Working Paper

SOCIAL BENEFITS OF CIM:
LABOR AND CAPITAL AUGMENTATION BY
INDUSTRIAL ROBOTS AND NC MACHINE TOOLS
IN THE JAPANESE MANUFACTURING INDUSTRY
(PAPER II)

Shunsuke Mori

May 1987
WP-87-40

International Institute for Applied Systems Analysis
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FOREWORD

Two papers are presented here together in one package. The first which follows, is a general introductory and theoretical discussion of the problem of economic benefits estimation for CIM technologies. It was written by Robert U. Ayres, leader of the CIM project and Jeffrey L. Funk, now at Westinghouse R&D center. The second paper presents a particular (macroeconometric) methodology as applied to the benefits of robots and NC machine tools for a single country: Japan. It was written by Shunsuke Mori, a member of the CIM project team at IIASA. It is hoped that the results will be of considerable interest in themselves, as well as providing a viable model for future extension to other countries.

Two earlier CIM Working Papers are relevant to the approaches discussed here, namely [Ayres 86f] and [Ayres 87b].

Thomas H. Lee
Program Leader
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ACKNOWLEDGMENT

I am very grateful to Prof. R.U. Ayres for his helpful discussions, suggestions and advice. However, the author alone is responsible for any remaining errors.

Introduction

The economic and societal effects of CIM systems have been widely discussed in the literature [Leontief and Duchin, 1985; MITI, 1985; Ayres and Miller, 1983; Jaikumar, 1984; Miller, 1983; Ayres, 1987a; Ayres, 1987b; JIRA, 1984 and 1985; Bessant and Haywood, 1986; Fleischer, 1982]. Ayres [1987b] classified the benefits of CIM systems into five categories: (1) labor force reduction, (2) capacity augmenting, (3) capital sharing, (4) product quality improvement and (5) acceleration of product performance improvement. It is clear that in the short run, the first three benefit items immediately contribute to the profitability of entrepreneurs. Industry reallocation and the unemployment problem might then be caused during the penetration of CIM systems. But on the other hand, in the long-term considerations, these benefits as well as product quality improvement and acceleration of product performance improvement will basically be passed on to the consumers through product price reductions and higher performance products [Ayres, 1987b]. This discussion is extended to the international economy [Kaya, 1986]. In other words, the social benefits of CIM systems may appear, from the dynamic point of view, as a result of their short-term profitability to firms, which provides a motivation for private firms to adopt a new technology [Ayres, 1987b].

The approaches taken by existing studies are mainly of two kinds within the above context. One deals with the labor substitutability and interaction among industries on the national level, based on a macroeconomic model. The I/O model, in paticular, has been used to evaluate the impacts of CIM systems [Leontief and Duchin, 1986; MITI, 1985]. The plausibility of these I/O studies depends on how the labor and capital coefficients are determined. These basic parameters should be estimated on the basis of historical data. However, because of lack of basic statistics, they are given as "appropriate" values. And, it is also difficult to include engineering and managerial issues.

Another approach discussed herafter is based on factory level surveys. Although the coverage of such surveys is restricted, detailed engineering information and a qualitative opinion of the managers can be obtained, as well as economic effects [Ayres and Miller, 1983; JIRA, 1984 and 1985; Jaikumar, 1984; Bessant and Haywood, 1986]. Based on these data, we can subsequently discuss the detailed effects and the potential labor displacement. However, since survey studies do not provide historical trends, another method is needed to evaluate the penetration behavior and market growth. It is difficult to guarantee consistency between the sample of surveyed factories and the total national economy. We hope to address these problems adequately.

The purpose of this paper is to evaluate the social benefits of industrial robots and NC machine tools -- based on national-level statistics -- resulting from increased productivity. By comparing the empirical results with the data based on a factory-level survey, one can verify the compatibility of the macro-level model with the micro-level survey results. This may permit the application of other detailed results from the factory level to the national level.

I. LABOR AUGMENTATION EFFECT OF INDUSTRIAL ROBOTS

1. Formulation of the Production Function Approach

As a starting point, we subdivide CIM equipment into two categories. The first is mainly concerned with labor augmentation, i.e. industrial robots and CAD/CAM systems. The second aims at an improvement of capital quality or capital augmentation, as for example, NC machine tools. Although most CIM systems involve more or less both attributes, the model should be formulated according to the basic purpose of implementation. Since statistics on the shipments of industrial robots and NC machine tools are already available from JIRA (Japan Industrial Robot Association) and MITI, their benefits can be estimated from the macroeconomic point of view. Data on other CIM equipment are not yet applicable. Labor substitutability of CAD/CAM systems may be a quite important and interesting problem and can be treated in the same manner. Unfortunately, although several survey reports on CAD/CAM have already been published [Yano Economic Institute, 1986; ILO 1986], their statistics are not developed and the definition of CAD/CAM systems are not even well established.

In this paper we focus on the social benefits of industrial robots.

Let us describe the formulation. The definition of symbols is summarized in APPENDIX-1. We begin with a production function which involves four heterogeneous production factors, namely Y(K,L,R,N), where Y, K, and L represent output in real terms, conventional non-CIM capital stock and labor, respectively. R and N denote the stock of industrial robots and NC machine tools, respectively. It is postulated that L and R are separable from K and N, namely

$$Y = Y(K,\ F(L,R),\ N) \qquad (1)$$

In the remainder of this section, N is ignored. It is reintroduced in the following sections. F(L,R) can be interpreted as an augmented equivalent labor force. It may be plausible to impose the following conditions:

$$F(L,0) = L \tag{2}$$

$$dF/dL > 0 \tag{3}$$

$$dF/dR > 0 \tag{4}$$

Linear homogeneity and the second order differen-tiability of F(L,R) are also postulated.

One of the simplest forms which satisfies the above conditions is

$$F(L,R) = (\, L^a + A \cdot R^a \,)^{(1/a)} \tag{5}$$

where a should be positive in order to meet condition (2). Equation (5) is a special form of the well-known CES production function. It should be noted that, because of condition (3), other production functions, such as the Cobb-Douglas and the trans-log type, cannot be adopted.

The optimal strategy of equation (5) is formulated as follows:

$$\text{max.} \quad F(L,R)$$
$$\text{subject to} \quad P_L L + P_R R = M \tag{6}$$

where M, P_L and P_R denote total installed cost, annual wage and rate of fixed cost to the capital stock on industrial robots, respectively. The equilibrium condition of (6) yields a well known equation

$$A \cdot (R/L)^{a-1} = (P_R/P_L) \tag{7}$$

Therefore we can estimate the parameters A and a employing a least squares method. Based on these parameters, we can evaluate the impact of industrial robots based on the following equations. Let L_R, E_R, B_R and R_R denote labor force augmentation, equivalent workers per unit industrial robot, profit of industrial robot and benefit rate of industrial robot, respectively. They are defined as follows:

$$L_R = F(L,R)-L \quad (8)$$

$$E_R = \{F(L,R)-L\}/U \quad (9)$$

where U denotes industrial robot population.

$$B_R = P_L \cdot F(L,R) - (P_L L + P_R R) \quad (10)$$

The first term on the right hand side represents labor cost if the entrepreneur wants to achieve the same labor force without industrial robots.

$$R_R = B_R/R \quad (11)$$

2. **Data Source and Availability**

Data availability on CIM penetration is summarized in Table 1. It should be noted that no import statistics on CIM systems are available for Japan since most items are not yet distinguished in the trade statistics code (SITC). Only export statistics on industrial robots have been available since 1978.

The next step is to develop a price index for industrial robots, since the capability and unit price are quite different among robot types, a divisia price index P [Jorgenson and Griliches, 1967],

$$\frac{\dot{P}}{P} = \sum_{i=1}^{N} S_i \frac{\dot{P}_i}{P_i} \quad (12)$$

where S_i denotes the cost share of i-th type, and

$$S_i = P_i x_i / \sum_{j=1}^{N} P_j x_j \quad (13)$$

where N denotes number of different types. P_i denotes the price of the i-th types and x_i denotes the consumption of the i-th type industrial robots, respectively. Unfortunately, the divisia index is not applicable before 1973 since industrial robot production data by robot type is available only from 1974 onwards, as is shown in Table.1. The average unit price for

Table 1

Data Availability on Japanese CIM Statistics
(I.R. and shp. denote industrial robot and shipment, respectively)

Item / Period	1970 -1973	1974 -1977	1978 -1983	1984
1. total I.R. production (in unit)	Y	Y	Y	Y
2. total I.R. production (in value)	Y	Y	Y	Y
3. I.R. production by type (in unit)	N.A	Y	Y	Y
4. I.R production by type (in value)	N.A	Y	Y	Y
5. I.R. shp. by type and industry (in value)	N.A	Y	Y	Y
6. I.R. shp. by type and industry (in unit)	N.A	N.A	Y	Y
7. I.R. shp. by type and process (in value)	N.A	N.A	Y	Y
8. I.R. shp. by type and process (in unit)	N.A	N.A	Y	Y
9. NC machine production by type (in unit)	Y	Y	Y	Y
10. NC machine production by type (in value)	Y	Y	Y	Y
11. total computer production (in unit)	Y	Y	Y	Y
12. total computer production (in value)	Y	Y	Y	Y
13. total PC production (in unit)	N.A	N.A	(1980-)	N.A
14. total PC production (in value)	N.A	N.A	(1980-)	N.A
15. total text processing machine shp. (in unit)	N.A	N.A	N.A	N.A
16. total text processing machine shp. (in value)	N.A	N.A	(1980-)	N.A
17. value added by industry; by EPA	Y	Y	Y	Y
18. capital stock by industry; by EPA	Y	Y	Y	Y
19. depreciation of capital; by EPA	Y	Y	Y	Y
20. labor input by industry (in number)	Y	Y	Y	Y
21. labor input by industry (in value)	Y	Y	Y	Y
22. capital formation by industry; by MITI	Y	Y	Y	Y
23. capacity utilization index; by MITI	Y	Y	Y	Y

Note: MITI (Ministry of International Trade and Industry)
EPA (Economic Planning Agency).

industrial robots was employed before 1974. Thus one can obtain a price index for industrial robots, which is exhibited in Table 2 and Figure 1.

The next problem is to estimate additional system cost which consists of peripheral equipment, operation training cost, engineering cost etc. This component of total system cost depends on the type of industrial robot and quite often exceeds its original price (see [Miller, 1983]). JIRA [1984] reported the ratio of initial system cost to the industrial robot price on the basis of 340 interviews. They are shown in Table 3.

In practice, training and engineering costs may decrease in proportion to the penetration level because of the learning effect. This may affect the total cost of industrial robots. According to Miller [1983], the development cost for each succesive application decreases by 10% for similar applications, where total initial investment is assumed to be 2-4 times the industrial robot price per se. However, when the above effect is taken into account in the macroeconomic investigations, one must define the penetration level of industrial robots in one user by robot type and process type. Here, because of non-availability of data, we assumed the ratios in Table 3 to be constant over time. But this effect may play an important role when we consider the future industrial robot market.

According to JIRA [1985], the average lifetime of industrial robots is about seven years. Based on the above data base and assumptions, the capital stock of industrial robots can be estimated in real value (in 1980 billion yen).[1] These are exhibited in Table 2 as well as wage and number of workers in the whole manufacturing industry.

In order to estimate the parameters a and A through equation (5), we need a fixed cost (or rental fee) of industrial robots. The fixed cost of durable capital per year is derived by

$$P_R \cdot R = P_I \cdot r \cdot R \qquad (14)$$

[1] In this paper "billion" represents "thousand million".

