	1955–1985	18.8	.986
8	Ropes	1966.8	−34.1	1950–1986	14.5	.968
	Conveyors	1966.8	+34.1	1950–1986	14.5	.968
9	Underground	1991.7	−96.5	1945–1986	30.3	.981
	Opencast	1991.7	+96.5	1945–1986	30.3	.981

[a]Inflection points (market share of 50%) refer only to phases of logistic growth/decline.
[b]Time in years to grow from 10% to 90% market share. +, growing market shares; −, declining market shares.