THE DIFFUSION OF FLEXIBLE AUTOMATION AND ROBOTS

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PREFACE

This working paper is based on the authors' contributions to the Innovation Management Workshop held at IIASA in June 1981. Chapters 1-4 were written by Heinz-Dieter Haustein; chapter 5 was prepared by Harry Maier.

The authors describe the role of flexible automation in increasing productivity, characterize flexible automation as a socioeconomic phenomenon, make a rough forecast of robot diffusion, and present some information on robots and national innovation policy using the GDR as an example.

CONTENTS

CHAPTER 1

INTRODUCTION

Since the 1950s the development of automation has undergone a number of ups and downs in all advanced industrial societies. Many of the optimistic dreams for the future of automation expressed at that time, described by Friedrich Pollock (1956) among others, failed to achieve fulfillment in the 1960s. NC machines, well-known since 1955, have diffused only very slowly: a higher growth rate of automation could be achieved through mass production and continuous-type output.

The automation coefficient of equipment (the share of automated and semiautomated equipment in total equipment by value) has now reached 50-65% in the advanced countries. The automation coefficient of labor, however, has failed to exceed 12-18%, and is showing a trend toward saturation. This is because most automation is special purpose automation in which automatic machines are used for mass production of goods. But according to Arthur D. Little, Inc. (see Factors Related to the Implementation and Diffusion of New Technologies 1979), four-fifths of the world's manufactured products continue to be produced in batch lots of between 10 and 50 units, usually at a cost of at least five times that of mass-produced items. Even in the US, 40% of value added in manufacturing is batch processed.

Thus it is not surprising that special purpose automation has reached the saturation level in terms of growth of productivity. Clearly, this plays a decisive role in the decline of productivity growth rates in the advanced countries. Moreover, existing forms of flexible automation (FA), such as NC (numerically controlled) machines, have been islands in the production system, with low levels of utilization.

The advent of microelectronics has changed this situation considerably. Microelectronics have given a remarkable push to FA, which follows a natural trajectory in a field of scientific, technical, economic, and social limits and chances.

At one time, about 50% of the cost of every NC machine was spent on devices for measurement, control, and steering. These functions were carried out using very expensive, large-scale conventional electronics. With the growth of microprocessor control systems, there has been a gradual reduction in costs. Today the control system accounts for about 20% of the total cost of each NC machine. The same has been true for robots, another type of FA, whose commercial and technical history began in 1962.

Experience indicates that FA will affect the national economy in the following ways:

1. Because of microelectronics, the second generation of FA will affect a larger share of manufacturing operations, especially in small batch production, and will lead to a considerable increase in productivity. However, FA could also lead to a high labor release effect and accompanying unemployment problems.
2. More important, FA will lead to more stable output levels and higher capital turnover ratios, which in turn will lead to more profitable industrial activities. But clearly this effect could be dampened by reductions in demand.
3. Another major factor will be savings in labor and wages per unit of output. But this can only be realized if higher stability in output and higher capital turnover ratios can be assured. In other words the success of FA depends on the its ability to improve the whole production system.
4. FA can also be applied to relieve human workers from strenuous types of work and unfavorable working conditions, as industrial robots gradually take over the heavy, dangerous, trying, and monotonously repetitive work that humans have been forced to do because of the difficulty in achieving automation. On the other hand, FA might lead to a sharper division of labor and an overall downgrading of the qualification requirements for the remaining workers.
5. FA will also help promote the development of new industries. The first factories for producing FA are already being built; these could become the core of a new industry. In addition, robot-like devices will help us to exploit the ocean; this could become a major industry in the 1990s. Thus FA will create new employment opportunities.

Benefits expected from FA include

- increased international competitiveness

- higher versatility in the production system
- an upgrading of the quality of human labor
- more consistency in product quality
- resource conservation resulting from reduced rejection rates and savings in materials.

Now in its second generation, FA is displaying shortcomings and limits that must be carefully studied in order to be overcome.

CHAPTER 2

SATURATION IN THE TRADITIONAL AUTOMATION OF MASS PRODUCTION

The structure of processing time in the metalworking industry (see Table 1 and Fig. 1) shows relative stability in the share of mass production. More than 70 percent of processing time is spent on unit production and small- and medium-sized batch production. Kops (forthcoming) estimates that on the average only 5% of a metal part's total time in-process is actually spent at the machine. The remaining 95% of the time is spent waiting or in transport.

This helps to explain the slow diffusion of NC machines in the past (see Table 2). Between 1958 and 1970 NC machines accounted for only 18% of sales of metal-cutting tools. At present only about 4% of all machine tools in US industry are numerically controlled (Kops forthcoming). Thus we see a tendency toward saturation in special purpose automation.

Automation can be measured in two ways:

1. By the automation coefficient of labor (a_L)
2. By the automation coefficient of equipment (a_M)

The automation coefficient of labor is much more significant than the automation coefficient of equipment.

We analyzed the relation of both indicators for many industries in the GDR and found that both indicators can be expressed as a logistic function. Looking at Figure 2 we can make several observations. First, real growth in the automation coefficient of equipment was much slower than

Table 1. Structure of processing time in the metalworking industry in the German Democratic Republic (in percent).

	1970	1978
I. Unit production		
A. Job shop production	6.3	6.0
B. Specialized production	2.2	2.4
B1. Automated production	6.3	6.0
C. Assembling	6.6	6.4
II. Series production		
A. Job shop production	19.8	18.8
B. Specialized production	22.9	22.7
B1. Production by groups	9.3	10.2
B2. Production line	10.8	9.7
B3. Production line with machines	2.8	2.8
B3.1 Automated line	0.6	0.6
C. Assembling	24.5	24.8
C1. Unit assembly	2.3	1.8
C2. Batch assembly	12.8	15.2
C3. Assembly line	9.4	7.8
C3.1 Automated assembly line	0.1	0.3
Potential for flexible automation (all categories except II-B3, II-B3.1, II-C3.1)	79.3	78.0
	0.2	0.3

Source: Statistical Yearbook of the GDR 1972,
Statistical Yearbook of the GDR 1980.

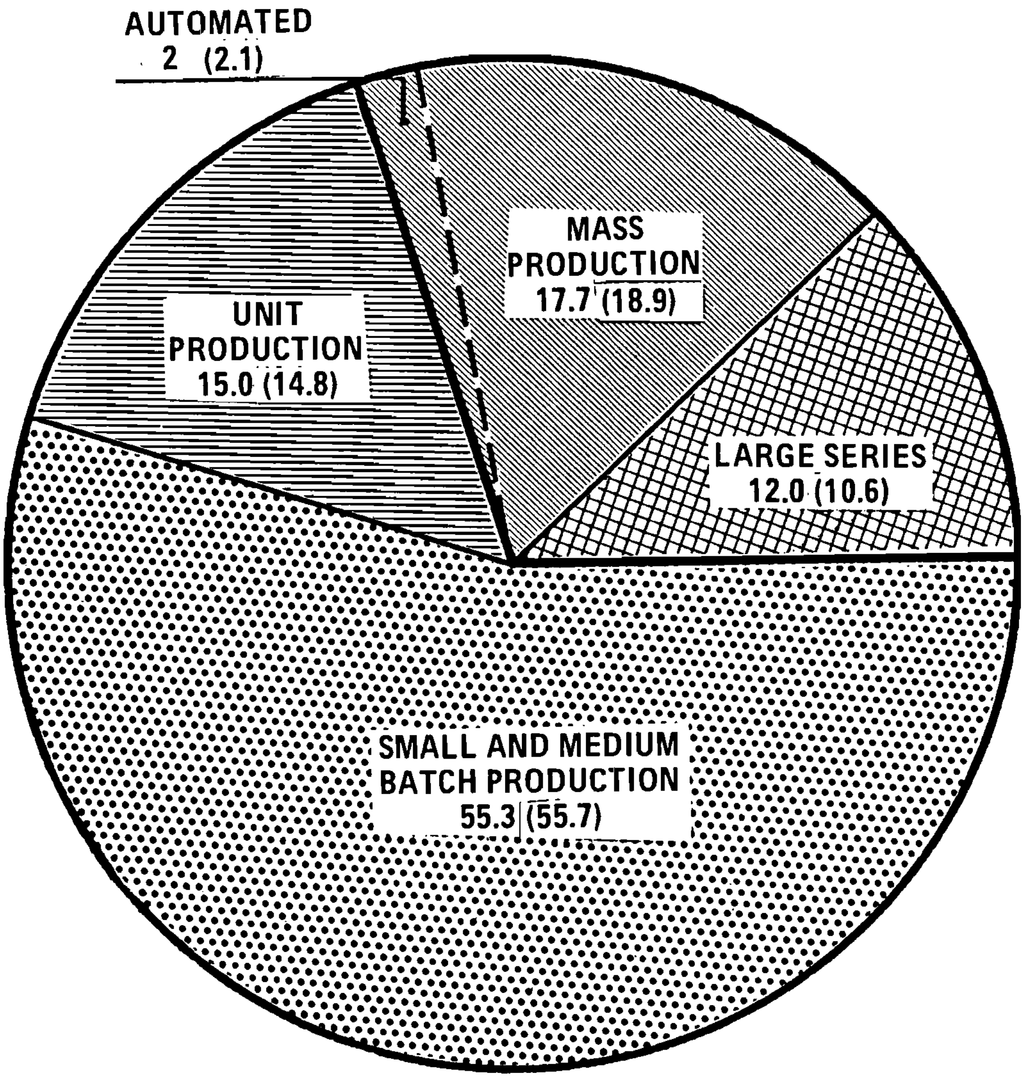

Figure 1. Structure of processing time in the GDR metalworking industry according to type of production (in percent) for 1970 (1978).

