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THE CYCLICAL DYNAMICS OF DIFFUSION RATES

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FOREWORD

The technological life-cycle is an organizing principle common to several of the investigations within the Technology-Economy-Society Program at IIASA. That is why the development of methodological approaches to life-cycle analysis is very useful for further applied research.

In order to classify and characterize the different phases of the life-cycle, we need a statistical method to identify transitional periods. The known approaches have been developed for commodity life-cycles and there are very few examples of applications to the technological life-cycle.

Prof. I. Tchijov proposes a new method of identifying intra-cycle boundaries, based on the dynamics of diffusion rates within business cycles. This method was validated by the use of statistical data for technological structure of steel production in the USA, as well as in great Britain.

Then he applied the proposed method for the case of computer-integrated manufacturing. Finally Prof. Tchijov delivers the theoretical base for the necessity of different methodological approaches to the analysis of a new technology diffusion in the embryonic and expansion phases of the technological life-cycle. This paper is presented within the Computer-Integrated Manufacturing Project of TES.

Robert U. Ayres

SUMMARY

A new approach to technological life-cycle analysis is proposed. It is based on the life-cycle division into four phases by using business cycle analysis. The proof of the proposed methods was made for different technologies in steel production as well as in numerical-controlled machines in metalworking industry.

INTRODUCTION

A well-known approach to the diffusion processes investigation is based on the following prerequisite: there are four phases in a technological life-cycle (1) embryonic or childhood ($t1 - t_2$), (2) expansion or adolescence plus maturity ($t_2 - t_4$), (3) saturation ($t_2 - t_3$), and (4) declining or senescence (t_5 -..). These are illustrated schematically in Fig. 1.

Of course, the exact form of the curve depends on specific features of a technology, real historical conditions, and a competitive situation. For example, in the case of two competing technologies (in the period $t_1 - t_4$) it is possible that one of them will achieve a 100% diffusion or penetration. But the rate will be less than 100% if a new additional technology appears on the scene. We define this rate as a new technology share in the total spectrum of technologies used for a certain item production.

It is very important to determine t_2 exactly for the technological life-cycle analysis, because it separates the embryonic phase from the expansion one. This distinction is necessary because of sufficient differences in driving forces, economic conditions, and dynamic features of the diffusion process in these two phases. For instance, a new technology might not yield net profits to the innovator in the embryonic phase. It demands very high risk investments and a stream of parallel inventions or improvements. The conventional technology is regarded as more reliable and profitable in this period. The new technology has to be adapted to many new fields of applications and penetrate new sub-markets. That is why a new embryonic technology is sometimes limited at first to big

$t_0 - t_1$ – premarketing period

$t_1 - t_2$ – embryonic (or childhood) phase

$t_2 - t_3$ – adolescence phase } $t_2 - t_4$ – expansion phase

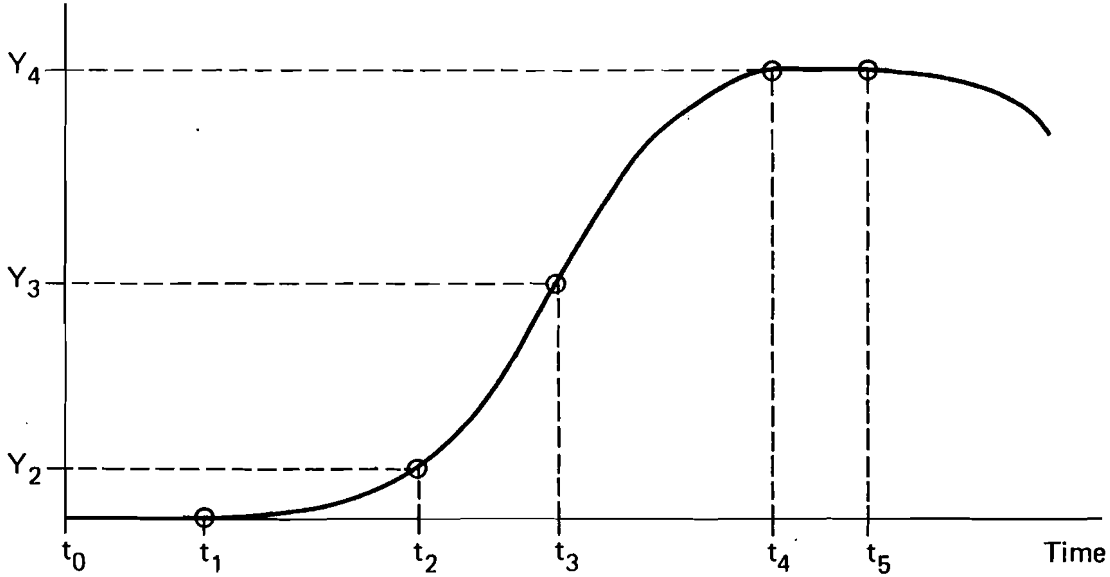
$t_3 - t_4$ – maturity phase }

$t_4 - t_5$ – saturation phase

$t_5 - \ldots$ – senescence (or declining) phase

t_3, Y_3 – inflexion point

Y_4 – saturation level



companies with very strong financial positions and R&D experience. It is a scale monopoly.