Table 2

Price Index, Capital Stock and Population of Industrial Robots, Annual Wage and Number of Workers in the Whole Japanese Manufacturing Industry

year	P_I price index of I.R. [1980=1]	P_L average wage (annual) in million yen	R I.R stock in 1980 billion yen	U I.R population in number	L number of workers in 1000
1970	1.77857	.742929	6.61204	2000	11392.1
1971	1.19354	.857976	15.2586	3200	11193.4
1972	1.69316	.978442	23.9051	4300	11180.4
1973	1.75534	1.2095	36.6205	7400	11370.3
1974	1.15822	1.52971	64.5757	11600	10904.9
1975	1.31297	1.71097	90.3563	16000	10660
1976	.88558	1.91975	131.256	23200	10537
1977	.865553	2.08524	184.669	29600	10246
1978	.982675	2.20746	246.846	38200	10232
1979	.945306	2.36786	357.03	51400	10211
1980	1	2.54608	544.529	67000	10292
1981	.975516	2.68867	771.122	83800	10565
1982	.88691	2.81852	1102.55	101700	10481
1983	.832657	2.928	1523.16	120800	10652
1984	.762313	3.06295	2158.17	145800	10798

Table 3

Ratio of Initial System Cost to the Price of Industrial Robots

robot type	price of industrial robot	cost of peripheral equipments	other cost (training, engineering)	total
manual manipulator	1.0	1.38	0.32	2.7
fixed sequence robot	1.0	2.29	0.31	3.6
variable sequence robot	1.0	0.94	0.06	2.0
play-back robot	1.0	0.81	0.19	2.0
NC robot	1.0	1.0	0.50	2.5
intelligent robot	1.0	0.54	0.16	1.7
(total)	1.0	1.13	0.27	2.4

(source: JIRA report in 1984)

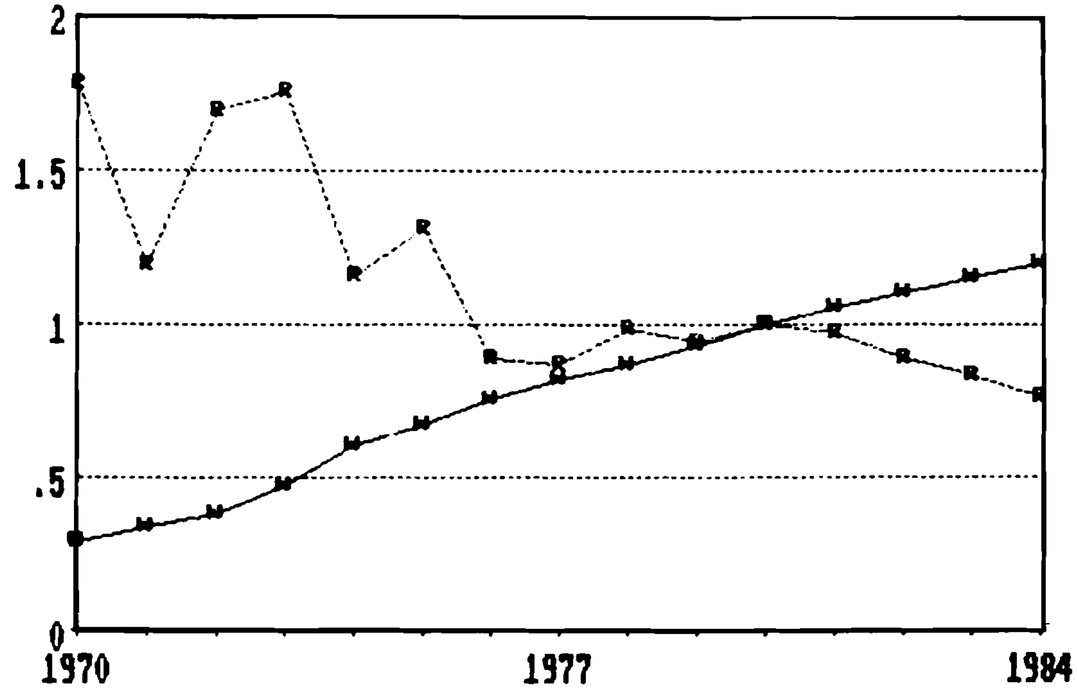

Figure.1 Price Indexes of Industrial Robots and Wage (1980=1)
W:wage ; R:industrial robots

where P_R, P_I, and r denote capital cost with respect to industrial robots, price index of industrial robots, and expense rate which consists of depreciation, operation and maintenance costs, real estate tax, etc.

The lifetime of an industrial robot is assumed to be seven years and real interest rates after 1970 range between 5% and 10%. According to the well known capital recovery equation [UNECE,1986]

$$r = i(1+i)^n/\{(1+i)^n-1\} \qquad (15)$$

where n and i represent repayment year and interest rate, respectively, we can obtain effective annual amortization rates ranging between 17.2% and 20.5%.

The real estate tax rate on industrial robots per se is unknown. But according to Noguchi [1985], the rate of local tax involving real estate tax to the total corporate tax is 12.3% and the effective corporate tax rate was 51.5% in 1983. Since gross output and capital stock of the whole manufacturing industry in 1983 were 83832 billion yen and 155980 billion yen, respectively, the rate of real estate tax to the capital stock was 3.4% in 1983. Taking into account the depreciation of capital stock according to EPA, National Wealth Survey [EPA, 1970], the annual effective tax rate obtained is 1.8%.[2]

JIRA [1984] mentions maintenance costs per total initial investment for industrial robot including system costs by robot type based on interviews. They are exhibited in Table 4. At first we calculated average maintenance cost rates by robot type. They are shown in the eighth column of Table 4. Then, weighting them by means of the stock value of 1984 by robot type, the mean maintenance cost rate is calculated, and 4.5% is obtained. Employing the base year 1984, average maintenance cost rates are also calculated by age of industrial robots, where the shipment values of robot types in the year of production are employed as

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[2] For the small and medium size companies, special taxation systems, for example reduction of legal repayment duration, are available. Therefore effective tax rate on industrial robots might be less than 3.4%. [Noguchi,1985]

Table 4

Annual maintenance cost as a percentage of total initial industrial robot investment; by robot type

	annual maintenance cost rate by age of industrial robot							
robot type age	0	1	2	3	4	5	6	mean
1. manual manipulators			(N.A)					(N.A)
2. fixed sequence robot	7.5%	3.5%	2.5%	3.5%	4.5%	5.5%	5.5%	4.6%
3. variable sequence robot	6.0%	3.3%	2.7%	3.3%	4.7%	4.7%	4.7%	4.2%
4. playback robot	5.9%	4.3%	4.4%	6.7%	5.8%	6.5%	7.8%	5.9%
5. NC robot	4.2%	3.5%	2.5%	2.3%	3.5%	4.0%	4.3%	3.5%
6. intelligent robot	5.0%	4.0%	2.0%	2.0%	3.0%	4.0%	4.0%	3.4%
7. year implemented	1984	1983	1982	1981	1980	1979	1978	(1984)
8. average, 1984 basis	5.4%	3.7%	3.2%	4.2%	4.5%	5.3%	5.6%	4.5%

(Source: JIRA report in 1984)

(*.1) Values in the 8-th row represent the weighted mean values of the corresponding column on a 1984 basis. The shipment values in the year of implementation, defined as 1984 minus age, are employed as the weight.

(*.2) Number of interviews are as folows: fixed sequence robot-2 , variable sequence robot-3 , NC robot-3 , playback robot-6 and intelligent robot-1.

(*.3) Definitions of industrial robots in Japan are as follows: [UNECE 1985]

1. manual manipulator: a manipulator directly operated by human workers

2. fixed sequence robot: a manipulator which functions by following a pre-established sequence, which cannot be easily changed.

3. variable sequence robot: a manipulator which functions by following a pre-established sequence, which can be easily changed.

4. playback robot: a manipulator that can repeat any operation after being introduced by a man.

5. NC robot: a manipulator which receives orders through numeric control.

6. intelligent robot: a robot which can determine the functions required through its sensing and recognitive abilities.

(*.4) Manual manipulators and fixed sequence robots are not included in the ISO definition. In order to take the labor substitutability of those primary industrial robots into account, we followed in this paper the JIRA's definition.

the weights. They are shown in the eighth row of Table 4. According to this estimate, the rate of maintenance costs is about 4.5% to the total initial investment for industrial robots.

Thus the total expense rate for industrial robots appears to be 23.5% to 26.8%. Assumptions on these values are quite important, while the estimated benefit is sensitive to the expense rate as is exhibited in Figure 2, and tax rate and interest rate are institutional parameters. Here, the benefits of industrial robots are evaluated, employing r to be 25% and 33.3%.

3. Evaluation of the Benefits of Industrial Robots

Based on the statistics described above, we can estimate the parameters of equation (7). Note that if r is assumed to be constant, then P_I can be used for the estimation instead of P_R as is shown in equation (16).

$$(A/r)\cdot(R/L)^{a-1} = (P_I/P_L) \qquad (16)$$

The estimated result is as follows:

$$\log (P_I/P_L) = \underset{(13.4)}{-.3912} * \log (R/L) - \underset{(16.2)}{2.138} \qquad (17)$$

$R^2 = .933$; $\bar{R}^2 = .927$
D.W = 1.19

Hence one obtains

$$a = .609 \qquad (18)$$

and

$$A = .118 \qquad (19)$$

It follows that

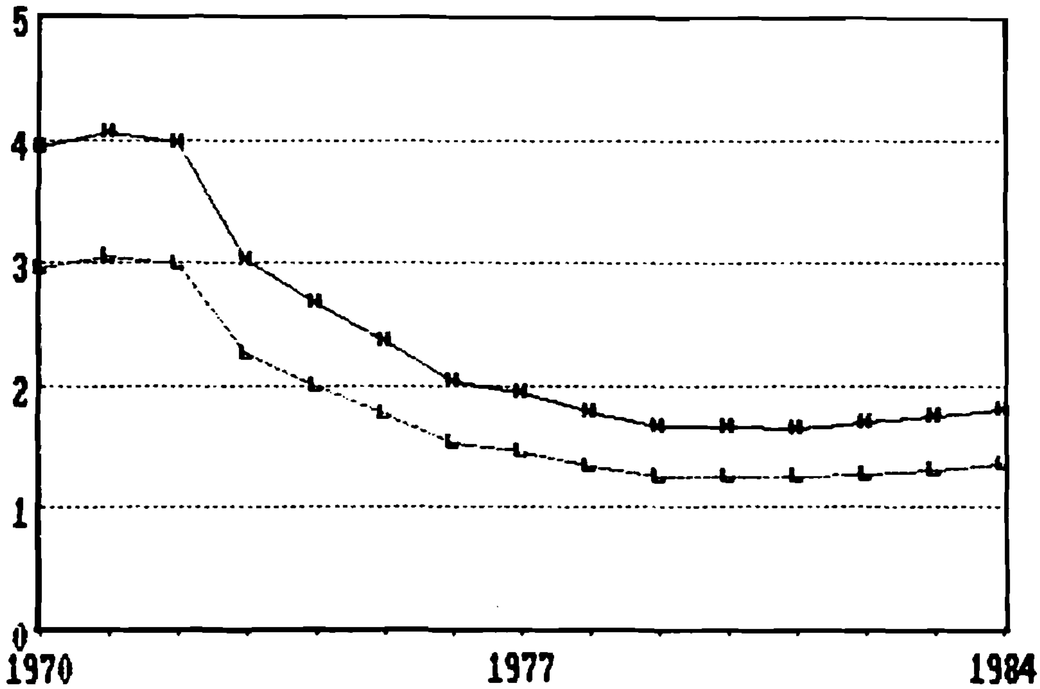


Figure.2 Equivalent Workers per Industrial Robots (EL)
H:expense rate=33% ; L:expense rate=25%

$$F(L,R) = (.118 \cdot r \cdot R^{.609} + L^{.609})^{1.642} . \qquad (20)$$

Using the above equation, one can now revaluate the equivalent labor force F(L,R) and labor force augmentation LA. The results are shown in Table 5. Equivalent labor force per industrial robot EL for r=25% and r=33% are shown in Figure 2. Since the gross benefits of industrial robots BR computed by the above procedure are obtained in current prices, discounting BR by GDP deflator, we calculate the real gross benefits of industrial robots in 1980 prices. They are shown in Figure 3. On the other hand, JIRA [1984] also surveyed average labor reduction per shift for each industrial robot for 277 companies. Average working hours of industrial robots by process type were also reported. The distribution of process type by industry sector is available in JIRA [1985]. Based on this information, one can calculate the average number of shifts for each industry sector. Then average labor reduction per industrial robot by industrial sector is obtained by multiplying the above two values. The results are shown in Table 6.

A historical relation between capital stock of industrial robots and their benefits in the case of a 25% expense rate is shown in Figure 4.

One can draw some interesting implications from a comparison between Table 5 and Table 6. Although the equivalent labor force augmentation per industrial robot strongly depends on expense rate r, the values corresponding to r=25% and r=33% in Table 5 are consistent with the average labor reduction per robot shown in the third column of Table 6 after 1977. This point suggests that the actual utilization rate of industrial robots is rather higher than the entrepreneur would expect before the robots are implemented.