Table 2. Sales of numerically-controlled metal-cutting tools as percent of all metal-cutting tools shipped in the US.

Year	Percent	f/1-f
1958	2	.02
1959	3	.03
1960	5	.05
1961	6	.06
1962	9	.10
1963	12	.14
1964	11	.12
1965	14	.16
1966	18	.22
1967	19	.23
1968	25	.33
1969	23	.30
1970	18	.22
1971	21	.27
1972	21	.27
1973	21	.27
1974	25	.33
1975	28	.39
1976	32	.47

Source: Factors Related to the Implementation and Diffusion of New Technologies 1979.

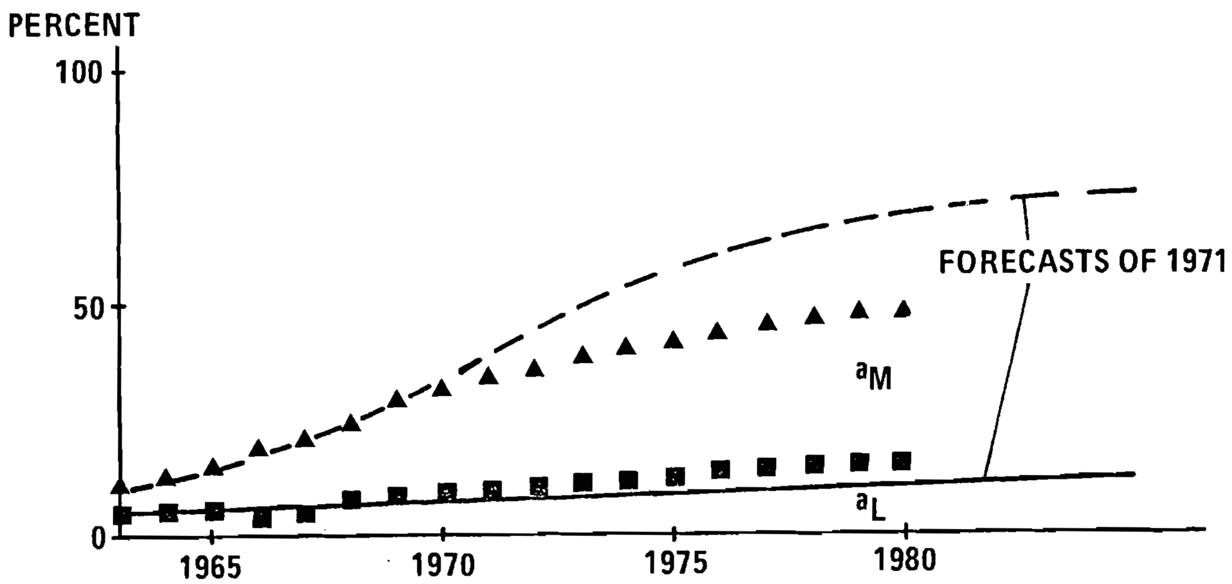

Figure 2. The automation coefficient of equipment (a_M) and the automation coefficient of labor (a_L) in GDR industry.

what was forecast ten years ago. Second, the real growth in the automation coefficient of labor was a slightly higher than what was projected 10 years ago. Third, it is somewhat disappointing that fifty percent automation in equipment only gives 14 percent automation in labor. This would imply that if we had 100 percent automation in equipment, we would have no more than 28 percent automation in labor.

Last of all, we can conclude from Figure 2 that the empirical data fits well into a regression that gives an empirical saturation level of 54% for the automation coefficient of equipment and 20% for the automation coefficient of labor.

The relationship between the automation coefficient of equipment (a_M) and the automation coefficient of labor (a_L) is identical with the following:

$$M = \frac{a_M}{a_L} = \frac{\text{value of automated equipment per worker at automated equipment}}{\text{value of equipment per worker}}$$

$$M = \frac{a_M}{a_L} = \frac{m_A}{m_S} \qquad (1)$$

Applying these calculations to GDR industry, we discovered an interesting phenomenon. Eight industries reached their maximum level during the past ten years and then began to decline. Figure 3 shows average figures for the industry as a whole.

The reason for this decline was not the faster development of automation in labor, but a saturation tendency in the automation coefficient of equipment.

The situation can be seen clearly in Figure 4, which shows the degree of automation in the GDR metalworking industry in three dimensions: the share of automated equipment, the share of labor working at automated equipment, and the share of automation in processing time. In terms of processing time the degree of automation is still very low.

This is why industry now needs a new push in the direction of flexible automation. Traditional special purpose automation has certain limitations:

- slow reaction times when new models are introduced
- a high rate of obsolescence
- high debugging costs
- low potential for automation of more complicated operation such as assembly and repairs.

Flexible automation offers new possibilities for overcoming these limits and creating a new logistic curve within the general development of automation.

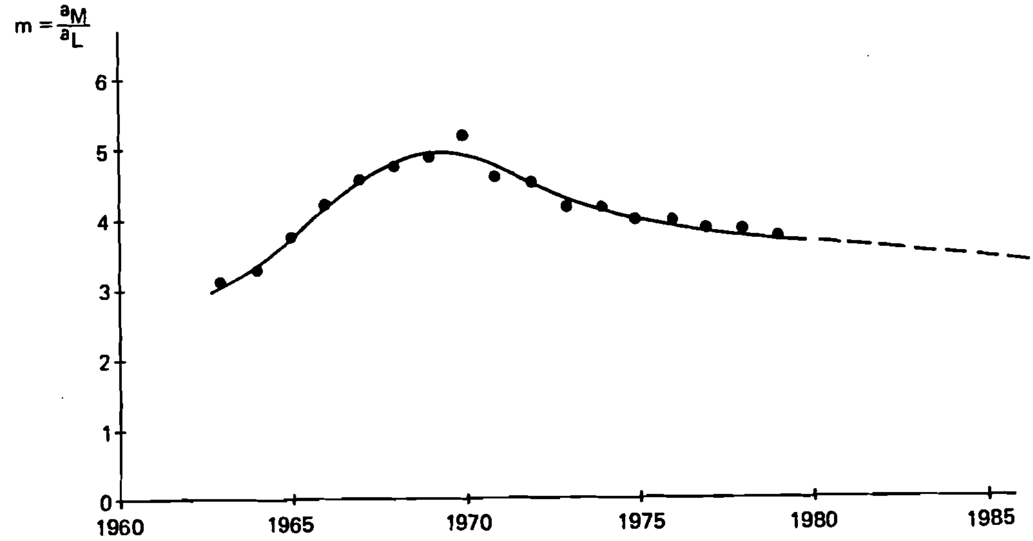

Figure 3. Relationship between the automation coefficient of equipment and the automation coefficient of labor in GDR industry 1963-1980 (with forecasts to 1986).