At the second stage (expansion) the new technology becomes more profitable and reliable enough compared with the conventional one and the number of vendors is tremendously growing until the inflexion point (when the second derivative in Fig. 1 $-Y_3/t_3-$ turns into zero. The rate of DR growth depends mainly on economic parameters: relative profitability, relative cost (differentiated into its main elements - labor, capital, material, and energy), investment supply, fixed-capital vintage structure, etc.

To summarize there are quite different theoretical approaches as well as analytical methods applicable for technological life-cycle investigations in these two phases. Thus the determination of the boundary point t_1 is quite important for purposes of refining the analysis of life cycles.

The development of life-cycle analysis was traditionally based on investigations of product life-cycles, especially for consumer durables.[1] In a product case (versus technology) the number of first producers or a monopolization rate is very important. But in a technology case the number of users or acceptors is more important, than the number of producers. A competitive market situation determines the life-cycle dynamics in a product case, but for new technologies a production side plays a great role. In the field of technological life-cycles the main researches dealt with the problem of interactions

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[1]There are also investigations of a corporate life-cycle, see, for instance: Miller D., Friesen P. A Longitudinal Study of the Corporate Life Cycle. Management Science, Vol. 30, N-10, October 1984, pp. 1161-1183.

between old and new technologies. For the statistically precise definitions of the different phases or stages of diffusion processes two main approaches were usually used. Let us demonstrate them by two concrete examples.

The first approaches to the life-cycle division into several phases is based on a scale of production. For example[2], new product life-time is divided into three phases: custom, batch and line production. The first one is characterized by tens of units produced a year, the second one by hundreds and the third one- by thousands.

For the case of Bombardier's Snow Vehicle history they determined the length of the phases as 11, 22 and more than 20 years, respectively.

Table 1

Bombardier's Snowmobile Making Operations

	Environment			
Modes	Technological	Market	Production & Development	Capital & Equipment
Custom 1926-1956	Use of Model "T" components & adaptation to snow	Hotel Managers, doctors, veterinarians, ambulances	Highly skilled mechanics	General purposes equipment
Batch 1937-1959	application of sprocket-thread system	Defence, petroleum, forest management, municipalities	Many mechanics and seasonal labor for hand assembly	Bombardier learns machine making some specialized vulcanizer for tread low and variable utilization
Line 1965 to present	Ski-Doo simple, reliable performant & dominant design distribution & servicing network	Unit price as low as 6000 $ assembly line up to 100,000/year by 1969:/million produced; 1980: 30% of North American market	Routinized automative assembly line with overhead serpentine	1967-1972 fixed capital investment phase specialized machinery

[2]De Bresson C., Lampel J. Beyond the Life Cycle. The Journal of Product Innovation Management, 1985, 3, pp. 170-195.

However, this approach was developed for the product (not technology) life-cycle and the life-cycle development was determined by market environment. The snowmobile did not substitute for any predecessor, that is why the absolute estimates are applicable instead of penetration or diffusion rates.

The absolute values for the definition of boundaries between different stages are not universal because they are dependent on specific features of a product, a market size, etc. That is why this approach might have only a restricted use for cases of technological diffusion processes.

The second approach to the phases determination based on the number of producers was used by Gort M. and Klepper S.[3] They divided a life-cycle into five stages. The first one begins with the commercial introduction of a new product by its first producer. The end of this stage is reached, when the total number of producers is no more than three.

The second stage is the period of sharp increase in the number of producers. Stage III is the period in which the number of entrants is roughly balanced by the number of exiting firms and net entry equals zero. The forth stage starts with the net entry becoming negative, and the fifth one is reached with the approximately zero net entry again but at a lower level.