It is often pointed out in practice that the capability of one industrial robot is basically equivalent to that of one worker at a time, although the robot can work longer hours and can therefore replace several workers in a multi-shift operation. It should be noted that this observation is supported independently by macroeconomic analysis. On the other hand, the imputed capability of industrial robots in the beginning of the

Table 5
Equivalent Labor Force of Industrial Robots; total and per unit industrial robot

	r=33.3%			r=25%		
year	$F(L,R)$ equiv. labor force in 1000	L_R labor force augment. in number	E_R equiv. workers per unit I.R	$F(L,R)$ equiv. labor force in 1000	L_R labor force augment. in number	E_R equiv. workers per I.R
1970	11400	7867.19	3.93359	11398	5899.41	2.94971
1971	11206.4	13014.6	4.06708	11203.2	9765.63	3.05176
1972	11197.5	17093.8	3.97529	11193.2	12823.2	2.98215
1973	11392.6	22309.6	3.01481	11387	16726.6	2.26035
1974	10935.9	31013.7	2.67359	10928.1	23247.1	2.00406
1975	10697.7	37712.9	2,35706	10688.3	28290	1.76813
1976	10584.1	47137.7	2.0318	10572.3	35344.7	1.52348
1977	10303.4	57414.1	1.93966	10289	43047.9	1.45432
1978	10300.5	68486.3	1.79284	10283.3	51348.6	1.34421
1979	10296.7	85695.3	1.66722	10275.3	64252	1.25004
1980	10403.2	111205	1.65978	10375.4	83354.5	1.2441
1981	10703.9	138907	1.6576	10669.1	104113	1.2424
1982	10653.3	172263	1.69383	10610.1	129090	1.26932
1983	10863.2	211183	1.7482	10810.2	158238	1.30992
1984	11060.7	262730	1.80199	10994.8	196810	1.34986

I.R.: industrial robots augment.: augmentation

Table 6

Average Labor Reduction per Unit Industrial Robot (in case of one shift operation), estimated average shift operations and their product in 1984

	industry	average labor reduction per shift	estimated average shift operation	average labor reduction per I.R
1.	fabricated metal industry	.9	1.339	1.21
2.	general machinery industry	.9	1.332	1.20
3.	electric machinery industry	1.3	1.347	1.75
4.	automobile industry	1.1	1.364	1.50
5.	precision machinery and plastics forming industry	1.0	1.455	1.46
6.	other manufacturing industry	0.9	1.346	1.21
7.	total	1.1	1.369	1.51
	food & textile industry		1.484	
	wood & paper industry		1.400	
	chemical products industry		1.475	
	rubber & cement industry		1.597	
	iron & steel industry		1.443	
	non-ferrous metals industry		1.484	

Source: JIRA[1984] and JIRA[1985]

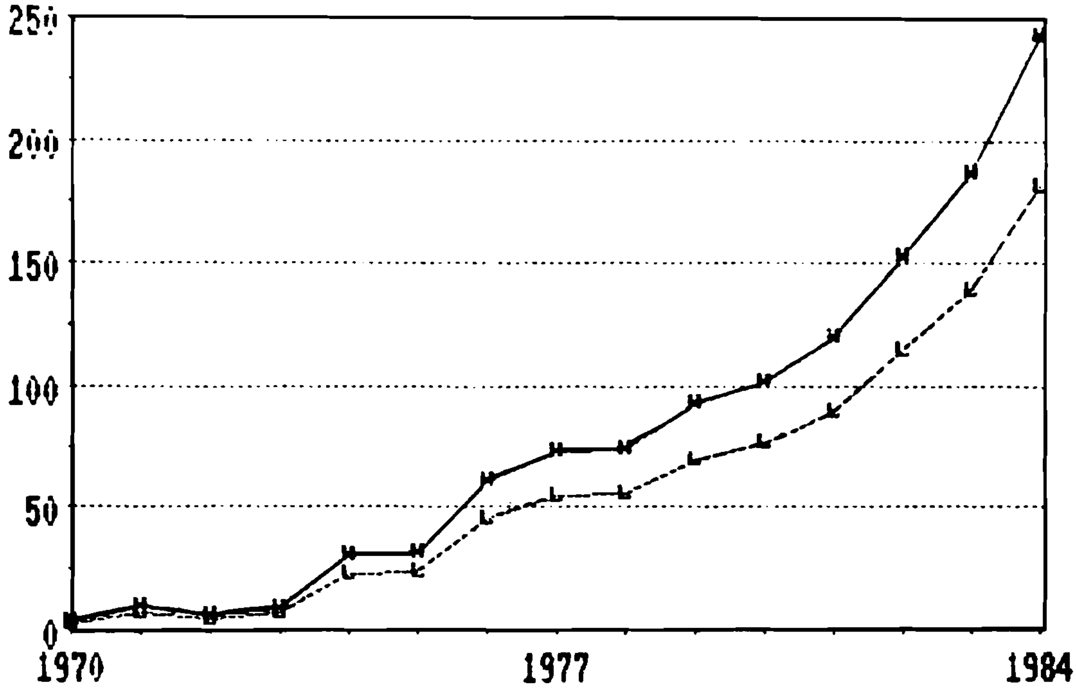


Figure.3 Benefits of Industrial Robots in 1980 billion yen
H:expense rate=33% ; L:expense rate=25%

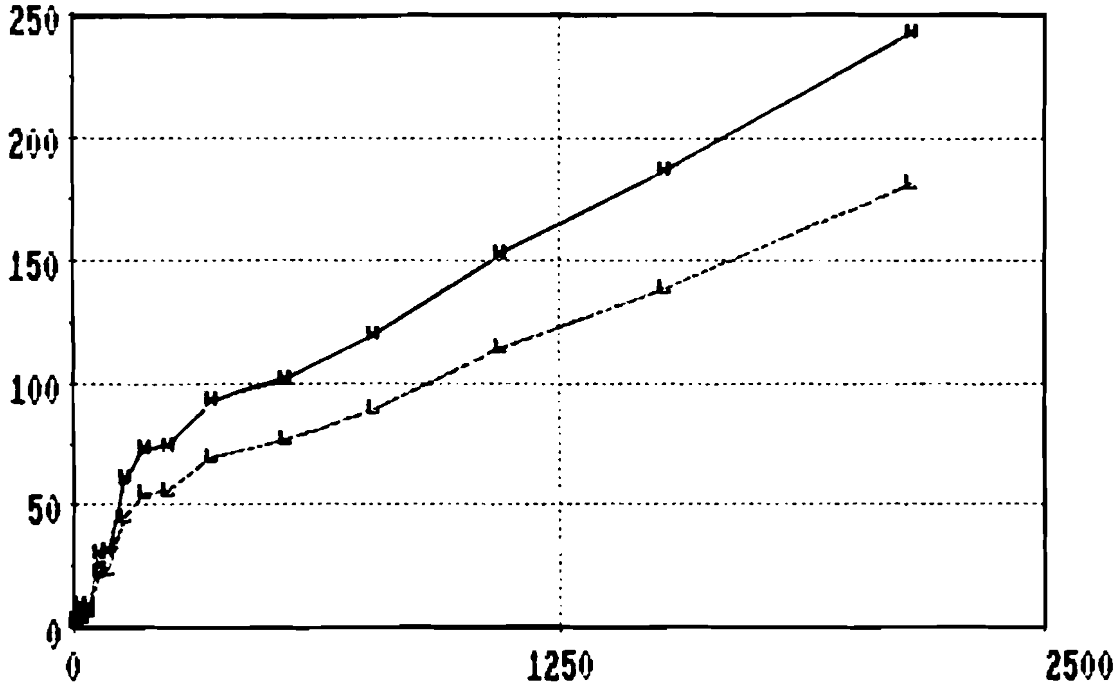


Figure.4 Benefit of Industrial Robots (vertical)
vs. Capital Stock of Industrial Robots (horizontal)
in 1980 billion yen
H:expense rate=33% ; L:expense rate=25%

1970's is probably exaggarated. The reasons may be the following:

1. The population of industrial robots, especially the simpler types, in the early 1970's might be underestimated.
2. In the first stage of penetration, robots substituted for workers in tasks where workers were least effective for various reasons. This point may be clarified from the practical and engineering point of view.
3. Since the procedure used to estimate the production function is not based on actual performance of industrial robots but on managerial assessments, it may well be concluded that these results reflect the "robot boom" atmosphere in the Japanese industry in the early 1970's.

The estimated gross benefits of industrial robots and the gross benefit rate to the capital stock of industrial robots are shown in Table 7. Figure 4 exhibits the trend of industrial robot benefit (in case of 25% expense rate) vs. capital stock of industrial robots. One observes that after 1979 the benefit of industrial robots increases almost linear to the growth of their capital stock. I.e., the marginal effect of industrial robot investments has been quite stable in recent years, although the share of high level robots has been increasing (see Figures 5 and 6). This observation may suggest that the present generation of industrial robots has already penetrated its most favorable markets.

JIRA [1984] evaluated the benefits of industrial robots by type based on a questionnaire which consists of 70 questions, covering 292 firms. The managers were asked for their assessment of the effect of industrial robots in the following manner:

(Q.1) What type of industrial robot is used most in your factory?

(Q.2) When was the use of these robots implemented?

(Q.3) How many workers could be reduced by these industrial robot implementations?

(Q.4) How much total labor cost could be saved?

(Q.5) At what percentage of the total effect do you assess the above labor cost reduction effect?

Table 7

Estimated Benefits of Industrial Robots (B_R) (in 1980 billion yen) and Rate of Return of Industrial Robots Capital Stock (R_R)

	B_R Gross Benefit in 1980 billion yen		R_R Gross Benefit Rate to Industrial Robot Stock	
Year	r=33.3%	r=25%	r=33.3%	r=25%
1970	3.89924	2.92295	59.0%	44.2%
1971	9.67999	7.26834	63.4%	47.6%
1972	5.83956	4.38452	24.4%	18.3%
1973	8.96355	6.71124	24.5%	18.3%
1974	30.1115	22.5562	46.6%	34.9%
1975	30.9951	23.2566	34.3%	25.7%
1976	60.3455	45.2409	46.0%	34.5%
1977	73.3282	54.9665	39.7%	29.8%
1978	74.2046	55.6164	30.1%	22.5%
1979	92.97	69.6813	26.0%	19.5%
1980	101.629	76.0963	18.7%	14.0%
1981	119.5	89.4484	15.5%	11.6%
1982	152.764	114.284	13.9%	10.4%
1983	186.238	139.264	12.2%	9.14%
1984	242.644	181.293	11.2%	8.40%

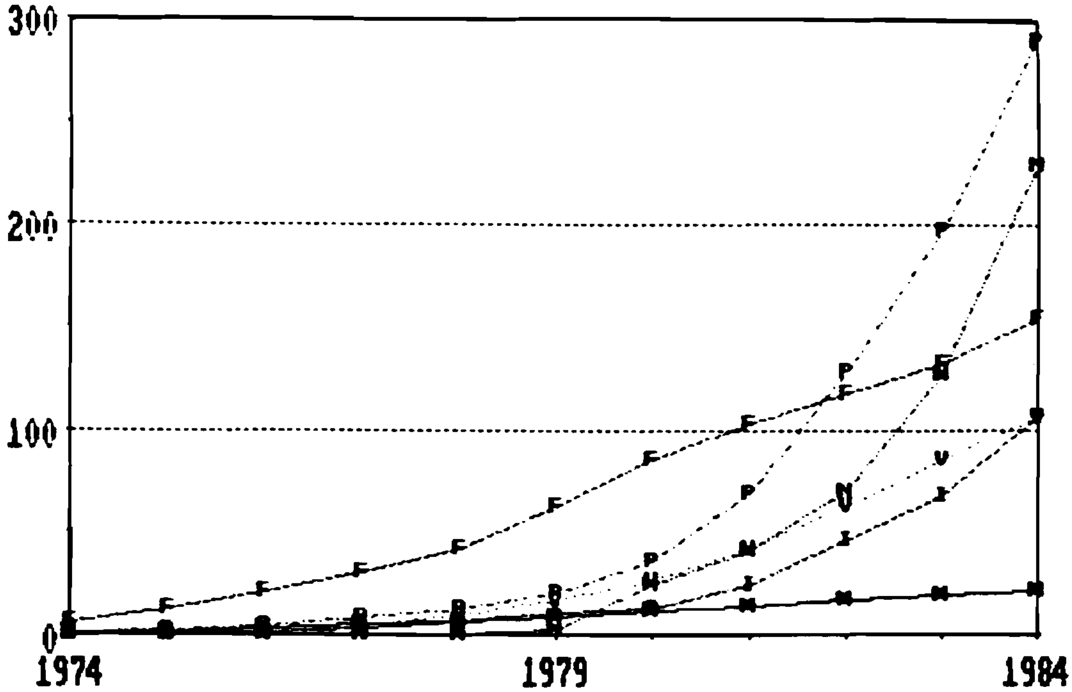


Figure.5 Capital Stock of Industrial Robots by Type in 1980 billion yen
M:manual manipulator F:fixed sequence robot
V:variable sequence robot P:playback robot
N:NC robot I:intelligent robot