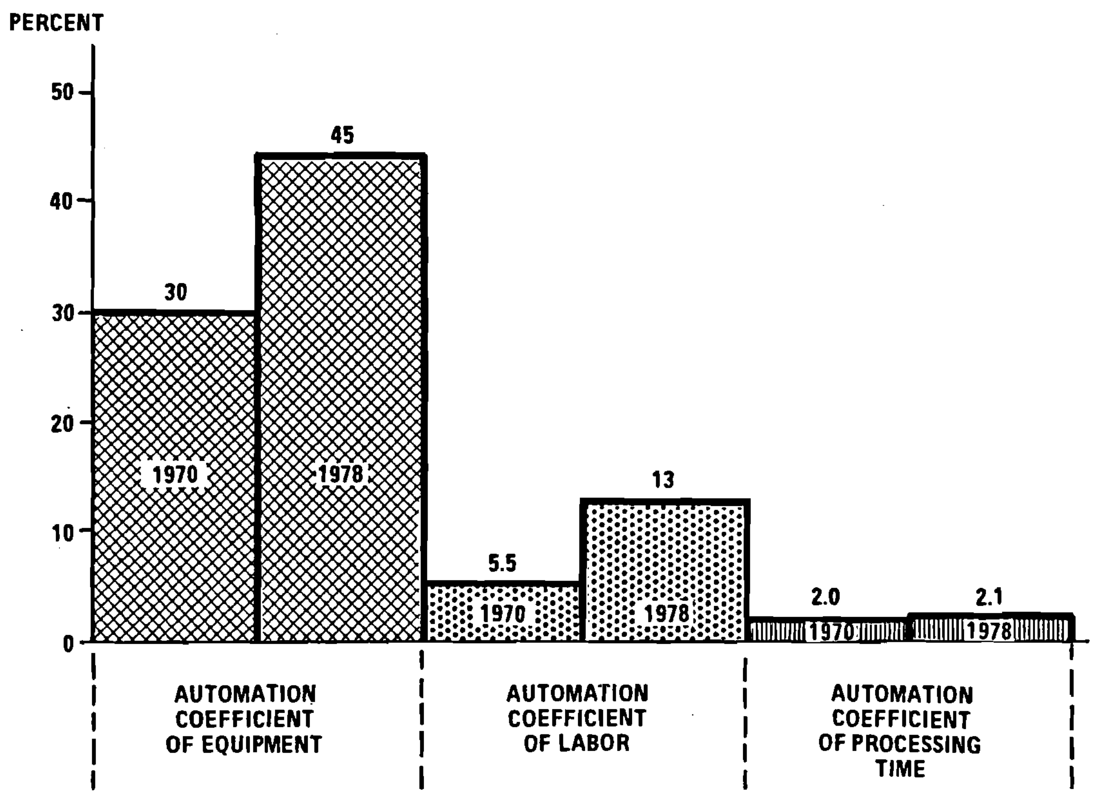

Figure 4. Degree of automation in the metal industry of the German Democratic Republic.

CHAPTER 3

THE POTENTIAL FOR INNOVATION IN FLEXIBLE AUTOMATION

Flexible Automation is an economically feasible means of applying automation principles to manufacturing processes in which quantitative and/or qualitative technical and economic requirements change relatively rapidly. A short history of robots is compiled in Table 3.

The first serious concept was put forward in 1944 and development began in 1947. The industrial history of FA began in 1955 with the first commercial NC (numerically controlled) machine. NC machines are controlled by a punched paper tape, which activates an automatic mechanical process. (A predecessor of this development was the Jacquard machine, developed in Napoleon's time.) The diffusion of NC machines began in the 1950s and 1960s; but by 1966 their share in the total stock of machine tools had reached only 0.088% in the United Kingdom, 0.081% in France, 0.036% in Italy, and 0.035% in the Federal Republic of Germany (Nabseth and Ray 1978).

In the 1970s the situation changed dramatically. The second generation of NC machines were computerized NC machines or CNC. These were controlled at first by minicomputers and later by microprocessors.

Another step in the history of FA was the introduction of direct numerical control or DNC, in which a number of NC machine tools are linked under the control of a computer.

Table 3. The history of robots.

400 B.C.	Archytas of Tarentum is said to have made a wooden pigeon that could fly.
1470	The German mathematician and astronomer Johannes Mueller (Regiomontanus) is said to have made an eagle that flew before the emperor Maxmilian as he entered Nuremberg.
	Wolfgang von Kempelen developed his famous mechanical chess player (containing a small Turk)--origin of the German saying "to build up a Turk".
1920	Karel Capek wrote the play R.U.R. (Rossum's Universal Robots).
1954	George C. Devol initiated robot development in the US.
1956	Devol applied for a US patent.
1958	The first prototype was produced in the US by Devol Consolidated Control Corporation.
1961	The first industrial robot was installed in the US.
1962	The Unimate Versatron was commercially introduced in the US.
1962	The Unimate model "1900" and the American Machine Foundry "Versatron" were introduced.
1968	The Japanese company Kawasaka Heavy Industries bought a license from Unimation, Inc. of the US to produced 6 types of robots, one of them in Japan.
1968	The USSR produced the first model of an underwater robot.
1968	Six robots were in operation in the US and Japan.
1971	The Soviet Union produced the first prototypes of the UM-1, the Universal 50, and the UPK 1.
1972	The number of robots in operation throughout the world reached 1150.
1973	71 firms were developing robots.
1977	150 firms were developing 200 types of robots.
1978	200 firms were developing robots.
1981	In the Japanese firm FANUC 3 engineers and 70 robots are producing 350 robots a month.

In 1962, when the first commercial robot was installed, robots became the other major type of FA. Industrial robots (IR) are programmable devices that can rotate around several axes in many directions and can repeat programmed operations as often as required. They must be distinguished from simple "pick and place" devices, which repeat the same simple motions and are used for a fixed purpose (The Blue Collar Robot 1980).

IR can operate in various industrial environments: at special jobs, in a transfer line, or in integrated production systems. Utilization of IR can change the production system from a man-machine systems to a man-robot-machine system. They can be supervised by humans and/or by computers (Zermeno-Gonzalez 1979)

A second generation of IR is now being developed. These will be able to determine their own behavior through their sensing and recognizing capacity (Umetani 1980).

The production of robots by robots is another intriguing idea, especially from the economic standpoint. In Japan this has already become reality.

The third main type of FA are flexible manufacturing systems (FMS), which were introduced in 1965. One of the first of these was the Sundstrand Aviation Line, which is a truly integrated system in that it includes not only machining operations, but can also carry out such technologically varied processes as cleaning, fluorescent dye inspection (for cracks), and anti-corrosion treatment (Toward the Factory of the Future 1980).

It should be noted here that fully automatic manufacturing systems that integrate diverse technological processes have existed since 1950. Probably the most famous of these is the Soviet "piston factory", which casts, machines, balances, and packs aluminum alloy pistons automatically. However, the fundamental difference between these early "automatic factories" and the Sundstrand Aviation Line is that the latter is an automated "job shop" rather than a factory. The distinguishing feature of a job shop is that it processes small batches of many different products. The Sundstrand Aviation Line manufactures cast magnesium alloy housings for speed control gears for electric aircraft generators. Approximately 70 different housings are processed in lots of 25 to 300 units. The entire operation is controlled by an electric relay system.

Computer-integrated manufacturing systems (CIMS) are the second generation of FMS. The introduction of the computer represented a quantum jump for the system, as it made it open-ended in terms of intelligence. The computer can not only sequence the machines and stations in a fashion far superior to that of the traditional process; it can also store all of the NC programs, analyze the status of the system and make operational decisions, as well as perform a magnitude of management functions, many of which are only now beginning to be identified.

There are now approximately 50 FMS in existence in the world. The great majority of them are intended for machining; a few have been built for forming, welding, and other non- machining processes (Buzacott and Shanthinkumar 1980).

One interesting FMS is a gear factory in the GDR. This is a computerized complex designed for the automatic manufacture of various gears in small and medium-sized batches. The complex has three sections: one for machining, one for heat treatment, and a third for grinding. Handling is carried out by simplified robots.

The major problems of FMS are reliability and maintenance. While on the whole FMS require less labor than traditional processes, the number of maintenance workers is higher.

The logical trend in FA is toward unmanned manufacturing (UM) or the unmanned factory (UF), now in the research and development stage in many countries. Two other developments supporting this trend are computer-aided design (CAD) and computer-aided manufacturing (CAM).

Figure 5 shows a historic overview of the development of FA. Table 4 shows the specific features of various types of automation.

Flexible automation is moving toward computer-aided manufacturing (CAM), which includes NC machines, robots, FMS, and CAD, and is linked with computer-aided management and planning. Figure 6 shows the Siemens Corporation's concept for CAM.

The field of FA shows major potential for innovation, from the standpoints of both needs and past experience. The greatest source of this potential is the drive toward rationalization in industry and the immense range of possibilities opened up by microelectronics.

The diffusion of flexible automation was rather slow at first. Ten years after their commercial introduction, the share of NC machines sales in all sales of metal-cutting tools in the US had only reached 14%. In the stock of metal-cutting tools it was even smaller. From 1968 to 1970 the share of sales dropped from 25% to 18%. It was only after 1973 that the growth rate of NC machines showed a noticeable increase. Behind this recent development has been their potential for relative efficiency, i.e., the efficiency of NC machines in comparison with traditional processes. Before the age of microelectronics, the same thing had occurred with robots: the first generation of flexible automation, without the benefit of microelectronics, had a relative efficiency near or below 1.

An economic calculation of robot application must include the following variable and fixed costs:

- purchase price or cost for own production including overhead
- costs for special tooling
- cost of installation
- maintenance costs
- operating expenses
- depreciation
- required capital.

and its economic advantages, including

- labor savings
- quality improvement
- increased throughput
- more rapid adaptation to product changes
- elimination of unskilled labor, hard manual labor, unpleasant work.