The authors investigated the specific features of the stages by using information for 46 different innovations, which included consumer goods (like electric shavers and blankets, shampoo, zippers, etc.), chemical inventions (like DDT, styrene,

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[3]Time Paths in the Diffusion of Product Innovations. The Economic Journal, 92 (Sept. 1982), pp. 630-653.

saccharin, nylon) and a lot of high-tech examples (computers, lazers, guided missiles, transistors, nuclear reactors, etc.). The main results are shown in Table 2.

Table 2

Gost and Clepper's estimates for 5-staged life cycles

Average estimates\Stages	I	II	III	IV	V
Number of years in each stage	14.4	9.7	7.5	5.4	-
Annual net entry rates	0.5	5.7	0.1	-4.8	-0.5
Percentage change in output[4]	57	35	12	8	1
Percentage change in real prices[5]	-14	-13	-7	-9	-5

The main distinction of this approach from the first one is that the former is predeterminantly based on the production side. But the shortcoming of this approach is due to the use of a number of producers, because this number does not reflect the volume of production and moreover, the share of a new product in total production of competing products.

The methodological problem of the use of this approach to the case of new technologies is connected with the necessity to deal with a number of acceptors or users and the estimates of the new technology diffusion among the conventional ones. The example of PCs shows that the new market was created by a number

[4]For 25 products

[5]For 23 products, estimated as: $P_t/CPI_t = (P_1/CPI_1)e_{t(t-)}$ where P_1, P_t - prices for the first and last years of a stage, CPI - consumer price index.

of small new entrants but the biggest monopoly in this field - IBM - was waiting for its time to come.

That is why we are going to propose an alternative method of technological life-cycle separation into different phases, based on cyclical dynamic analysis of relative shares of new technologies.

STEEL PRODUCTION CASE

The traditional approaches to the technological life-cycle analysis are based on the use of long-term statistical time-series of the new technology diffusion or penetration rate.[6] They are usually smoothed or interpolated to estimate the main long-term dynamic parameters and do not reflect the cyclical features of the dynamics.

When we tried to investigate the technological substitution processes in the periods of recessions or decreases of production by using researching technologies we got rather interesting results (see Table 3).

Looking through the data in Table 1, it is possible to see that the new technology's behavior in the recession periods depends on its share in total production. When the share is below 9-10% of total production, the value of the share usually decreases in the recession periods.

For the period when the new technology's share increases from the 9-10% level up to the end of the saturation upper limit (point t_5) its values rise in recessions, especially within the phase t_2 - t_4. And after t_5 (in the declining phase) the technology's share decreases tremendously in the recessions.

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[6]See, for instance, the publications of Mansfield, E., Martino, J., Fisher, J., Pry, R., Marchetti, C., Nakicenovic, N., Haustein, K., and Kleinknecht, A.

TABLE 3: Changes in Technology Shares (percent points) versus Changes in Steel Production (%) in the USA.

Years of decrease in production	Changes in steel production, %	Changes in Shares of Technologies, p.p.	
		Open hearth	Electr.
1883-84	-10.7	-0.7	-
A - A			
1888	-11.3	+1.2	-
1891	-9.0	+2.7	-
1893	-18.6	+4.7	-
1896	-13.8	+5.9	-
1903-04	-7.3	+4.7	-
1908	-39.4	+7.1	-
1911	-8.4	+3.0	-0.1
1914	-24.9	+4.2	-0.0
1919	-22.3	+0.2	-0.1
1921	-53.1	+1.3	-0.4
1924	-15.4	+3.5	-0.0
1930	-27.8	+0.4	-0.2

Years of decrease in production	Changes in steel production, %	Changes in Shares of Technologies, p.p.	
		Open hearth	Electr.
1931	-35.8	+0.7	+0.2
1932	-44.0	+0.1	+0.1
1945-46	-25.7	+1.6	-0.9
1949	-7.0	+0.6	-0.8
1954	-20.9	+1.0	-0.3
1957	-2.2	+0.9	-0.4
B - B			
1958	-24.4	-1.2	+0.7
C - C			
1967	-5.1	-8.0	+0.8
1970-71	-12.0	-13.6	+3.1
1975	-20.0	-5.4	-0.2
1980	-18.0	-2.4	+3.0
1982	-38.2	-3.0	+2.9

A-A line means t_1 for open hearth (≈ 10%)

B-B line means t_2 for open-hearth (≈ 90%)

C-C line means t_1 for electric-furnace technology (≈ 9%)

Sources: Historical Statistics of the U.S. - Washington, 1975;
Statistical Abstract of the US, 1984.