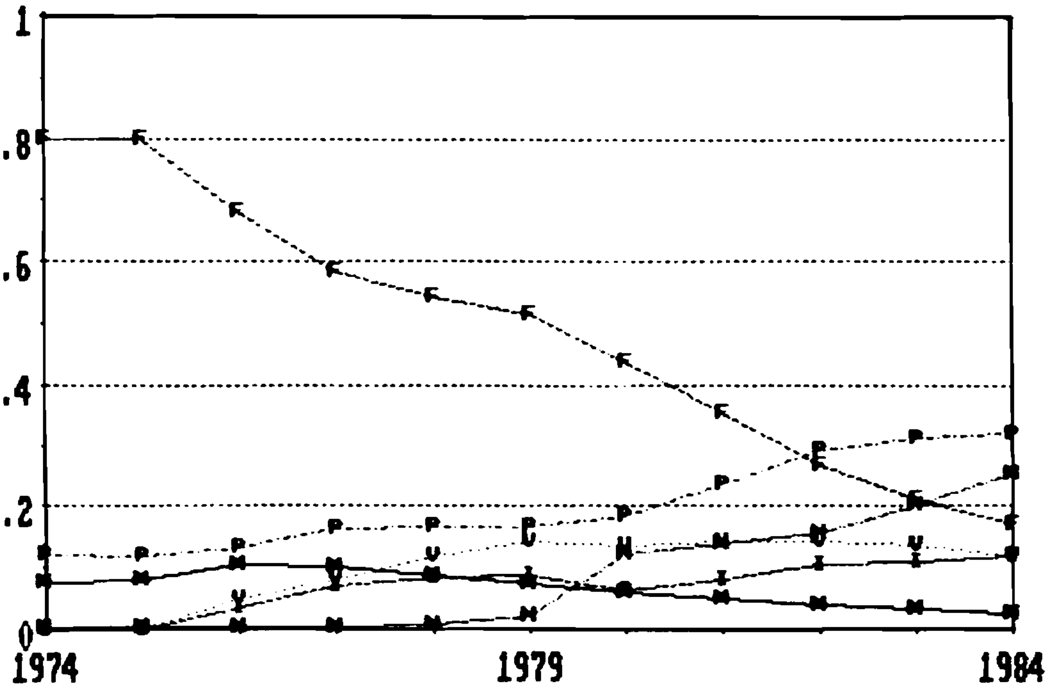


Figure.6 Share of Each Industrial Robot Type Capital Stock
M:manual manipulator F:fixed sequence robot
V:variable sequence robot P:playback robot
N:NC robot I:intelligent robot

Based on (Q.4) and (Q.5), JIRA evaluates the total benefit of industrial robots to firms. The percentage of other indirect contributions are then explored. For instance:

(Q.6) At what percentage of the total effect do you assess the capacity utilization rate improvement effect?

Questions (Q.7) to (Q.12) concern the percentage of the effect of quality improvement, labor conditions improvement, flexibility and space saving factor, managemental change, and others (impression of the company, reallocation of workers, etc.). Each question consists of several additional questions. These results are shown in Table.8.

Based on the above questionaire, the total benefits of the initial industrial robot investment to firms are also evaluated by type and age. The results are shown in Table 9. Since only the labor augmentation effect has been considered in this paper, the 32.5% (contribution of labor saving to total benefit estimated by JIRA) -- shown in Table 9 -- can be compared with the results in Table 8. One can observe that they are reasonably consistent in 1984. JIRA [1984] also estimated the cumulative labor cost reduction resulting from industrial robots implemented during 1977 to 1983 as 744 billion yen (current yen). Hence the total imputed benefit of industrial robots to firms is 2290 billion yen. Note that these values are recovered during 1977 to 1989. Therefore this value cannot be directly compared with our previous results.

It must be emphasized that JIRA's results are based on subjective opinions of the managers. It is practically doubtful whether it is justified to define the total benefit simply as direct labor cost reduction divided by estimated fractional contribution of labor saving benefits. Nonetheless, this may be the only available means of quantitatively estimating the indirect effects, at present. Taking into account the above points, one can evaluate the more detailed effects of industrial robot penetration based on this preliminarly assessment.

Table 8

Distribution of the Effect of Industrial Robots Based on Managers' Assessment (287 companies)

effect items	distribution of the effect	
1. labor cost saving	32.5%	
2. capacity utilization improvement	11.2%	
3. product quality improvement	14.4%	
-1. stability of product quality		24.0%
-2. stability of process		23.1%
-3. high level product quality		13.0%
-4. defect reduction		17.4%
-5. reduction of claim expense		5.3%
-6. positive administration		6.9%
-7. reduction of equipment loss		6.7%
-8. others		3.7%
4. factory circumstance improvement	12.8%	
-1. reduction of heavy work		13.2%
-2. reduction of monotonous work		34.1%
-3. reduction of dirty work		10.4%
-4. reduction of foul or noisy work		9.6%
-5. reduction of overtime work		2.1%
-6. reduction of worker shortage problem		3.9%
-7. reduction of worker transfer		4.4%
-8. improvement of workers' morale		11.0%
-9. operability by high age worker		8.2%
-10. others		2.2%
5. capital saving and capital efficiency	8.6%	
-1. by product multiplicity		24.2%
-2. by reduction of production line change		25.4%
-3. by reduction of work in process		11.6%
-4. space saving		6.3%
-5. by concentration of process		18.1%
-6. by modification of product design		10.5%
-7. material saving		3.9%
6. improvement of process management	11.6%	
-1. process management on the data base		17.3%
-2. management coping with demand change		17.4%
-3. production technology improvement		17.5%
-4. acquisition of robotics technology		27.0%
-5. reduction of loss by low level workers		5.4%
-6. acquisition of electronics technology		15.5%
7. others, reallocation of workers, etc.	8.6%	
-1. reallocation to other process		26.4%
-2. reallocation to other department		12.8%
-3. trust of parent company and customers		5.5%
-4. acquisition of higher business ability		8.8%
-5. impression as high technology company		10.1%
-6. impression as high reliability company		12.9%
-7. somehow better impression		2.7%
-8. the company is better known.		4.7%
-9. energy saving		4.0%
-10. motivation towards new business		12.1%

(Source: JIRA report [1984])

Table 9

Annual Salvageable Benefit per Initial Industrial Robot Investment: by robot type

	benefit per initial industrial robot investment							
robot type / age	0	1	2	3	4	5	6	mean
1. manual manipulators	7.9%	7.9%	7.9%	13.2%	34.2%	34.2%	34.2%	19.9%
2. fixed sequence robot	8.3%	12.3%	13.3%	16.5%	37.6%	36.6%	36.6%	23.0%
3. variable sequence robot	9.8%	12.5%	13.1%	16.7%	32.2%	32.2%	32.2%	21.2%
4. playback robot	9.9%	11.5%	11.4%	13.3%	31.1%	30.3%	29.0%	19.5%
5. NC robot	11.6%	12.3%	13.3%	17.7%	33.3%	32.8%	32.5%	21.9%
6. intelligent robot	21.3%	22.3%	24.3%	29.6%	49.6%	48.6%	48.6%	34.9%
7. year implemented	1984	1983	1982	1981	1980	1979	1978	(1984)
8. weighted mean value by shipment in 1984	11.8%	13.1%	14.0%	16.9%	37.6%	35.4%	35.6%	22.7% (18.1%)
9. contribution of labor cost reduction	3.8%	4.3%	4.6%	5.5%	12.2%	11.5%	11.6%	7.4% (5.9%)

Source: JIRA [1984]

(*.1) Maintenance cost (exhibited in Table 4) is taken into account except for manual manipulators.

(*.2) JIRA assumed lifetime and repayment duration of industrial robots to be 7 years and 3.8 years, respectively. Hence the benefit rate of robot older than 4 years is higher than for the younger ones.

(*.3) Average benefit rate on a 1984 basis is calculated as the weighted mean value of the corresponding column values. The shipment values in the year of implementation defined as 1984 minus age are employed as the weight. For the mean value in the 8-th column, the stock of industrial robots by type in 1984 is employed. The values in parentheses are also the weighted mean values of the average benefit rate during 1978 to 1984. The total shipment values of industrial robots in the corresponding year of implementation are employed as the weight.

II. BENEFITS OF NC MACHINE TOOLS

1. Model and Formulation

The next step towards an overall CIM social benefit evaluation model is to formulate the effect of other CIM systems, particularly those contributing to capital augmentation including quality improvement. It can be argued that NC machine tools differ from conventional machine tools mainly in terms of improved precision and reliability. It should be noted that the attributes of NC machine tools are quite different from those of industrial robots. Therefore the calculation of the benefits of industrial robots described in the previous section should be modified in order to take the difference into account. Here, the formulation of the indirect effects of NC machine tools and some empirical results are discussed.

Let us return to the production function $Y = Y(K, F(L, R), N)$ which contains three input factors, namely K, traditional capital stock, F, equivalent labor including the effect of industrial robots and N, capital stock of NC machine tools. Since NC machine tools are machining tools with a different mode of control, their machining capability is basically identical with that of conventional machines. In this sense, standalone NC machine tools are homogeneous with conventional machines. But owing to computerized control systems, NC machines can be switched from production of one part to another part by simply changing control data [UNECE, 1985]. Stability of product quality is automatically achieved, with minimal setup time or "learning" time. Besides these capabilities as a direct substitute of conventional machining tools, NC machine tools are the main factos of advanced manufacturing systems, namely FMS or CIM. By integrating NC machine tools and other CIM systems, such as CAD/CAM and LAN, one can achieve further overall productivity improvement.

In this section we focus on the two properties of NC machine tools underlined above. The capital stock of NC machine tools is assumed to be additive to traditional capital goods. In order to take this effect of NC machine tools into account, we rewrite Y as follows:

$$Y = G(\ Q((K+N),F)\ ,\ N\ )\cdot\beta\cdot e^{ct} \qquad (21)$$

where β and c denote the scaling constant and the exogeneous technological progress rate derived by various means other than industrial robots and NC machine tools, respectively. The technological progress term of the Hicks type is postulated. It should be noted that c involves not only the effects of progress in production technology but also managemental effects such as the Just-In-Time method and TQC. It is also noteworthy that many investigations have been developed in order to embody this "exogeneous" technical progress term as "endogeneous" in the optimal investment strategy including the R&D project [Kennedy, 1966, Wyatt, 1985 and Ayres, 1986]. Obviously, no technical progress could be achieved without the entrepreneur's (sometimes risky) investment. Since the investigation of the contents and incentives of "technical progress" is one of the main objects of our reserch, these should be discussed further from various points of view.

Assuming linear homogeneity of G, equation (21) can be rewritten as

$$Y = Q(K+N,F)\cdot G(1,N/Q)\cdot\beta\cdot e^{ct}\ . \qquad (22)$$

It is usually plausible to impose the following conditions.

$$dY/dK > 0 \qquad (23)$$
$$dY/dF > 0 \qquad (24)$$
$$dY/dN > 0 \qquad (25)$$

plus the requirement that

$$\text{if } K,F > 0, \qquad Y(K,F,0) = Q(K,F)\beta\cdot e^{ct} > 0 \qquad (26)$$

that is,

$$G(1,0) = 1\ . \qquad (27)$$

Evidently $G(1,x)$ and $Y(K,L,0)$ represent indirect productivity improvement effects of NC machine tools and conventional production capacity, respectively.[3]

One of the simplest forms which satisfy the above conditions is

$$Y = \{Q^b + B \cdot N^b\}^{(1/b)} \cdot \beta \cdot e^{ct} \quad , \qquad (28)$$

where b should be positive and

$$Q = (K+N)^{\alpha} F^{(1-\alpha)}. \qquad (29)$$

Equation (28) is a special form of the well known CES type of production function.

The optimal strategy for investing in K, F, N is formulated as maximizing output Y under total cost constraint, say T. Namely,

$$\max.\ h(K,F,N,s) = Y(K,F,N) - s \cdot (P_K K + P_F F + P_N N - T) \qquad (30)$$

where P_K and P_N denote the price of capital services on conventional capital stock and NC machine tools, respectively. P_F is defined as

$$P_F = (P_R R + P_L L)/F(L,R) \qquad (31)$$

The equilibrium conditions of (30) are as follows:

$$dh/dK = \{Q^b + B \cdot N^b\}^{(1/b)-1} \cdot \beta e^{ct} \cdot \alpha/(K+N) \cdot Q^b - s \cdot P_K = 0 \qquad (32)$$

---

[3]An alternative formulation concerning with the effects of NC machine tools might be

$$K'(K,N) + (K^m + M \cdot N^m)^{(1/m)} \qquad (m>0), \qquad (*.1)$$

which focuses on the capital augmentation similarly to the labor augmentation effect of industrial robots. However, the explanatory power of this model is quite lower than that of the model based on the equation (28) (see APPENDIX-2). Hence the latter model has been adopted for the analysis.

$$dh/dN = \{Q^b+B\cdot N^b\}^{(1/b)-1}\cdot\beta e^{ct}\cdot\{\alpha/(K+N)\cdot Q^b+B\cdot N^{b-1}\} - s\cdot P_N \qquad (33)$$

and

$$dh/dL = \{Q^b+B\cdot N^b\}^{(1/b)-1}\cdot\beta e^{ct}\cdot(1-\alpha)/F\cdot Q^b - s\cdot P_F = 0. \qquad (34)$$

(32) and (34) yield

$$\alpha/(1-\alpha) = P_K\cdot(K+N) / (P_F\cdot F) \qquad (35)$$

The parameter α can be estimated easily and then we can calculate Q.