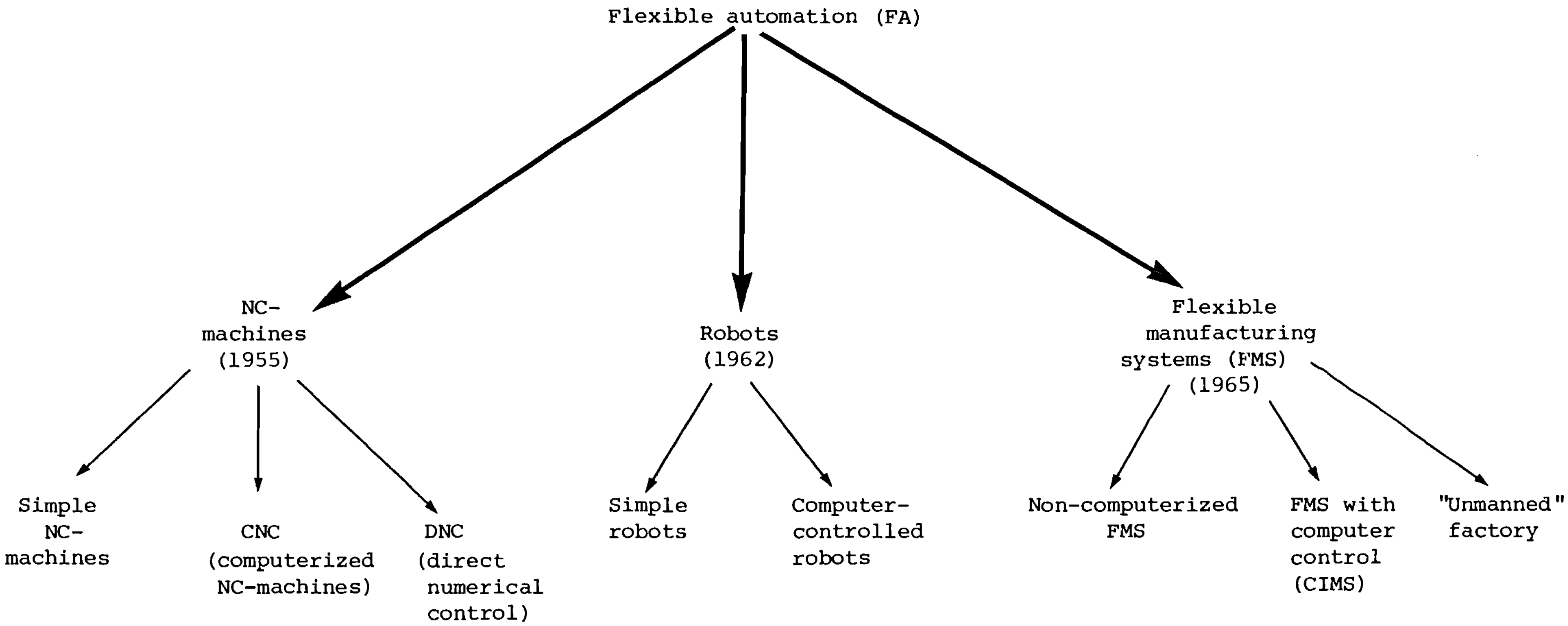

Figure 5. Classification of flexible automation.

Table 4. Specific features of various types of automation.

Specific features \ Type of automation	Standard machinery with special tooling	Specially dedicated machinery	Transfer line	NC - stand-alone	CNC - stand-alone	DNC	FMS without computers	FMS with computer	UF
1. Man-machine operations	X	X	X						
2. Programmable machining				X	X	X	X	X	X
3. Programmable transfer and storage							X	X	X
4. Programmable assembling									X
5. Programmable inspection									X
6. Computer-aided design									X
7. Computer-aided management									X

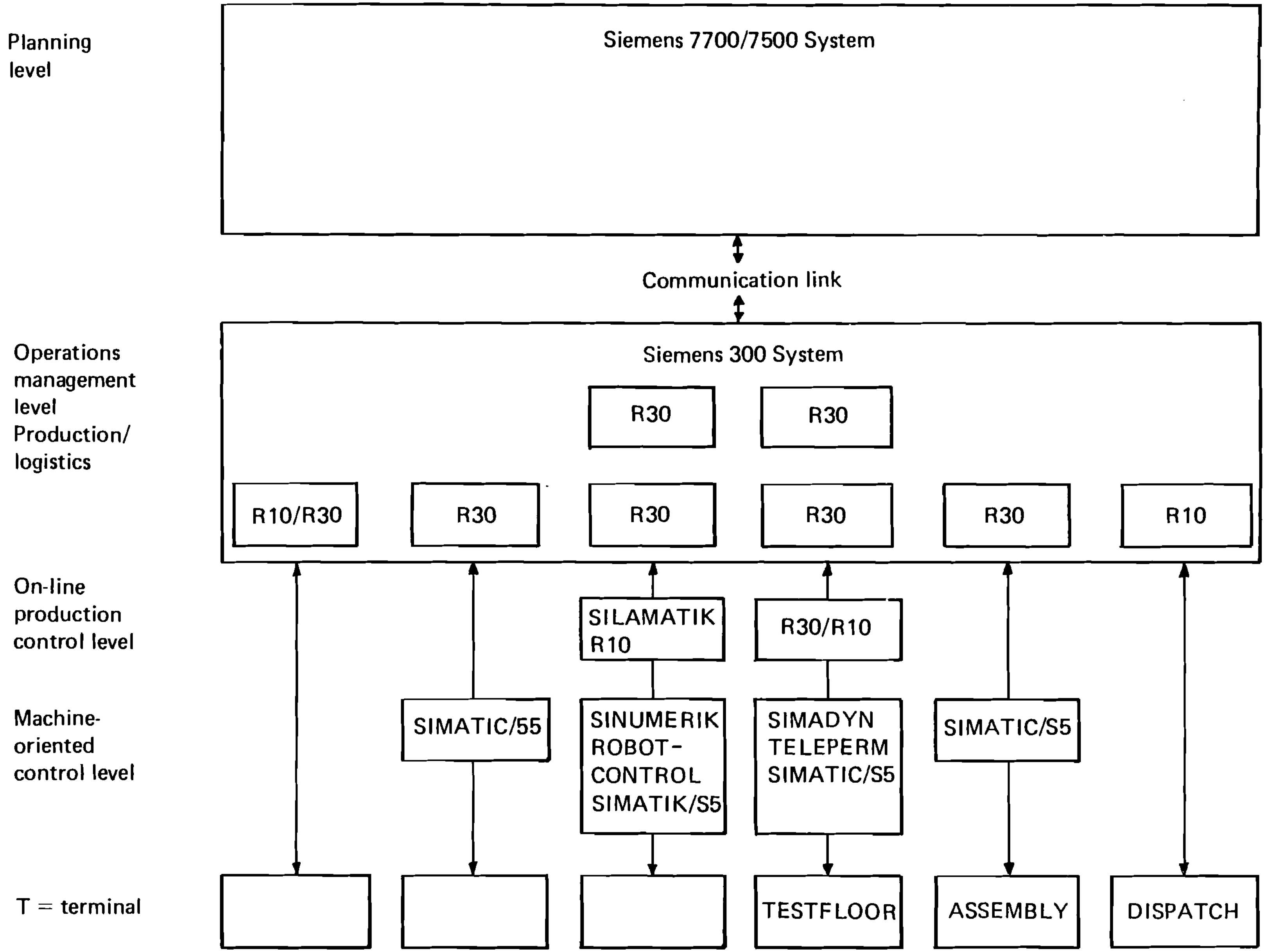

Figure 6. Hierarchy of industrial automation in the Siemens Corporation.

SOURCE: Charlish 1981

An economic assessment of robots would normally include such indicators as

- direct investments
- related investments
- labor costs
- number of shifts
- maintenance costs
- prime costs
- depreciation rate
- lifetime of the equipment.

In market economies the payback method and return on investment method are used for economic assessment (Brodbeck 1976). These are comparable to the normative value method used in planned economies (see Table 5).

The early slow diffusion of NC machines and robots seems to point to many hindrances in their socioeconomic and technological environment. But microprocessors are bringing about environmental changes, and with them, new potential for FA. The future will bring new applications for robots: machining robots, assembly robots, maintenance robots for reactor furnaces, robots that are movable under water.

Before FA can be introduced, at least the following factors must be taken into account:

- capital demand
- special needs of the user
- policy regulations
- the market situation
- standards
- type of production organization
- type of manufacturing
- engineering base
- qualification requirements
- labor conditions

Hindrances and stimuli to the diffusion of FA can be identified (1) at the micro-level, or market stage, where there is resistance to change by employers and employees and in the organization of production, and (2) at the macro-level, where international competitiveness and governmental policy toward science and technology play a role.

Flexible and universal automation has been developed for many industries. The leading industry in the use of robots is the automotive industry, followed by electrical machinery, molded plastics, iron and steel, and precision machines. Current applications for robots include:

- die casting

Table 5. Methods used for economic assessment of robot application in market and planned economies.