It is completely confirmed by the data for the open-hearth technology which passed sequentially the embryonic phase (up to 1887), the expansion phase (from 1887 up to 1940), the saturation phase (from 1940 up to 1957) and the declining one (from 1958). We observe the same results for the electric-furnace technology in steel-making. It passed from the embryonic phase (1909 up to 1957) to the expansion one (1958 up to now). There were only 3 exceptions from the rule (1931, 1932, 1975) when the share of the embryonic technology did not decrease (the first two cases) and the share of the expanding technology did not increase (the last one). But the deviations from the rule were very small.

Unfortunately, we could not get the same results for the embryonic phase of the basic-oxygen furnace (BOF) technology because it grew too fast and passed this phase between two sequential recessions (1958 and 1967). But after 1964 when the share of the last technology reached 12% it behaved like an expanding technology.

Summing up the tendencies in the technologies' shares in the US steel-making it is possible to find the following total estimates. During 60 years of the decline in the Bessemer share, 50% of the reduction took place during 24 recession years and only three years (1893, 1896, 1908) the Bessemer share reduced by 18 percent points, or 10% of the total decrease.

There is the same situation in the open-hearth declining phase when 1/3 of the total reduction (from 90% in 1957 up to 7% in 1983) took place during 4 recession years -1967, 1970-71, 1975.

The growth of electric-furnace steel-making in its embryonic phase was interrupted by the decreases in recession years. The total growth was from 0 in 1909 up to 9% in 1959 and at the same time there was a 3 percent point reduction of the share during 13 recession years.

In order to confirm these results we tried to check the situation in British steel-making, but we could not get the same results for all recession periods because of high instability in steel production in Great Britain[7]. That is why we can present only the aggregated data.

During the expansion phase the share of the open-hearth technology increased during 12 recession years and decreased slightly during only two years (1924 and 1925). In the embryonic phase of electric-furnace technology (from 1914 to 1963 when it reached 10%) there were two stagnation periods in steel production: 1918-1931 and 1940-1945. The share of this embryonic technology decreased from 1.3% in 1917 to 1.1 in 1931 in the first period and from 4.4% to 4.1 in the second one. But in the expansion phase the share of the electric-furnace technology increased from 16% to 32% when the total steel production reduced from 27 mil. tons (in 1970) to 15 mil. tons (in 1980).

The BOF technology starting from 2.5% in 1934 reached 6.6% in 1938 and after that during the stagnation in production oscillated at the same level up to 1945. In the expansion phase (reaching the 9% level in 1961) the share of BOF increased up to 68% in 1980 in spite of the stagnation in steel production.

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[7]Statistical Source: Abstract of British Historical Statistics, Mon. N 17, 18, Cambridge, 1971, ECE Annual Bulletin of Steel Statistics for Europe, UN.

These effects can be explained from the economic point of view. In the embryonic phase the competitive positions of a new technology is very low, the rate of risk in investments is too high. That is why during the recessions firms prefer to rely upon conventional technologies and the share of a new technology declines.

On the other hand in the expansion phase the competitive positions of a new technology becomes stronger, the firms gain the scale effect by using the new technology and the rate of decrease in production, when the conventional technology is used, is higher than in the case of the new technology during recessions. Moreover, the share decrease rate of the conventional technology is higher for recession periods than for growth periods.

The main proposal we can draw from this analysis is the determination of the boundary between the embryonic phase and the expansion one concerning the cyclical behavior of the new technology's share. In the case of steel production the criterion level of the share (DR_1) might be defined as 9-10% of the total production.

Researching the situation in other industries, we also found several cases which showed similar results. There is Piggyback Train Service which might be treated as an embryonic new technology in transportation. The share of "revenue car loadings piggyback" in "revenue car loading all traffic" grew from 3.1% in 1964 to 5.8% in 1974[6]). During the 1970 and 1975 recessions the

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[6]Martino J. et al. Predicting the Diffusion Rate of Industrial Innovations. Report, March 1978, Dayton.

share decrease took place (from 4.8% to 4.6% and from 5.8% to 5.3%, respectively). At the same time the total revenue reduced by 4% and 11%. The similar situation was observed in some other cases.

NC-MACHINES CASE

Now let us look at the dynamics of the diffusion of Flexible Manufacturing (FM) equipment in metal working industry from the same point of view. Unfortunately, we could not find the reliable long-term statistical data concerning the share of the FM product in industrial production as a whole, as well as the cyclical dynamics of the share of FM machines in the total number of metal working machines installed.

That is why we can rely only on the information about the share of certain FM-type machines production in total metal-cutting machines production and only for the recent years.

Table 4: The share of numerically controlled (NC) machining centers (MC) and horizontal-spindle turning machines (TM) production in total metal-cutting machines shipments %, value in current dollars, USA.