Next, (32) and (33) yield

$$P_N/P_K = 1 + B\cdot(K+N)/\alpha\cdot N^{b-1}\cdot Q^{-b}$$

$$= 1 + (B/\alpha)\cdot(N/Q)^b\{1+(K/N)\} \qquad (36)$$

Hence defining the following J, we can obtain

$$J = \alpha\cdot\{(P_N/P_K)-1\}/\{1+(K/N)\}$$

$$= B\cdot(N/Q)^b \quad . \qquad (37)$$

Since the left side value of (37) is already known, both B and b can be easily estimated by log linear regression.

Finally, the technological progress term c and the constant term H can be obtained from

$$(V/u)/[\{Q^b+B\cdot N^b\}^{(1/b)}] = \beta e^{ct} \qquad (38)$$

where V and u denote actual output and capacity utilization rate given by MITI [MITI, 1985a], respectively.

2. Data and Empirical Results

The first step for empirical analysis is to determine the price index of NC machine tools. Since price and production of NC machine tools are available by type [MITI, 1985b], we can calculate a divisia price index. It is exhibited in Figure 7. The next problem concerns data on the shipments of NC machine tools to the domestic Japanese market. Unfortunately, the export/import data is not available since NC machine tools are not yet specified in SITC. As regards shipments, only one figure for 1983 is available from MITI [MITI, 1985]. This is shown in Figures 8 and 9. Accordingly, the share of domestic shipment is 70.0% (1983). Since most shipments to the non-manufacturing industry involve leasing firms, most of whose customers are also manufacturers, we assumed that the use of NC machine tools in non-manufacturing industry is negligibly small. It is also assumed that this value is constant throughout the period.

According to the National Wealth Survey [EPA,1970], the legal lifetime of machining tools and production equipment is eleven years. We employ this value as the life time of NC tools. Assuming the expense rate of NC machine tools r to be 25% and 33%, namely low case and high case respectively, the stock of NC machine tools and fixed cost, say N and q_N respectively, can be estimated.

Next, fixed cost of conventinal capital stock is estimated. The rate of fixed cost to the capital stock on conventional equipment can be defined as

$$q_K = (d+X-q_N N-q_R R)/K , \qquad (39)$$

where q_R, d and X denote the rate of fixed cost to the capital stock on industrial robots, depreciation of whole capital stock and tax payment, respectively. d and X are available in National Accounts. It should be noted that the above q_K and q_N do not include capital return. In the context of macroeconomics, nominal value added $P_Y \cdot Y$ is basically attributed to labor and capital, where P_Y denotes output deflator. The price of capital services is usually defined within this context [Christensen and Jorgenson, 1969]. Since the equilibrium conditions of our model

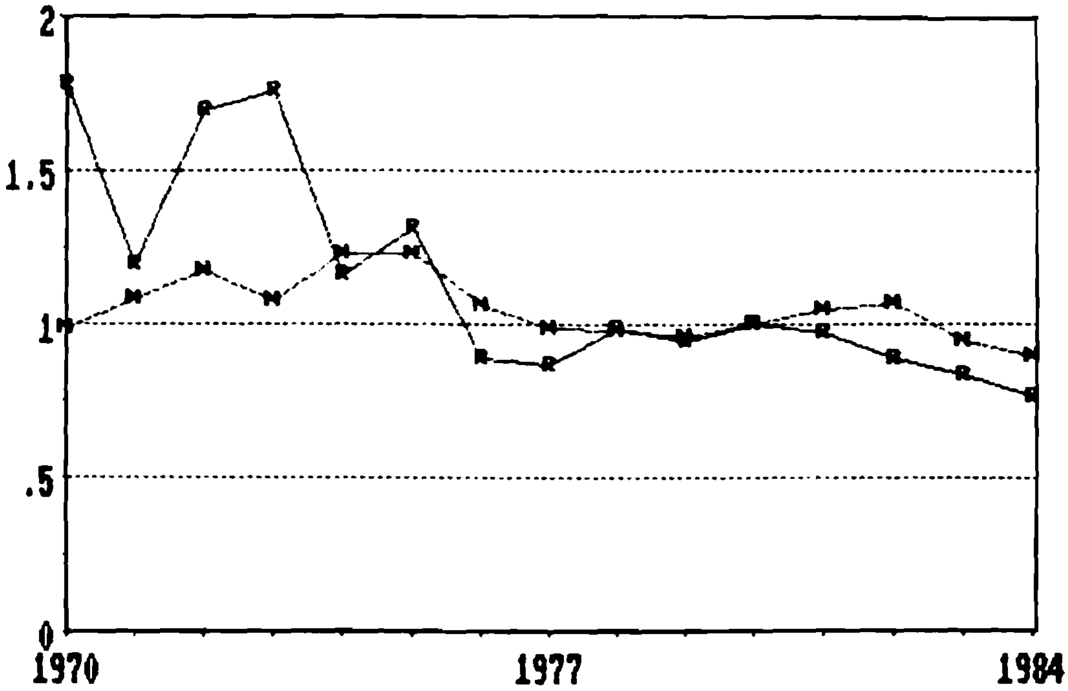
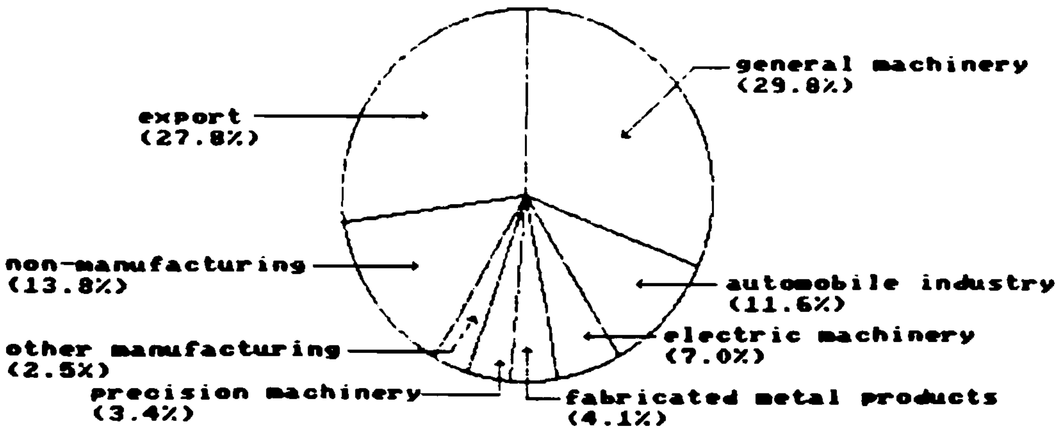
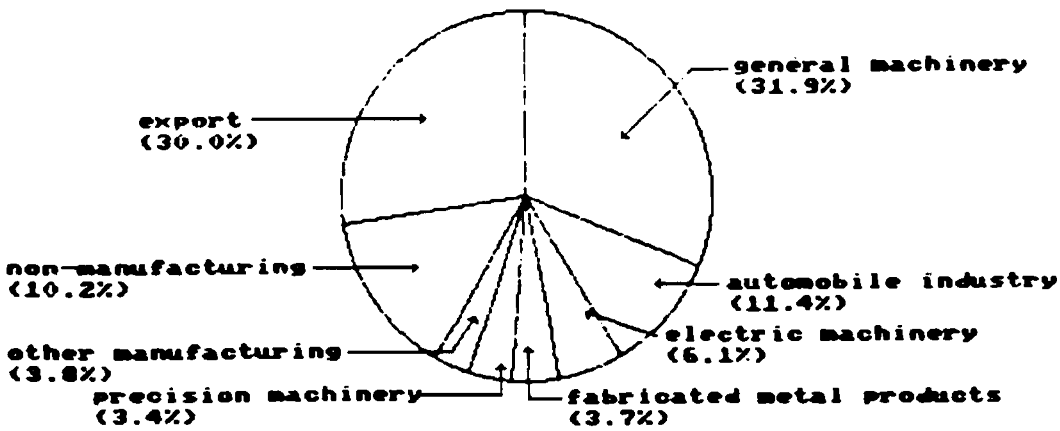


Figure.7 Price Indexes on Industrial Robots (R) and NC Machine Tools (N) (1980=1)



total shipment = 24766 (unit)

Figure.8 Distribution of NC machine tools in 1983 in unit



total shipment = 407.183 billion yen

Figure.9 Distribution of NC machine tools in 1983 in value

(30) to (32) are concerned with the distribution of value added, P_K and P_N must involve not only fixed costs, but also capital return. The ideal method is to identify the distribution of value added among the capital equipment. But this may be impossible. Therefore we multiplied q_K and q_N by z so that

$$P_Y \cdot Y = z \cdot q_N N + z \cdot q_K K + P_F F \qquad (40)$$

may hold. P_N and P_K are defined as $z \cdot q_N$ and $z \cdot q_K$, respectively. The results of P_K and P_N are exhibited in Table 10 and Figure 10.

According to the above discussion and equation (35), parameter d can be estimated for the period 1970 to 1984. Namely,

A: low case (r=25%)

$$\text{mean value of } \alpha = .6101$$
$$[\text{standard deviation} = .0233] \qquad (41)$$

B: high case (r=33%)

$$\text{mean value of } \alpha = .6099$$
$$[\text{standard deviation} = .0233] \qquad (42)$$

Next, parameters b and B are estimated according to (37).

A: low case (r=25%)

$$\log (36) = \underset{(19.2)}{.702} * \log (N/Q) - \underset{(13.1)}{2.572} \qquad (43)$$

$R^2 = .966$ $\quad\bar{R}^2 = .963$
D.W = .909

Hence

$$b = .707 \qquad (44)$$

and

$$B = .0764 \; . \qquad (45)$$

B: high case (r=33%)

$$\log J = \underset{(23.5)}{.735} * \log (N/Q) - \underset{(11.5)}{1.946} \qquad (46)$$

$R^2 = .977$ $\quad\bar{R}^2 = .975$
D.W = .913

Hence

$$b = .735 \qquad (47)$$

and

Table 10

Price Index, Stock, and Capital Services Price of NC Machine Tools and Capital Services Price of Conventional Capital Stock

year	P_I price index of NC mach.	N stock of NC mach.	expense rate=25% P_N price of capital; NC mach.	P_K price of capital; convent.	expense rate=33% P_N price of capital; NC mach.	P_K price of capital; convent.
1970	.988768	17.2174	.693375	.253369	.924592	.253353
1971	1.08679	33.4249	.658535	.216412	.878157	.216391
1972	1.17143	48.1948	.684975	.216648	.913524	.216607
1973	1.07685	79.0751	.714517	.257912	.953045	.257852
1974	1.22974	112.358	.918929	.278324	1.22578	.278261
1975	1.22776	135.082	.739733	.220552	.986894	.220458
1976	1.05942	168.976	.70463	.251165	.940044	.251077
1977	.984687	226.236	.622505	.260575	.830563	.26046
1978	.979902	303.133	.6278	.278203	.837854	.278034
1979	.954929	453.739	.659495	.314478	.880433	.314252
1980	1	678.437	.709677	.331724	.948047	.331378
1981	1.04758	951.265	.716487	.320346	.957649	.319895
1982	1.06977	1211.05	.704577	.31577	.942134	.315216
1983	.94605	1511.94	.608009	.307744	.813517	.30706
1984	.898023	1940.75	.630573	.332745	.844623	.331905