	Investment	Associated investment	Labor costs for 2 shifts	Maintenance costs for 2 shifts	Prime costs	Depreciation of associated investment (15%)
	I	A	L	M	C	D
Robots	55,000	200,000	-	5,000	27,000	30,000
Traditional	-	200,000	48,000	-	-	30,000

Lifetime $t_n = 7$ years

MARKET ECONOMIES

Payback method

$$T = \frac{I}{L - M}$$

$$T = \frac{55,000}{48,000 - 5,000} = 1.28 \text{ years}$$

Improved payback method

$$T = \frac{I}{L - M + q\ (L + D)}$$

where q = production rate coefficient

$$T = \frac{55,000}{43,000 + 0.2\ (48,000 + 30,000} = 0.94 \text{ years}$$

Return on investment method

$$R_{rob} > R_{norm}$$

$$R = \frac{\text{annual savings through robots}}{\text{investment costs}}$$

PLANNED ECONOMIES

Normative value method I

$$V_{rob} < V_{trad}$$

$$n = 0.2$$

$$V = I \cdot n + C$$

$$V_{rob} = 255,000 \cdot 0.2 + 27,000 = 78,000$$

$$V_{trad} = 200,000 \cdot 0.2 + 70,000 = 110,000$$

Normative value method II

$$V = I \cdot p^{t_n} + C\ \frac{p^{t_n} - 1}{p - 1}$$

p = accumulation normative = =.062

$$V_{rob} = 616,539$$

$$V_{trad} = 895,884$$

- spot welding
- investment casting
- forging
- presswork
- spray painting
- molding of plastics
- foundry
- machine tool loading
- heat treatment
- palletization
- brick manufacture
- glass manufacture

In the future robots will be able to take over activities suitable to special purpose automation. Robots have the advantages of shortened reaction time (i.e., shortened cycle time for introduction of new models), lower debugging costs, and resistance to obsolescence.

CHAPTER 4

A FORECAST OF ROBOT DIFFUSION

Man has long dreamed of creating a being similar to himself (but not too similar!) This dream has been the source of hope and fear--from the threatening Golem to Homunculus accompanying Faust on his way to Helena's cheerful world.

The age of machines produced a new version of the old Homunculus story. In Karel Capek's play *Rossum's Universal Robots*, (1920), the rebellion of the robots destroys the human world. Capek gives us exact figures: there are 347,000 robots in stock and the price of one robot is 150 dollars. One robot could replace 2.5 workers at an operating cost of 0.75 cent per hour (at a time when one pound of bread cost 2 cents). At present prices, one robot would cost 4,500 dollars or 22.50 dollars per robot hour.

Capek's figures are no longer purely science fiction. The age of programmable industrial robots began in 1962 when the first commercial robot was installed. There are now about 17,500 robots in the world, costing nearly 80,000 dollars apiece; maintenance costs amount to about $1.30 per robot hour.

While the robot business is still very unpredictable, interest in forecasts is great. Governments are interested because their technological policies try to ensure international competitiveness. Corporations are interested because they are always looking for ways to make business more profitable. And unions are concerned about job security, safe working conditions, and job content.

Tables 6 and 7 show some forecasts of the diffusion of robots.

Table 6. Predicted increases in the number of robots in the US.

Forecaster	Annual Growth 1980-1990	Annual Growth 1980-1985
Joseph Engelberger	30%	-
Laura Conigliaro	50% (max.)	-
Arthur D. Little Co.	-	50%
International Resources Development, Inc.	11-14%	-

Table 7. World Diffusion of Robots

Robots in Use (in Units)		
Country	Period	Percent
Western Europe	1980-1990	23.6%
Japan	1980-1985	71.9%
Robot Sales		
World	1980-1985	Million $ 44.3%
World	1979-1990	Million $ 23.3%
Japan	1980-1985	Million $ 29.9%
Japan	1979-1990	Bil. Yen 22.8%

There are several reasons for the uncertainty in forecasting robot application:

1. There is uncertainty about future applications for the present types of robots.
2. The range of applications may change due to improvements in robots.
3. Future prices of robots are uncertain, as they depend not only on the development of production, but on other factors as well.
4. The future growth of wages, a main factor in the decision to apply robots, is difficult to anticipate.

Reliable statistics on robots are not available. One has to collect figures from various sources and compare them with the definition used by each source. Simons (1980) understands the definition of robots to be "reprogrammable multi-axis mechanical manipulators" The Robot Institute of America defines an industrial robot as "a reprogrammable, multifunctional manipulator, designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks" (Engelberger 1980, p.8).

In 1979, Japan had 70,000 industrial robots, including the simpler "pick-and-place" devices. But only 7,000 of these are freely programmable. Table 8 shows the number of robots and other simpler manipulators in 1977.

Table 8. World distribution of robots and simpler manipulators (1977).

	Number	Percent of total
I. "Pick and place" devices	8,000	40
II. Robots - Category 1 (3 degrees of freedom and a maximum of 6 programmable positions per degree of freedom)	9,000	45
III. Robots - Category 2 (3 or more degrees of freedom, freely programmable)	2,600	13
IV. Robots - Category 3 (as category 2 but with optical sensors and optimization)	400	2
Total robots	12,000	60
Total including simpler "pick and place" devices	20,000	100

Source: Paessler et al. 1977.

An international comparison and forecast of robot diffusion is possible only if robot application is measured in relative terms. This can be done using the following relationship:

$$F = \frac{\textit{number of jobs replaced by IR}}{\textit{number of jobs replaced or replaceable by IR}} \tag{2}$$

$$F = \frac{c \cdot R}{c \cdot R + \dfrac{p \cdot k \cdot E}{s \cdot c}} \tag{3}$$

where

- R = number of programmable robots
- E = number of employees in manufacturing, mining, and construction
- p = share of production workers in all employees
- k = share of work places that in principle can be replaced by robots
- s = shift factor
- c = number of jobs replaced or replaceable by one robot.

And one obtains

$$F = \frac{1}{1 + \dfrac{p \cdot k \cdot E}{s \cdot c^2 \cdot R}} \tag{4}$$

The diffusion rate is

$$\frac{F}{1 - F} = \frac{s \cdot c^2 \cdot R}{p \cdot k \cdot E} \tag{5}$$

According to (4) the real diffusion rates in 9 countries and the world totals for 1968-1980 were computed (see Figure 7). Assuming a logistic model, one can expect

$$\ln \frac{F}{1 - F} = -a + bt \tag{6}$$

These functions were computed and are shown in Figure 7 as straight lines. The model can answer the following questions:

- what will be the diffusion rate in a given country at a given year?
- What will be the number of robots in a given country in a given year using the equation

$$R = \frac{F}{1-F} \frac{p \cdot k \cdot E}{s \cdot c^2} \tag{7}$$

- What time lag or time lead (δt) exists between two countries i and j in the diffusion of robots using the equation