	1979	1980	1981	1982	1983	1984
M C	8.3	7.9	8.2	8.0	6.4	6.8
T M	6.5	6.1	5.9	5.4	6.0	5.8
Average	7.4	7.0	7.1	6.7	6.2	6.3
Change in industrial production index						
-manufacturing	+4.6	-4.5	+2.5	-8.5	+7.7	+2.6
-non-electrical machinery	+6.6	-0.5	+5.2	-13.0	+1.1	+3.1

Sources: 1986, US Industrial Outlook
Economic Report of the President, 1984.

The data shown in Table 4 demonstrate the situation which took place in the case of embryonic technologies in steel production. In 1980 and 1982 when the production in main NC-machines consuming industries (non-electrical machinery or manufacturing as a whole) decreased, the substantial declines in the NC production share were observed. And vice versa, the increase in the share corresponded to the growth of industrial production.

In 1982 during a severe recession in the USA, the spot-welding robots production decreased from 644 to 434 (-33%)[9]. At the same time the total production of welding apparatus decreased only by 25%[10] that means a reduction of the welding robots share in the total production of such a type of equipment.

The same situation can be observed when we deal with the total production of NC-machines as a part of metal-cutting machine production. The share reached 1.3% in 1968 and decreased later because of the crisis in the US economy up to 1.0% in 1970 and 0.8% in 1972. A certain lag also took place in the share dynamics in the 1974-75 recession. The share of NC-machines in metal-cutting/forming machines production decreased only in 1976 from 1.5% to 1.4%. It is possible to make two conclusions. (1) The NC-machines production is the embryonic phase now, concerning the share behavior during recessions. (2) The decreases in NC and robots production at the beginning of the 80's were not to discourage their supporters because they reflected the temporary

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[9]Computerized Manufacturing Automation- Washington 1984, p. 290.

[10]1986 US Industrial Outlook.

break connected with the business cycle situation or possibly the break between two generations of the NC-machines.

NC machines are a wide spectrum of different types (turning, boring, drilling, etc.) and different classes (single machine, machining center, flexible manufacturing cell or system). They make different functions with different rates of flexibility. Moreover, the first generation of NC-machines, based on perforated tape control is being substituted for the second one, based on computerized control (individual, or direct).

Each type has its own boundary between the embryonic and expansion phases. The quantitative estimates of the boundary depend on the choice of substituted technology measurements: either it is the total population of the machines of a certain type, or the specific tools. For example, if we estimate the share of NC turning machines in the total number of turning machines in the US metalworking industry we get 9.1% for 1983. But for the youngest generation (0-4 years old) of machines we get 37.1% and for the second one (5-9 years old) - 15.5%. If we exclude four types of turning machines, which are not applicable to flexible manufacturing and are used in automated production, from the total population of turning machines, the share of NC turning machines will grow up to 12%[11].

This means that the quantitative estimates are very relative and the analysis of cyclical behavior of the share might be extremely useful for the boundary estimation.

CONCLUSIONS

This estimation, as it is, plays not only a pure theoretical role, but it is very important for the analysis and forecasting

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[11]The 13th American Machinist Inventory.

of a future new technology development. The analysis of two phases (embryonic and expansion) has a lot of methodological differences, corresponding to final tasks, methods and information provision. We tried to describe the differences in Table 5.

Table 5. Two Types of New Technology Analysis

Phase	Information Provision	Methods	Targets	Flexible Manufacturing Cases
Embryonic (t_1-t_2)	Absence of regular statistical data within the traditional statistical system (national income and product account, industrial statistics, etc.). Quite short time-series and imcomparability of data. Static occasional estimates of important economic information (cost of production, profitability, capital/labor saving etc.).	Expert's estimations, interviews, factor analysis, estimates of confidence intervals, descriptive models.	Solving the problem: dead end or prosperity, estimation of relative preferences, determination of potential niches, estimation of potential scale effect. t_2 determination.	The newest technologies for next century: CAD/CAM, FMS, sophisticated robots, DNC-machines.
Expansion (t_2-t_4)	Rather long-term comparable and reliable statistical data, the estimates of economic efficiency for certain cases. The information within macrolevel and industry-level regular statistical sources.	Econometric methods, input-output analysis, logistic-type interpolation and extrapolation methods.	Long-term forecast of new technology development, socio-economic impact estimates, determination of the rate of penetration. t_3, t_4 and t_5 determination.	New technologies: NC/CNC-machines, NC-control in production processes; primitive robots.