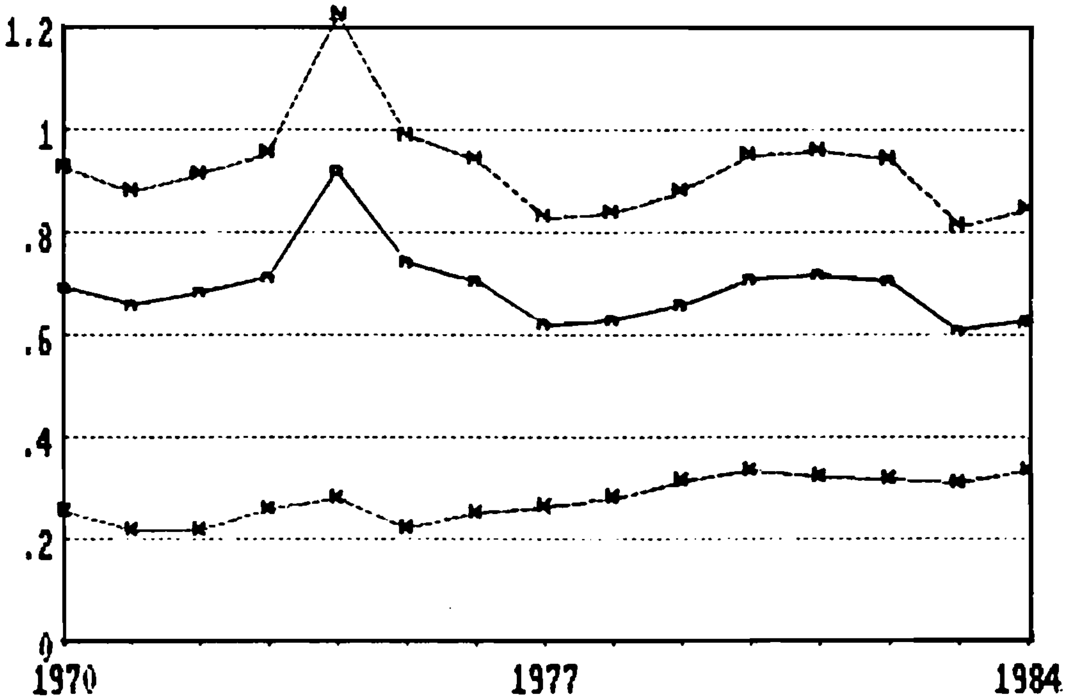


Figure.10 Price of Capital Services
N:NC Machine Tools (expense rate=33%)
n:NC Machine Tools (expense rate=25%)
K:Conventional Capital Equipments
(Indistinguishable between r=33% and r=25% cases.)

$$B = .143 \quad . \qquad (48)$$

Finally, the exogeneous technological progress rate c and the constant term β can be estimated as follows:

A: low case (r=25%)

$$\log \left[(V/u)/\{Q^b + B \cdot N^b\}^{(1/b)} \right] = \underset{(18.2)}{.0228} \cdot \text{year} + \underset{(15.3)}{.157} \qquad (49)$$

$R^2 = .962$ $\qquad \bar{R}^2 = .959$

D.W = 1.72

Hence

$$c = 0.0228 \qquad (50)$$

and

$$\beta = 1.170 \quad . \qquad (51)$$

B: high case (r=33%)

$$\log \left[(V/u)/\{Q^b + B \cdot N^b\}^{(1/b)} \right] = \underset{(18.0)}{.0224} \cdot \text{year} + \underset{(15.4)}{.158} \qquad (52)$$

$R^2 = .961$ $\qquad \bar{R}^2 = .959$

D.W = 1.73

Hence

$$c = 0.0224 \qquad (53)$$

and

$$\beta = 1.171 \quad . \qquad (54)$$

One can now obtain the production function as follows:

A: low case (r=25%)

$$Y(K,F,N) = 1.170\left[\{(K+N)^{.610} L^{.390}\}^{.702} + .0764 \cdot N^{.702} \right]^{1.425} \cdot e^{.0228t} \quad . \qquad (55)$$

B: high case (r=33%)

$$Y(K,F,N) = 1.171[\ \{(K+N)^{.610} L^{.390}\}^{.735} + .1428 \cdot N^{.735}\ ]^{1.361} \cdot e^{.0239t} \quad . \qquad (56)$$

The "gross" benefit of NC machine tools in nominal price can be defined as

$$G_N = P_Y \cdot \{Y(K,F,N) - Y(K+N,F,0)\} \qquad (57)$$

and it follows that "net" benefit of NC may be defined as

$$N_N = G_N - (q_N - q_K) \cdot N \quad , \qquad (58)$$

Discounting by GDP deflator, we calculate the gross and the net benefit in 1980 real prices. The values (G_N/N) and (N_N/N) can be interpreted as indirect effect coefficients of NC machine tools. They are exhibited in Table 11. Figures 11 and 12 visualize the behavior of gross and net benefit in 1980 billion yen and their ratio to the capital stock of NC machine tools, respectively. Since q_K involves non-production equipment, such as structures and buildings (whose depreciation rates are relatively low), q_K might be lower than the fixed cost of production systems. Therefore the value represented by (58) might be slightly pessimistic. We again observe rather exaggerated values in the early 1970's, similar to the case of industrial robots. After the middle of the 1970's, the net benefit rate lies around 40% per year even in the low case (expense rate = 25%). This is much higher than that of industrial robots (around 9-10%). It is noteworthy that, when effects of industrial robots other than labor cost reduction are taken into account (according to JIRA -- see Table 8 -- where the contribution of labor cost saving is 32.5%), both benefit rates are close together. Needless to say, this comparison is only justified if we can assume other indirect benefits of NC machine tools to be negligibly small, that is, if

Table 11

Estimated Benefits and Benefit Rates of NC Machine Tools

	expense rate=25%				expense rate=33%			
	G_N gross benefit in 1980 billion	N_N net benefit in 1980 billion	G_N/N gross benefit rate to NC mach.	N_N/N net benefit rate to NC mach.	G_N gross benefit in 1980 billion	N_N net benefit in 1980 billion	G_N/N gross benefit rate to NC mach.	N_N/N net benefit rate to NC mach
year	yen	yen	stock	stock	yen	yen	stock	stock
1970	26.3426	20.8711	153.0%	121.2%	36.6411	28.2952	212.8%	164.3%
1971	40.8017	29.2189	122.0%	87.4%	57.4501	40.1154	171.9%	120.0%
1972	53.716	36.2904	111.5%	75.3%	76.042	50.1175	157.8%	104.0%
1973	80.78	58.8337	102.2%	74.4%	115.394	81.9926	145.9%	103.7%
1974	106.806	74.5937	95.1%	66.4%	153.214	105.591	136.4%	94.0%
1975	117.249	81.1421	86.8%	60.1%	168.36	115.09	124.6%	85.2%
1976	140.226	106.638	83.0%	63.1%	201.603	150.602	119.3%	89.1%
1977	171.105	135.368	75.6%	59.8%	246.875	190.621	109.1%	84.3%
1978	212.078	168.443	70.0%	55.6%	307.101	237.293	101.3%	78.3%
1979	301.898	243.626	66.5%	53.7%	440.482	344.978	97.1%	76.0%
1980	408.709	318.38	60.2%	46.9%	600.419	453.321	88.5%	66.8%
1981	527.035	392.915	55.4%	41.3%	777.715	562.321	81.8%	59.1%
1982	627.891	456.787	51.8%	37.7%	928.074	652.975	76.6%	53.9%
1983	728.374	560.219	48.2%	37.1%	1077.67	795.037	71.3%	52.6%
1984	894.019	699.213	46.1%	36.0%	1324.76	990.931	68.3%	51.1%

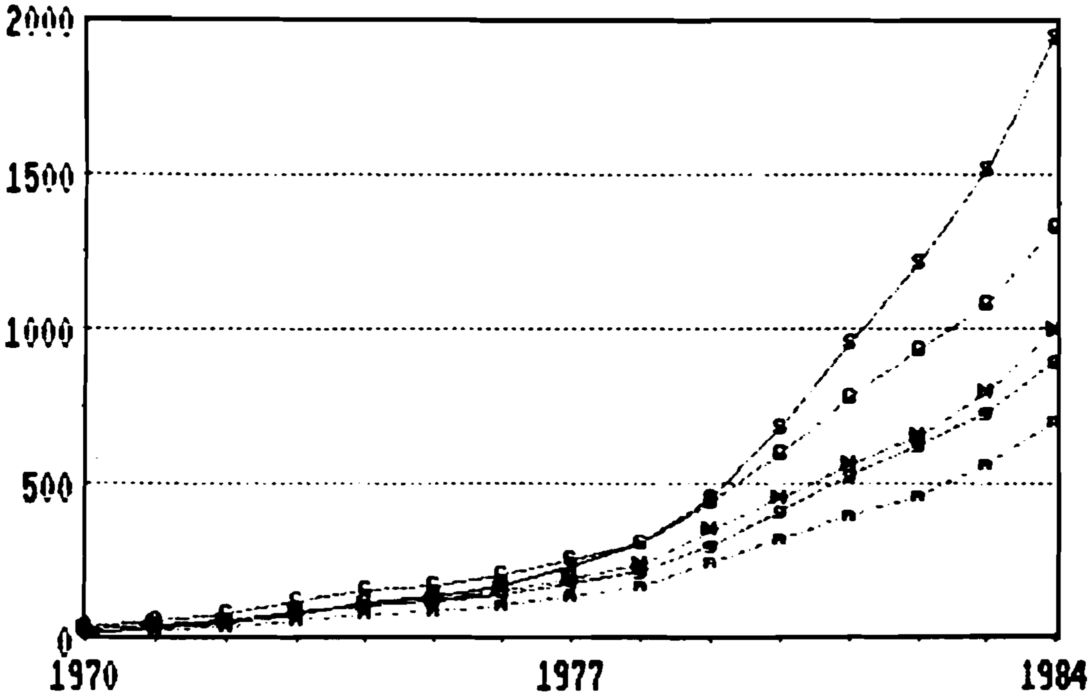


Figure.11 Capital Stock of NC Machine Tools, Gross Benefits
and Net Benefits of NC Machine Tools
S:capital stock of NC machine tools
G:gross benefits (expense rate=33%)
N:net benefits (expense rate=33%)
g:gross benefits (expense rate=25%)
n:net benefits (expense rate=25%)

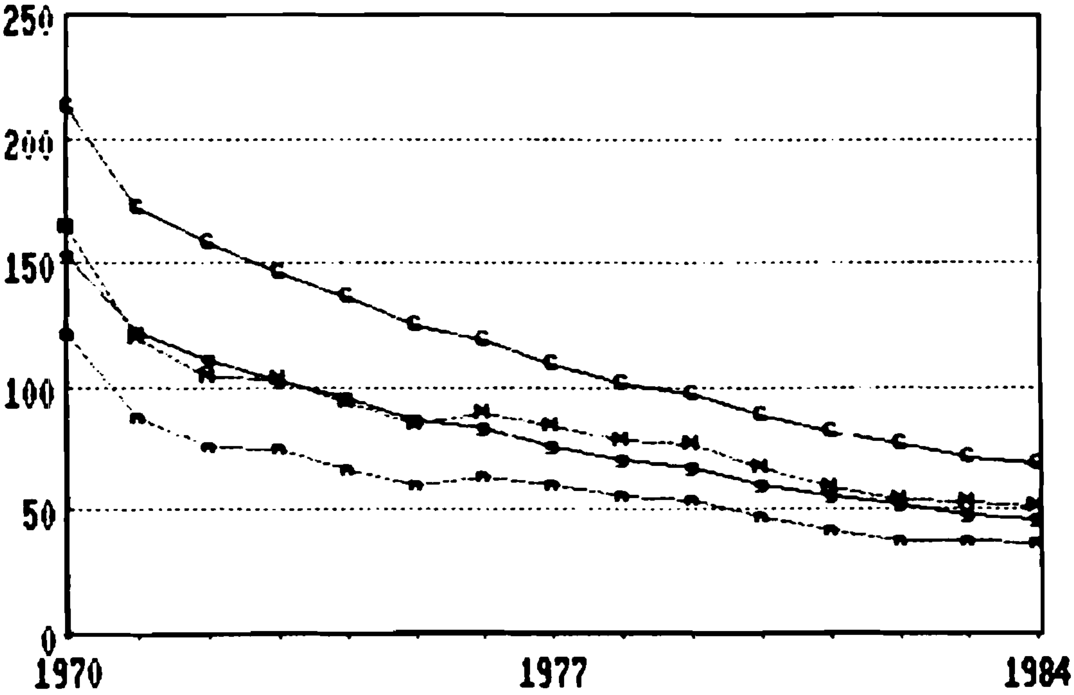


Figure.12 Gross and Net Benefit Rate of NC Machine Tools
G(r=33%) and g(r=25%):gross benefit rate
N(r=33%) and n(r=25%):net benefit rate

most of the benefits of NC machine tools are already known to the entrepreneur and have been taken into account.

Figure 13 exhibits the relation between net benefit of NC machine tools and capital stock of NC machine tools. Here we also observe stable marginal returns on their investment. This also suggests that the technology of NC machine tools may be in a "maturity phase", as applies for industrial robots.