$$a_i + b_i \cdot t = a_j + b_j(t + \delta t) \tag{8}$$

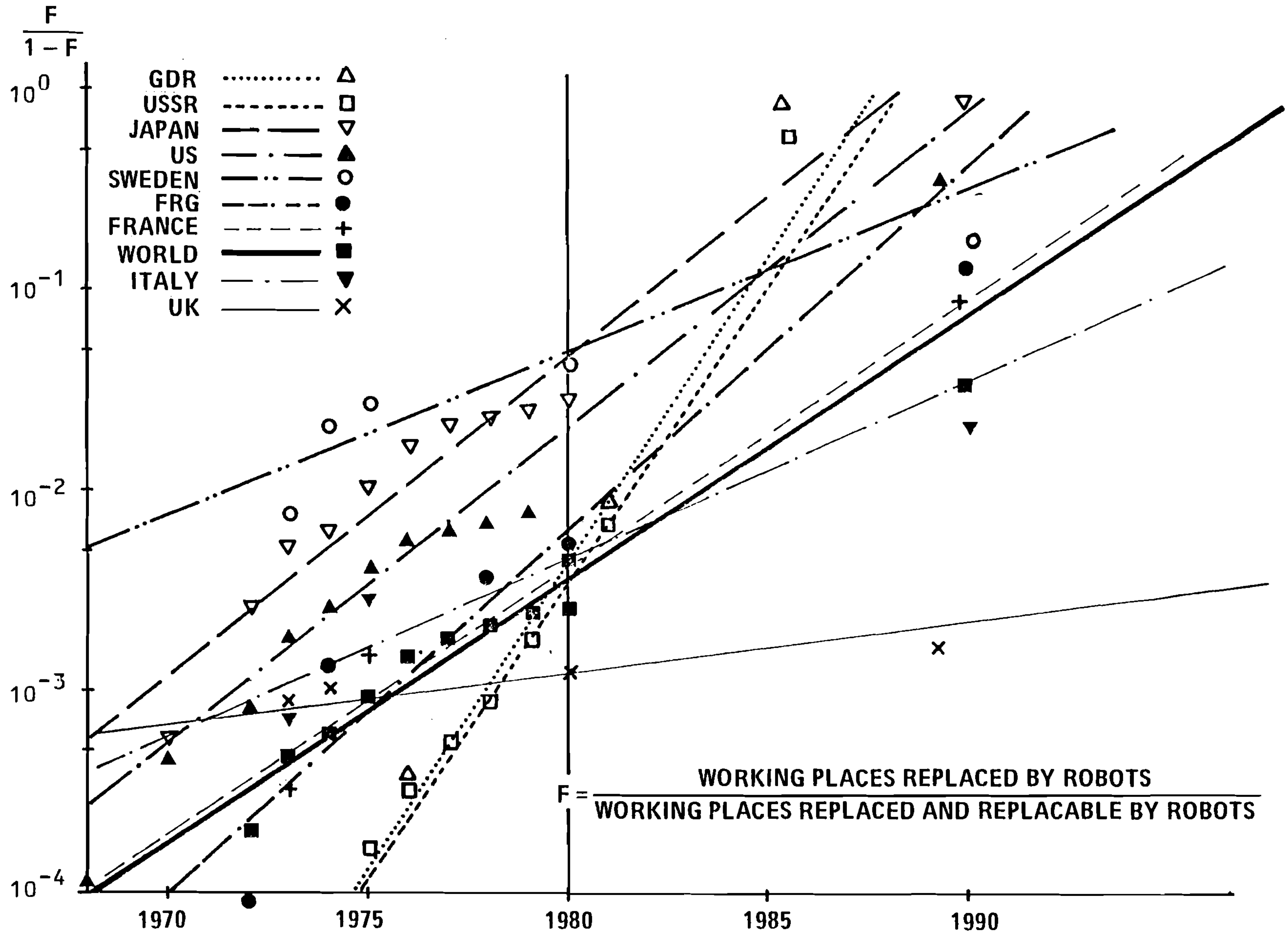

Figure 7. Diffusion of programmable industrial robots in nine countries.

Sources: Beljanin 1975, Cooper 1980, Yonemoto 1978, Enzelberger 1980, Simons 1980, World Casts 1980, Paessler et al. 1977, Yearbook of Labour Statistics 1980.

$$\ln \frac{F}{1-F} = a + bw \tag{10}$$

$$\ln \frac{F}{1-F} = 1.42966 + 0.02495w \tag{11}$$

where w = hourly wages relative to the FRG level in DM (German marks) in percent (FRG = 100). This applies to all of the eight countries except Japan (not included in the regression) and Sweden (see Figure 8). But maybe in the future Japan and Sweden will move nearer to the the general tendency.

The same dependency can be analyzed by using a time series. In Figure 9, the diffusion of robots in the US is shown over the index of hourly real wages of production workers in manufacturing. (Data on real wages are from the Statistical Abstract of the US 1974-1979). Over a time period, this dependency becomes more stable because of the lower growth in both directions.

We can now further develop our formula for robot development. The logarithm of (4) is:

$$lnR = \ln \frac{F}{1-F} + \ln \frac{p \cdot k \cdot E}{sc^2} \tag{12}$$

Using (6), we obtain

$$lnR = a + \ln \frac{p \cdot k \cdot e}{sc^2} \tag{13}$$

$$R = e^{a + bw} . \frac{p \cdot k \cdot E}{s \cdot c^2} \tag{14}$$

In this formula, the diffusion of robots depends on five more or less statistically identifiable factors:

- wages
- number of production workers
- range of application
- number of shifts
- substitution rate

To give an example, according to formula (7) the number of robots in the US in 1985 could be:

$$R = 1300 \cdot 10^{-4} . \frac{0.68 \cdot 0.15 \cdot 29 \cdot 10^6}{1.5 \cdot 4.84}$$

$$R = 52967$$

This would mean a growth rate of 57 per cent, which is certainly an overestimation. Assumii.g that the trends of the last five years continue we get:

$$R = 550 \cdot 10 - 4 \cdot \frac{0.68 \cdot 0.15 \cdot 29 \cdot 10^6}{1.5 \cdot 4.84}$$

$$R = 22409$$

$$\delta t = \frac{a_i - a_j + (b_i - b_j)t}{b_j} \qquad (9)$$

Table 9 shows the time lags or leads of countries in comparison with the US for 1975, 1980, and 1985.

Table 9. National time-lags or time-leads (-) in the diffusion of programmable industrial robots (PIR) in comparison with the US.

Country	1975	1980	1975 (forecast)
US	0	0	0
Japan	-4	-5	-2
Sweden	-5	-2	0
France	2	5	8
Italy	1	5	6
UK	3	8	12
FRG	2	4	4
USSR	6	5	0
GDR	7	5	0
World total	3	5	6

Let us look at the results of our investigation. Although the data are scattered, we can compare the different countries and get an interesting overview.

In terms of the relative diffusion rate, Sweden shows itself to be the most advanced country. But Sweden also shows a lower growth rates for the past five years. When measured by the diffusion rates, Japan and the US have nearly the same growth rates.

Japan is becoming the world leader in robot application, not only in terms of number of robots but also in relative terms, i.e., in relation to the national work force. Japan's secret is R.U.R.: Robots Unbagging Robots, again a realization of one idea of Karel Capek. In the firm FANUC (Fujitsu Automatic Numerical Control) three engineers and 70 robots produce 350 robots a month. The FANUC Corporation is typical for an industry of the future: an industry producing means for Flexible Universal Automation (FUA).

As can be seen from the data, the diffusion rates slowed between 1975 and 1980. It is not yet clear why this has occurred in the advanced countries. One explanation is the much slower growth in real wages. The USSR and the GDR, on the other hand, have a very fast growth. They tend to catch up with the advanced countries. Taking the past growth rate for all countries in the next five years, the USSR will reach the level of the US in 1985 (see Table 9).

The extrapolation of the diffusion rate could be the first and simplest approach. It could be improved by including more important causal factors for the diffusion of robots. One economic factor for the diffusion of robots is wages. We compared hourly wages with the diffusion rates of robots in eight countries and obtained the following regression:

This would mean a growth rate of 36.3 per cent, which is more reasonable.

A second forecast is possible on the basis of formula (14). If one assumes for 1985 w = 110, and slightly other values for c and k, then one gets:

$$R = 183.49 \cdot 10^{-4} \cdot \frac{0.68 \cdot 0.20 \cdot 29 \cdot 10^{6}}{1.5 \cdot 4}$$

$$R = 12061$$

This would mean a growth rate of 22.9 per cent. While this seems rather high from the standpoint of real wages and the trends of the last five years, strong competition from the Japanese and the development of other factors might change the situation considerably. Perhaps our first attempt to measure robot diffusion could be the core of a learning system for analysis and forecasting.

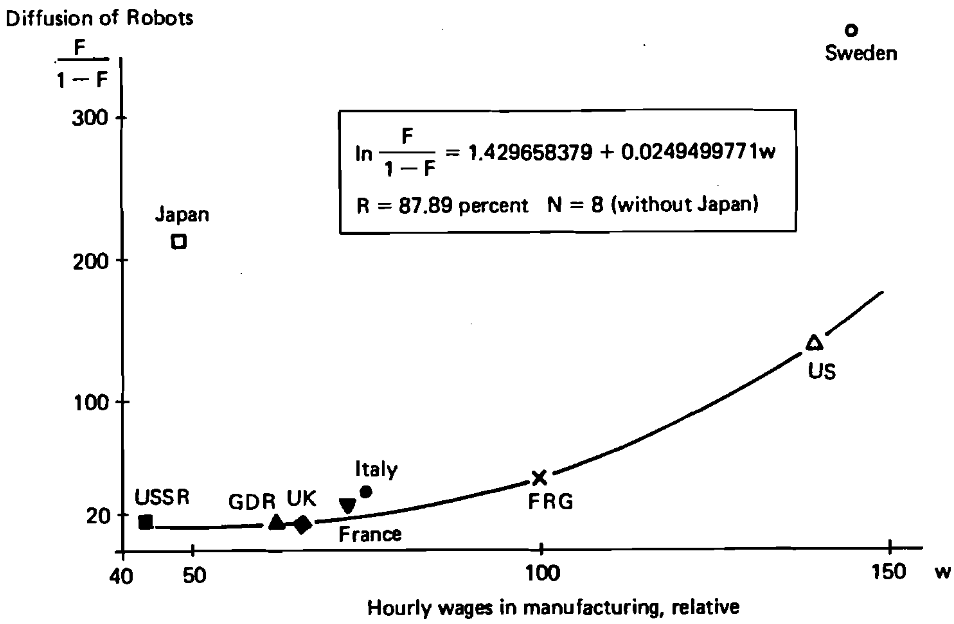

Figure 8. Diffusion of robots as a function of hourly wages (1978).

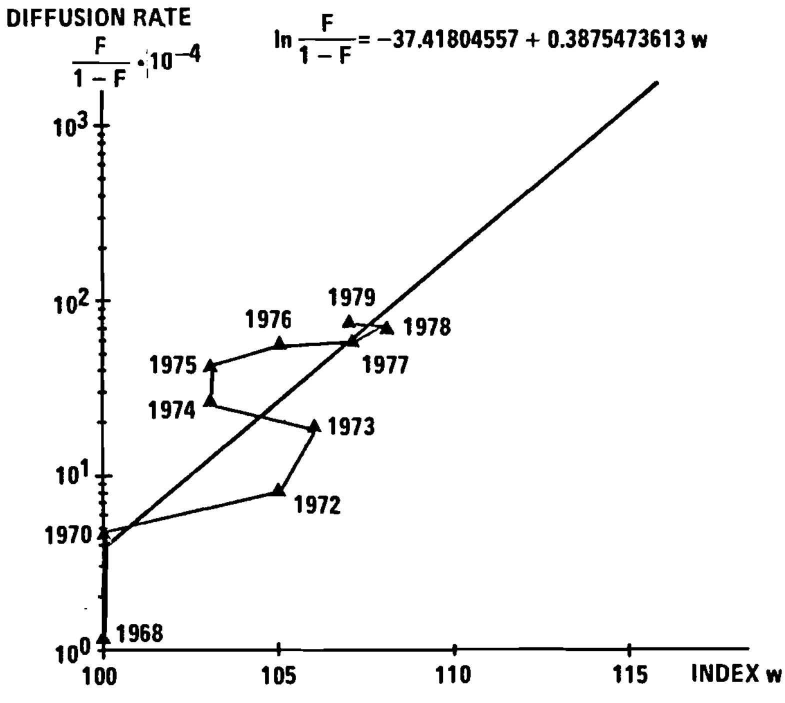

Figure 9. Diffusion of robots as a function of hourly wages (US). (Source: US Statistical Abstract 1980.)

CHAPTER 5

ROBOTS AND NATIONAL INNOVATION POLICY: THE CASE OF THE GDR

In the GDR economic strategy for the 1980s, the industrial robot is regarded as a basic innovation, which together with the biotechnologies, other basic innovations such as microelectronics, and sources of energy such as nuclear power and coal liquefaction, will be decisive in building up a new level of productivity during the 1980s and 1990s.

An essential feature of basic innovations is that they reward those who create and implement them with increased productivity while punishing those who were unable to recognize their potential for efficiency, or who were unable to use them, by undermining their existing productivity level. National economic performance will very much depend on the ability of basic innovations to contribute to this new productivity level.

THE ROLE OF ROBOTS IN GDR ECONOMIC STRATEGY

In the GDR economic strategy for the 1980s, industrial robots are playing an important role in efforts to attain high productivity growth and reduce hard manual and unskilled work. The production and installation of industrial robots is an integral part of the program to improve labor conditions. For this program we must devise goals and rules for the installation of robots.

Critical to the planning and management of robots as an innovation is the relationship between the implementation of robots and the development of socioeconomic efficiency. We must ask the same very critical questions about robots as we would ask about any other basic innovation:

1. What is their potential for increasing efficiency?
2. What is required economically and socially in order to use this potential for efficiency?
3. What are the technological alternatives to robots?

Clearly, robots are now at the beginning of the rapid growth phase. If we look at the predicted growth rate of robot installations from now until 1990 as they were quoted in Chapter 4, it would appear that we are approaching a "robot revolution". However, there have been many similar predictions during the last two decades, and yet the expected high diffusion rate has not occurred. Obviously conditions have not been conducive to securing a dynamic efficiency above that of other forms of automation and mechanization. If we are to successfully forecast the future development of robots, it will be necessary to investigate the changes needed for the application of industrial robots and their influence on the development of the efficiency of robots.

During the next five years (1981-1985), the installation of industrial robots will play an important role in the economic strategy of the GDR. The number of new robots is expected to double in each of these years.

It is hoped that three main goals will be achieved by this rapid increase in robot application:

1. A higher level of automation in small and medium-sized production systems.
2. The creation of conditions prerequisite to the implementation of other basic innovations.
3. A significant reduction of the share of heavy manual and unskilled labor.

INCREASING AUTOMATION LEVELS IN SMALL AND MEDIUM-SIZED PRODUCTION SYSTEMS

Let us look at the first of these three goals. 84.8% of production in the GDR mechanical engineering and vehicle industries and 75.2% of production in the electrical and computer industries is currently being carried out on a small or medium scale basis. In the last decade, through the introduction of numerical-control machinery, it has become possible to automate much of the manufacturing process. But for the most part, handling and transportation of working components and tools have not yet been automated. The industrial robot holds great potential for integrating the main handling and auxiliary processes.

In other words, the robot is not an alternative to the existing types of automation. It represents an important step toward overcoming the bottlenecks hindering improved efficiency in automation.

The industrial robot is an important result in a long chain in the development of manipulatory equipment incorporating the achievements of microelectronics and data processing. It is a key technology in current attempts to improve

- the efficiency of the entire manufacturing system
- product quality
- technological discipline and continuity in production.

In some enterprises in the GDR machine tool industry, the installation of robots has made it possible to release 50 to 70% of the working forces. Labor productivity has increased by 200 to 400% and production space has been reduced by 50% in comparison with customary workshop production.

Industrial robots are not only important as an innovation; they are also a very important factor in increasing the innovativeness of many branches, especially mechanical engineering production. Their high flexibility allows a reduction in the time needed to modify production systems to produce new products and the efficient production of these products on a small and medium scale. Analyses of GDR industry have shown that firms producing 1,000 to 100,000 units per year (accounting for more than 40% of all GDR enterprises) were unable to apply the traditional form of automation in an efficient manner. Here the industrial robot has proved very important for promoting dynamic efficiency.

CREATING THE PRECONDITIONS FOR OTHER BASIC INNOVATIONS

With regard to the second main goal named above, it should be noted that the high employment-release effect helps to establish important preconditions for the implementation of basic innovations that have a high employment effect. This is especially true in the fields of energy, environment, and biotechnology. Normally, basic innovations have a high employment effect and a low efficiency effect in the first two phases of the relative efficiency cycle.

The industrial robot is one of the few basic innovations that continue to show relatively high employment-release and productivity effects in the second phase. This means that they are suitable for creating the preconditions for innovations with a high employment effect in the first phase of the relative efficiency cycle. This attribute is very important for the industrial strategy of the GDR. One of the strategic goals of the five year plan for 1981-1985 is to release the working time of 300,000 workers. A quarter of this is to be achieved through the installation of industrial robots. Experience has shown that it is possible to release 1.4 to 3 workers per industrial robot, depending on the type of robot. These figures have been confirmed through studies in other countries (see Table 10). It has been estimated that in the GDR 40% of manual production work and 70% of assembly work could be reduced significantly through the use of industrial robots.

Table 10. Job substitution factor of industrial robots.

		1 shift	2-3 shifts
Industrial robots	B	1.5	4.0
	S	1.4	3.0
Component manipulators	B	2.1	6.2
	S	1.6	3.3
Tool manipulators	B	0.9	1.7
	S	0.43	0.8

B = Battelle Frankfurt
S = Sociological Institute Goettingen

Source: Lehmann 1980.

REDUCING THE NEED FOR HEAVY MANUAL AND UNSKILLED LABOR

Finally, let us look at the third goal. During the 1970s, the share of automated industrial equipment in all industrial equipment increased significantly. Such branches as the chemical industry, the energy and fuel industries, the electrical industry, light industry, and the textile industry now have a share of automated equipment above 50%. The current trend in automation is toward a polarization of employment requirements. The number of jobs for skilled workers is increasing and at the same time many unskilled and hard manual laborers are being replaced. Figure 10 shows the results of an empirical study in the GDR that included 50% of all industrial workers. Here we see that as automation takes over many of the more highly skilled jobs, many of the workers' qualifications are no longer needed. The industrial robot is an important tool for eliminating jobs with low skill requirements involving hard manual labor.

In Figure 11, which shows a comparison of the technological costs of a welding robot in the GDR and the cost of manual welding, we can see that one important result of the application of robots is a reduction of labor costs (due to the high replacement effect). But fixed costs must also be taken into account. These are much higher for robot installation than for manual handling. Depending on the type of robot, they may be between 4 and 10 times the cost of manual working places. To compensate, normative efficiency achieved through the use of the robot must be much higher than where the normal capital investment is required (Schilling 1980).