It would be interesting to compare the above discussion with factory level surveys. Unfortunately, in case of NC machine tools, such a detailed survey is not available. Furthermore, in order to evaluate the effect of NC machine tools more concretely, the capital stock should be disaggregated. In this sense, our study still remains at its initial stage.

Nonetheless, it may be concluded that the general method and the results described above are useful for future research.

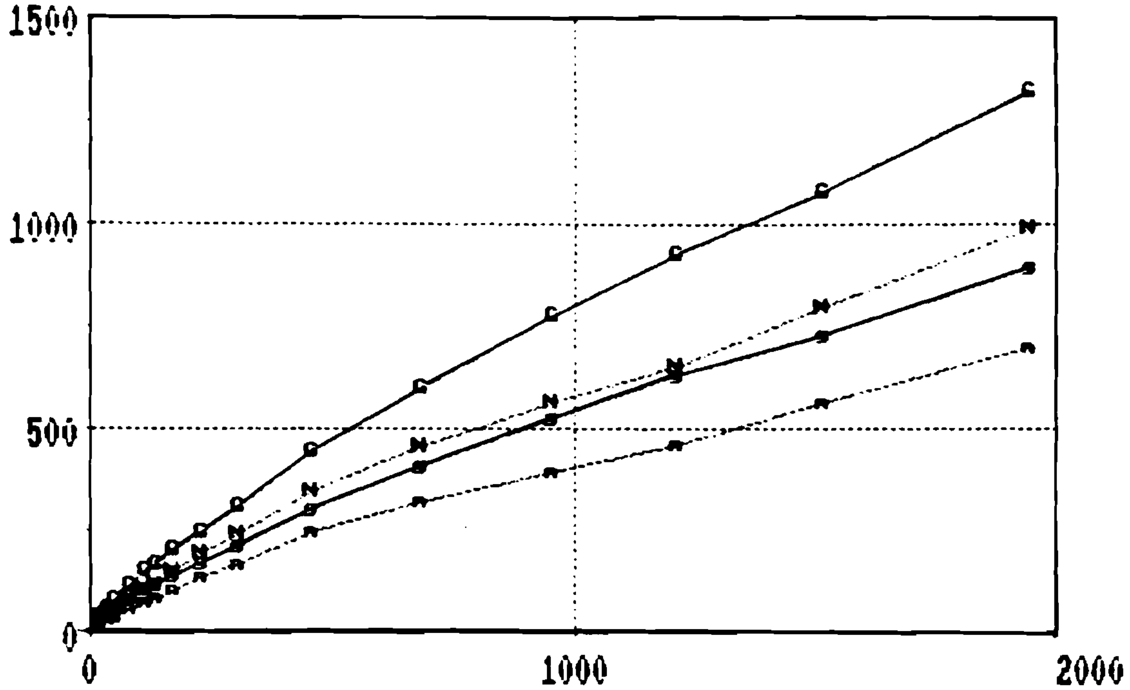


Figure.13 Capital Stock of NC Machine Tools (horizontal)
vs. Gross and Net Benefits of NC Machine Tools (vertical)
G(r=33%) and r(r=25%):gross benefits in 1980 billion yen
N(r=33%) and n(r=25%):net benefits in 1980 billion yen

III. BENEFITS OF INDUSTRIAL ROBOTS AND NC MACHINE TOOLS; BY INDUSTRY SECTOR

Methods to evaluate the social benefits of industrial robots and NC machine tools as well as some empirical results have been described in the previous sections. In order to discuss CIM benefits in depth, these methods are applied to the case of manufacturing industry sectors.

1. Benefits of industrial robots in sixteen manufacturing industries

In this section, the method of evaluating the labor augmentation by industrial robots, as described in Section I, is applied to sixteen manufacturing industry sectors separately. Again, we assume the expense rate of industrial robots to be 25%, which appears most plausible based on the results of Section I. The lifetime of industrial robots is assumed, as before, to be seven years. Unfortunately, statistics of industrial robot shipments by industry sector before 1974 are not available. Therefore it is possible that the stock of industrial robots in the mid-1970's might be underestimated. Industrial robots shipment data in units are available only after 1978. Therefore an accurate estimation of the Japanese population of industrial robots by sector is only possible in 1984. The estimated capital stock in 1980 billion yen and population of industrial robots are exhibited in APPENDIX-3 as well as annual wages by industry sector.

The labor augmentation subproduction function represented is

$$F(L,R) = (L^a + r \cdot A \cdot R^a)^{(1/a)} \qquad (5)$$

where r has been assumed to be 25%. The parameters are summarized in Table 12. Here we can see the explanatory value R^2 of the above model. In brief, it yields good values except for three cases: D. wood and wood products (R^2=.663), G. petroleum and coal (R^2=.393), and Q. other manufacturing industry (R^2=.413).

Labor force augmentation (L_R) and its benefits (B_R) in real

Table 12

Estimated Parameters of Sub-production Function
Concerning Labor Augmentation

industry sector	a	(t.V)	A	(t.V)	R^2	D.W
A.whole manufacturing	.609	(13.4)	.118	(16.2)	.927	1.19
B.food,beverage & tabacco	.835	(7.25)	.153	(10.9)	.838	2.29
C.textile	.793	(8.06)	.190	(10.8)	.865	1.95
D.wood & wood products	.740	(4.54)	.088	(6.07)	.663	1.50
E.paper & pulp	.752	(8.55)	.067	(13.1)	.889	1.46
F.chemical products	.747	(9.99)	.164	(25.8)	.908	1.50
G.petroleum & coal	.442	(2.73)	.043	(4.62)	.393	1.18
H.rubber	.846	(4.71)	.137	(8.82)	.702	1.21
I.cement and glass	.737	(7.51)	.093	(11.5)	.847	1.22
J.iron & steel	.727	(5.32)	.107	(11.9)	.732	1.28
K.non-ferrous metals	.810	(6.14)	.196	(16.6)	.786	1.30
L.fabricated metal	.773	(9.96)	.177	(18.7)	.908	1.31
M.general machinery	.772	(12.4)	.140	(25.3)	.939	1.34
N.electric machinery	.792	(8.85)	.231	(17.6)	.885	1.36
O.transportation mahinery	.769	(10.5)	.194	(28.0)	.917	1.36
P.precision machinery	.719	(7.41)	.180	(13.8)	.843	1.37
Q.other manufacturing	.834	(2.84)	.145	(5.52)	.413	1.56

(t.V):t-statistics

prices have been defined in Section I as equations (8) and (10), namely

$$L_R = F(L,R)-L \quad (8)$$

$$BR = P_L \cdot F(L,R)-P_R \cdot R-P_L \cdot L \quad . \quad (10)$$

The results are also exhibited in APPENDIX-3 by industry, where benefits are exhibited in 1980 prices discounted by GDP deflator. Because of non-availability of data on industrial robot allocation by sector described before, the results on equivalent workers per unit industrial robot in the first several years are overestimated. The average benefit rates to the capital stock of industrial robots during 1982 to 1984 are summarized in Table 13 by industry sector. It may be noteworty that the annual average benefit rate values for industrial robots during 1982 to 1984 range from 5.4% to 9.3%, except for B. food, G. petroleum, H. rubber industries, and J. iron and steel, while the results on equivalent workers per industrial robots differ by much greater factors. By comparing these 1984 values with those in Table 6 (given by JIRA, 1984), we can observe that the values in APPENDIX-3 and JIRA's survey are roughly compatible. In the fabricated metal products industry, the computed value is slightly high. Comparisons are summarized in Table 14. Based on computed equivalent workers per unit industrial robot and benefit ratio in 1984, one can classify the manufacturing industry sectors into nine groups. They are displayed in Table 15.

One can observe that the effect of industrial robots in the primary metal industry is relatively higher than in the others. The reason may be that industrial robots, especially manual manipulators (which are relatively cheap), have effectively substituted the workers in the casting and die-casting process where labor costs and the share of 2-3 shift workers (70.4%) are relatively high [JIRA, 1985].

In the case of the chemical products industry, the share of low level industrial robots (fixed and variable sequence robots) is also high (about 90%) according to JIRA [1985]. Here equivalent workers per unit industrial robot indicates quite a low value, while the benefit rate is around average. According

Table 13

Average Benefit Rate to the Capital Stock of Industrial Robots during 1982 to 1984

industry sector	average benefit rate	industry sector	average benefit rate
A. whole manufacturing	9.30%	J. iron and steel	11.8%
B. food, beverage & tabacco	4.11%	K. non-ferrous metals	5.49%
C. textile	6.31%	L. fabricated metal	6.30%
D. wood & wood products	7.08%	M. general machinery	6.38%
E. paper & pulp	5.68%	N. electric machinery	5.44%
F. chemical products	8.13%	O. transportation machinery	6.48%
G. petroleum & coal	45.2%	P. precision machinery	7.12%
H. rubber	3.29%	Q. other manufacturing	6.14%
I. cement and glass	6.64%		

Table 14

Comparison of Equivalent Workers per Unit Industrial Robot between Estimated Values and JIRA Survey in 1984

	[estimated]	[given by JIRA]	
industry	equivalent workers per unit robot	average labor reduction per shift and unit	average labor reduction per unit robot
A. whole manufacturing	1.35	1.1	1.51
L. fabricated metal products	1.66	.9	1.21
M. general machinery	.90	.9	1.20
N. electric and electronics	1.82	1.3	1.75
O. transportation machinery	1.55	1.1	1.50
P. precision machinery	1.14	1.0	1.46

(*)Plastic forming industry is included in P. precision machinery industry in JIRA's data.

Table 15

Classification of Manufacturing Industry Sectors

		benefit ratio to industrial robot stock		
		larger than aveage	middle	less than average
equivalent workers per unit I.R	larger than average	iron & steel	textile wood & wood products non-ferrous metals elec. mach.	food & beverage
	middle		fabricated metal transportation others	paper & pulp cement & clay
	less than average	petroleum	chemical products, general machinery, precision machinery	rubber

to JIRA, industrial robots in the plastic forming industry are mainly utilized as product extractors. Therefore it might be concluded that industrial robots in this sector are a part of the process line rather than labor substitution.

The number of equivalent workers per unit robot in the electric machinery sector is relatively higher than in other machinery industry sectors, while benefit rates are not so different among these sectors. This point presents quite a contrast to the effects of NC machine tools as will be discussed later.

These observations are well compatible with labor substitutability data surveyed by JIRA [JIRA, 1984] through interviews and questionnaires. We can also observe that the labor substitutability of industrial robots in the light industry is high. It may be noteworthy that the share of high-level industrial robots in these industries is high. (For example, the shipment share of play-back robots in the food industry is more than 50% in 1984.)

2. Benefits of NC machine tools in five industries

In this section, the effects of NC machine tools are estimated by industry sector according to the method described in the previous section. The production function to be identified is equation (27) in Section II, namely

$$Y(K,F,N) = \beta \cdot e^{ct} (N^b + B \cdot Q^b)^{(1/b)} \qquad (27)$$

where

$$Q = (K+N)^{\alpha} F^{(1-\alpha)}. \qquad (28)$$

The next step is to disaggregate the shipments of NC machine tools into manufacturing industry sectors. As is also mentioned in the previous section, the distribution of NC machine tools shipments among industry sectors and exports are available only for 1983 [MITI, 1985], as shown in Figures 8 and 9, where only five manufacturing industry sectors are specified. Therefore, we will hereafter focus on these five industry sectors, i.e. L. fabricated metal products industry, M. general machinery industry, N. electric and electronics machine industry, O. transportation machine industry and P. precision machine industry. The contribution of NC machine tools might be especially large in these sectors. Assuming the distribution of Figure 8 to be identical throughout the period, stock data on NC machine tools can be estimated. The useful life of NC machine tools is assumed to be eleven years as is described in the previous section. Here, the contribution of leases included in the non-manufacturing sector is ignored since no information concerning this point is available.

The estimated capital stock of NC machine tools are exhibited in Table 16. Following the procedure described in Section II, we can now estimate the parameters of (28) and (29). The estimated d's of equation (29) are exhibited in Table 17.

Next, parameters b and B in equation (27) are estimated. They are summarized in Table 18.

One can now compare the above results with those in Table 12. It is evident that

$$F(X,Y) = (X^a + A \cdot Y^a)^{(1/a)} \qquad (59)$$

is an increasing function of A. Therefore A briefly represents the degree of marginal effect of investment Y.

In Table 12 one can observe that B is largest for sector N, electric machinery industry, while its B value in Table 18 is the smallest. This is a strong contrast to the case of sector L, fabricated metal products industry, and sector M, general machinery industry. In other words, the benefits of NC machine tools are not as high as those of industrial robots in the case of the electric machinery industry as compared with other machinery industries. This tendency appears more clearly when we compare the benefits of NC machine tools with those of industrial robots, as discussed later.