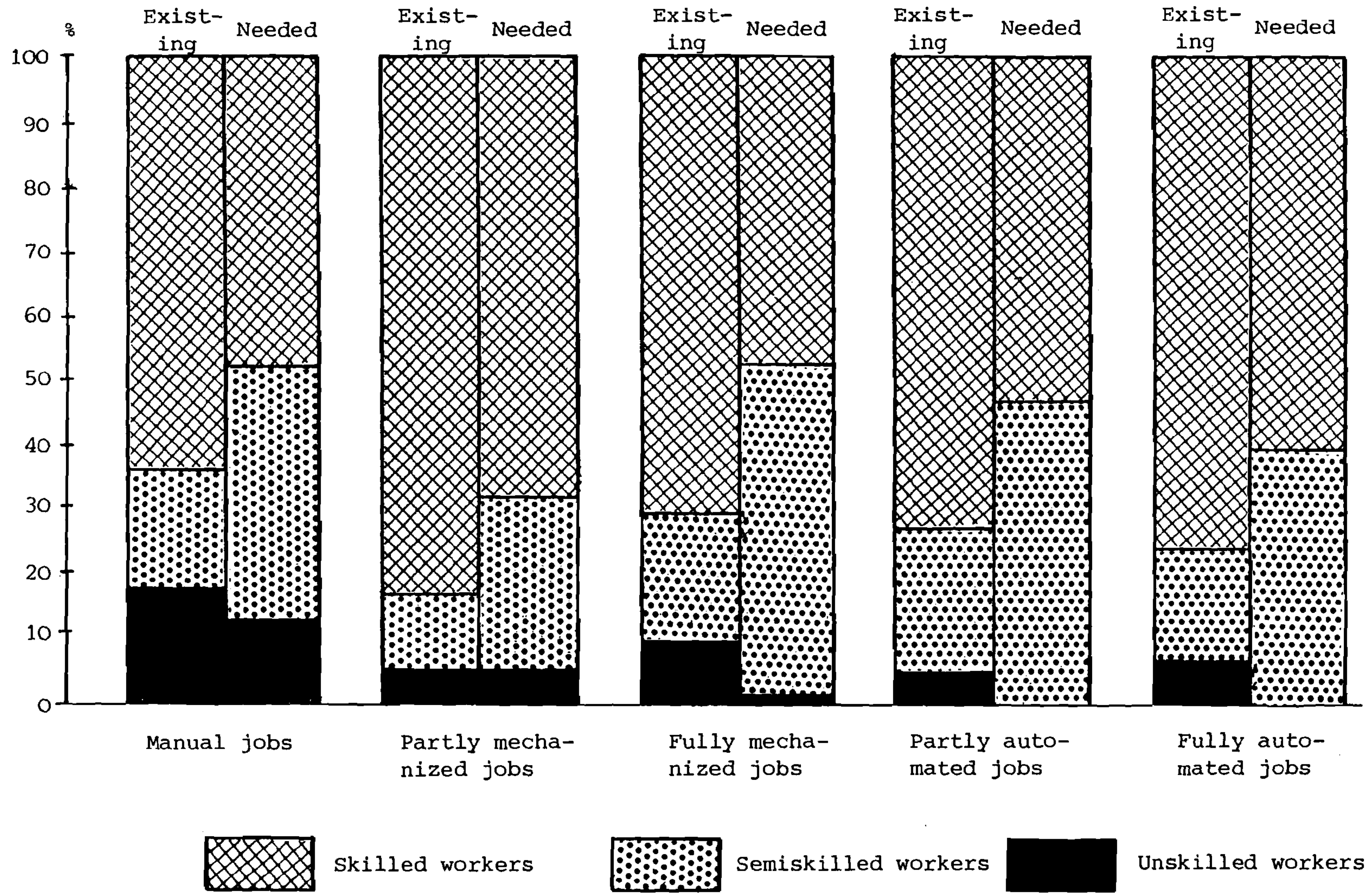

Figure 10. Existing and needed job qualification structures for production workers at various levels of technological development (in percent).

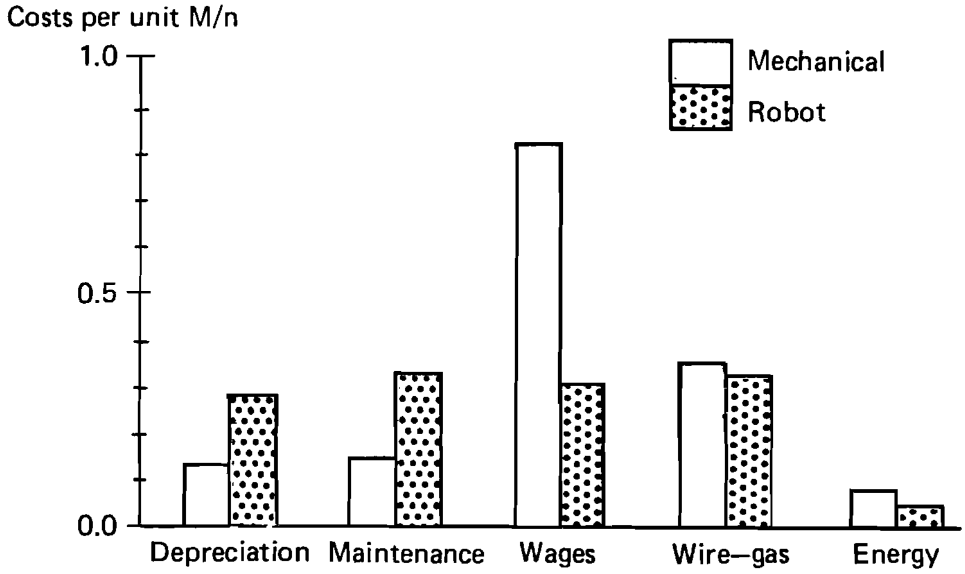

Figure 11. Comparison of the costs unit for the robot welding and CO_2 mechanical welding.

In the GDR, for the normal capital investment, the lowest efficiency normative is 6%; this means a return of the capital within 12 years. For robot installation the lowest efficiency normative is 35%; this means a capital return within 3 years. To secure this very high efficiency normative, it is necessary to use the robots in 2 or 3 shifts.

A third important part of the robot's costs are variable and fixed peripheral costs. The creation of the appropriate working environment for the robot incurs a great deal of additional expense, ranging from 50 to 100% of the fixed cost of installing the robot.

The benefits include quality improvement, reduced costs, increased continuity in production, and the labor-replacing effect. The average cost for replacing one worker in the GDR economy is currently 100,000 marks. If we consider that the cost of one welding robot is approximately 300,000 marks, and that it can replace 2 to 3 workers per shift, we see that from the point-of-view of releasing labor forces, the robot is a very good investment indeed.

THE NEW GENERATION OF ROBOTS

One can describe an innovation as the fusion of a relevant economic demand with a technological feasibility. From this standpoint, it is not difficult to foresee that the current generation of robots will soon approach its outer limits. Limitations upon the growth of robots can only be overcome with a new generation of robots. This new generation is urgently needed for automating assembly work. The present generation of robots must follow a fixed program; it will be incapable of learning from its specific working situation. The new generation of robots, on the other hand, is able to adapt to changing situations, as it will be equipped with tactile, visual, and/or acoustic senses.

In the GDR, this will be especially important for the mechanical engineering and vehicle industries, where more than 30% of the work is assembly work, and for the electrical and electronic industries, where more than 40% is assembly work. As only 1-2% of assembly work has been automated, this is likely to be an important area for the application of the second generation of robots.

The future of robots and the role they can play will very much depend on their ability to adopt improvement innovations, which in turn can help overcome the present barriers to broader application of robots. The demand for improved capabilities in industrial robots is very high. It is not yet clear whether the next generation of robots will be able to meet these requirements.

CHAPTER 6

SOME CONCLUSIONS

Because of the tremendous socioeconomic problems associated with structural adaptation to FA, the innovation has become the subject of governmental policies in a number of economies, both market and planned. Many governments assume that there is a direct link between FA and productivity growth in manufacturing. In countries that are far behind the advanced level, governmental action seems to be an important factor in promoting FA.

At the Innovation Management Workshop in 1981 the following research questions were selected for study.

1. What forecasts exist or can be developed (and how reliable are they) for predicting the future of automation, and especially of FA? What can we learn from a study of FA and its international socioeconomic consequences?
2. How can the coordinates and dimensions for technological forecast be determined and what conditions are needed for overcoming technical limits and shortcomings? What specific capabilities do individual countries have for promoting the technological development of FA?
3. Seen from a broader context including socioeconomic consequences, what are the economic impacts of FA? What factors influence the relative efficiency of FA?

4. How does selection environment function in various countries? How can the methodology for factor analysis developed at IIASA be applied to innovations in the field of FA?
5. How can a methodology for selecting areas of application FA be developed and applied? This methodology should consider functions of labor, types of organization in manufacturing, and the type of manufacture.
6. How can we analyze and compare policies on flexible automation in planned and market economies? (See Table 11.)

Not all of these questions can be answered by IIASA research. But future IIASA research in this field should give a strong impetus to research teams IIASA's National Member Organizations (NMOs).

Table 11. Policy issues in the field of flexible automation.

Problem	Market economies	Planned economies
1. Labor release effect (dimension)	Unemployment	Real possibilities for labor force transfer
2. Job satisfaction	Central question in European countries	Planning of working conditions
3. Support for higher research efforts	Governmental programs in some countries (Japan, Sweden, FRG)	Tasks or programs at the national level
4. Incentives	Wage level-a major factor in diffusion	High propensity to to invest in FA because of planning mechanism
5. Participation		Extremely important aspect of FA application; promotion of implementation teams
6. Production of hardware	Specialized firms plus production with corporations themselves.	
7. Delivery of parts and aggregates	Specialized firms	Centralized production; planned specialization.
8. Software, engineering, consulting	Specialized firms	Organization of technological centers for types of robots (welding, mechanical, etc.); central data banks.
9. Education, qualification	Market forces	Changes in vocational programs
10. Social concept		Complex solutions for avoiding extreme specialization or dequalification
11. Cooperation among industry, research institutions, and universities		Ad hoc organizations.

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