Finally, the exogeneous technological progress rate c and constant term H are obtained. They are shown in Table 19. Here the computed technological progress rate of the fabricated metal products industry and transportation machinery industry is not statistically significant, while that of the electric and electronics machinery industry is quite high. The reason might be that the products of this industry have changed enormously in the

Table 16

Stock of NC Machine Tools (N) by Industry Sector in 1980 billion yen

year	whole manufac-turing	fabricated metal products	general machinery	electric machinery	trans-portation machinery	precision machinery
1970	17.2174	.910062	7.84621	1.50037	2.80398	.713292
1971	33.4249	1.76674	15.2322	2.91274	5.44348	1.38474
1972	48.1948	2.54744	21.963	4.19983	7.84886	1.99664
1973	79.0751	4.17969	36.0357	6.89083	12.878	3.27597
1974	112.358	5.93895	51.2033	9.79124	18.2984	4.65485
1975	135.082	7.14005	61.5589	11.7714	21.9991	5.59626
1976	168.976	8.93159	77.0048	14.7251	27.5189	7.00043
1977	226.236	11.9582	103.099	19.7149	36.8442	9.37265
1978	303.133	16.0227	138.142	26.4158	49.3673	12.5584
1979	453.739	23.9834	206.775	39.5401	73.8947	18.7978
1980	678.437	35.8603	309.174	59.121	110.488	28.1067
1981	951.265	50.2811	433.505	82.8959	154.92	39.4095
1982	1211.05	64.0125	551.892	105.534	197.228	50.172
1983	1511.94	79.9168	689.012	131.755	246.23	62.6375
1984	1940.75	102.583	884.428	169.123	316.065	80.4026

Table 17

Estimated Parameter α of Production Function (28) by Industry Sectors

industry sector	α	standard deviation
A. whole manufactuing	.610	.0233
L. fabricated metal products	.557	.0296
M. general machinery	.549	.0321
N. electric machine	.624	.0372
O. transportation machine	.577	.0257
P. precision machine	.512	.0199

Table 18

Estimated Parameters b and B of (27)

industry sector	b	(t.V)	B	(t.V)	$\bar{R}^2$	D.W
A.whole manufactuing	.702	(19.2)	.0764	13.1	.963	.909
L.fabricated metal products	.904	(39.6)	.510	5.44	.991	1.53
M.general machinery	.832	(35.6)	.295	14.2	.989	1.36
N.electric machinery	.579	(9.42)	.0336	10.3	.862	.915
O.transportation machinery	.633	(17.2)	.0474	17.3	.955	.888
P.precision machinery	.809	(26.6)	.156	14.3	.981	.952

(t.V): t-statistics

Table 19

Estimated Parameters; technological progress rate c and constant term β

industry sector	c	(t.V)	β	(t.V)	$\bar{R}^2$	D.W
A.whole manufactuing	.0228	(18.2)	1.170	(15.3)	.959	1.72
L.fabricated metal products	-.0071	(2.13)	1.408	(12.5)	.202	1.63
M.general machinery	.0246	(6.02)	1.494	(11.9)	.716	1.28
N.electric machinery	.1428	(15.3)	.388	(12.3)	.943	.952
O.transportation machinery	.0068	(1.33)	1.749	(13.3)	.052	.943
P.precision machinery	.0528	(6.08)	1.093	(1.24)	.720	1.09

(t.V): t-statistics

past fifteen years, while those of other industries have not changed so much.

The gross and the net benefits and the benefit rates are exhibited in APPENDIX-4 in 1980 prices. Their behavior is exhibited in Figure 14. The benefit rates in the fabricated metal products industry and the general machinery industry are much higher than the others. This point may be qualitatively understandable. Let us compare the benefit of NC machine tools shown in APPENDIX-4 with that of industrial robots in APPENDIX-3. As is shown in Table 20, the social benefits of industrial robots and NC machine tools show rather different properties among industries. This point can be interpreted as the difference of process type distribution among industries. According to JIRA [1985], for example, in the electric and electronics machinery industry the share of the assembly process in the total process steps is 26.2%, while that of the fabricated metal products industry is 11.8%. The reasons for this difference should be discussed further from an engineering point of view.

Table 20

Effect of Industrial Robots and NC Machine Tools

		Benefit of NC machine tools		
		high	middle	low
effect of industrial robot	high	fabricated metal		electric machinery
	middle			transportation machinery
(workers per I.R)	low	general machinery	precision machinery	

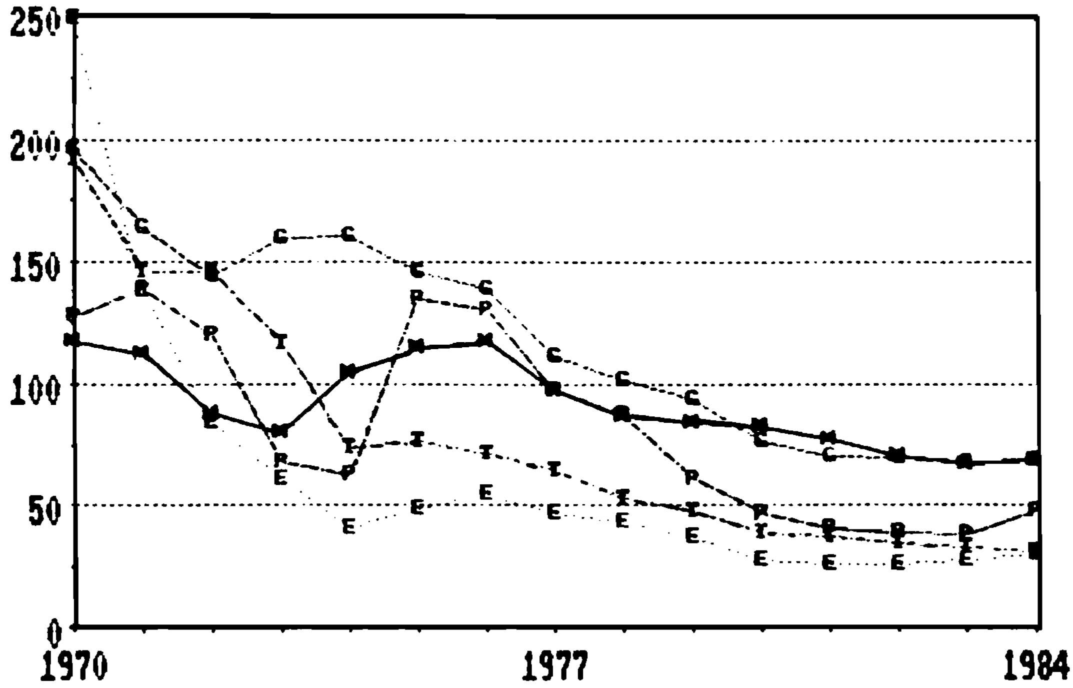


Figure.14 Net Benefit Rates of NC Machine Tools by Industry
M:fabricated metal products G:general machinery
E:electric machinery T:transportation machinery
P:precision machinery

IV. CONCLUSIONS

As is mentioned several times in this paper, basic statistics on CIM systems are not yet well established. This problem occurs especially when we want to discuss their social and economic impacts. Therefore we are obliged to impose many arbitrary assumptions. In this sense, the investigation of CIM benfits is still in its beginning stage.

Nonetheless it must be emphasized that the impacts of CIM systems are quite complex and should be studied not only from an engineering point of view, but also from their economic and sociological aspects.

There are two directions one might take in further investigations: One is to extend towards international comparison and then to discuss the interactions of CIM systems from an economic point of view. Another is to clarify the reasons for the patterns observed and use the results to assess future trends.

Since the results described in this paper are concerned with the national economic level but are compatible with factory level survey data, it may be concluded that the methods proposed here can be regarded as a useful step towards more interdisciplinary investigations.

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APPENDIX-1

Notation of Variables

variable	definition
Y	output in real prices (theoretical)
V	output in real prices (actual)
L	number of workers
K	capital stock of conventional equipment (in 1980 billion yen)
R	capital stock of industrial robots (in 1980 billion yen)
N	capital stock of NC machine tools (in 1980 billion yen)
U	population of industrial robots (in numbers)
F	augmented labor force (in persons)
M	labor force cost constraint in current prices
P_L	annual wage in current prices
P_I	price index of industrial robots (NC machine tools)
P_R	rate of fixed cost to the capital stock on industrial robots
P_F	average price of equivalent labor force; $P_F=(P_L L+P_R R)/F$
q_N	rate of fixed cost to the capital stock on NC machine tools
q_K	rate of fixed cost to the capital stock on conventional capital
P_N	price of capital services of NC machine tools as fraction of nominal value added
P_K	price of capital services on conventional capital stock as fraction of nominal value added
P_Y	output deflator
L_R	labor force augmentation; $L_R=F-L$
B_R	benefits of industrial robots; $B_R=(P_L-P_F)F$
r	expense rate of industrial robots (NC machine tools)
c	exogeneous annual technical progress rate
G	productivity improvement coefficient on NC machine tools
Q	subproduction function in terms of conventional inputs
d	depreciation of capital stock in current prices
X	tax payment in current prices
u	capacity utilization index
G_N	gross benefits of NC machine tools; $G_N=P_Y\{Y(K,F,N)-Y(K+N,F,0)\}$
N_N	net benefits of NC machine tools ; $N_N=G_N-(q_N-q_K)N$
a	parameter of labor augmentation subproduction function
A	parameter of labor augmentation subproduction function
b	parameter of production function Y
B	parameter of productionn function Y
c	exogeneous technical progress rate
α	parameter of subproduction function Q
H	parameter of subproduction function Q

APPENDIX-2

Comparison with an Alternative Capital Augmentation Model

An alternative model to evaluate the capital augmentation effect of NC machine tools might be the following.

$$K' = (K^m + M \cdot N^m)^{(1/m)} \qquad (A.1)$$

where m should be positive. The equilibrium condition yields the well known equation

$$(P_N/P_K) = M \cdot (N/K)^{m-1}. \qquad (A.2)$$

The estimated results are

A: low case (r=25%)

$$\log (P_N/P_K) = - .134 \cdot \log (N/K) + .0960 \qquad (A.3)$$
$$(5.28) \qquad\qquad (.603)$$

$R^2 = .682$ $\bar{R}^2 = .657$

D.W = .921

hence

$$m = .866 \qquad (A.4)$$

and

$$M = 1.10 \quad . \qquad (A.5)$$

B: high case (r=33%)

$$\log (P_N/P_K) = - .133 \cdot \log (N/K) + .396 \qquad (A.6)$$
$$(5.22) \qquad\qquad (2.49)$$

$R^2 = .677$ $\bar{R}^2 = .652$

D.W = .922

hence

$$m = .867 \qquad (A.7)$$

and

$$M = 1.486 \; . \qquad (A.8)$$

One can observe that the explanatory powers R^2 of this model are quite a bit lower than those of the model described in Section 2, equations (42) and (45), where we obtained

A: low case (r=25%)

$$\log J = \underset{(19.2)}{.702} \cdot \log (N/Q) - \underset{(13.1)}{2.572} \qquad (42)$$

$R^2 = .966$ $\bar{R}^2 = .963$
D.W = .909

and

B: high case (r=33%)

$$\log J = \underset{(23.5)}{.735} \cdot \log (N/Q) - \underset{(11.5)}{1.946} \qquad (45)$$

$R^2 = .977$ $\bar{R}^2 = .975$

D.W = .913

APPENDIX=3

Stock of Industrial Robots, Labor Force Augmentation, Benefits, and Ratio of Benefit to Industrial Robot Stock by Industrial Sector (I.R denotes industrial robots)

A. Whole manufacturing industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1970	6.61204	5.89941	2.94971	2.92206	44.1900%
1971	15.25860	9.76563	3.05176	7.26873	47.6300%
1972	23.90510	12.82320	2.98215	4.38389	18.3300%
1973	36.62050	16.72660	2.26035	6.71132	18.3200%
1974	64.57570	23.24710	2.00406	22.55750	34.9300%
1975	90.35630	28.29000	1.76813	23.25730	25.7300%
1976	131.25600	35.34470	1.52348	45.24180	34.4600%
1977	184.66900	43.04790	1.45432	54.96570	29.7600%
1978	246.84600	51.34860	1.34421	55.61610	22.5300%
1979	357.03000	64.25200	1.25004	69.68190	19.5100%
1980	544.52900	83.35450	1.24410	76.09570	13.9700%
1981	771.12200	104.11300	1.24240	89.44830	11.5900%
1982	1102.55000	129.09000	1.26932	114.28400	10.3600%
1983	1523.16000	158.23800	1.30992	139.26300	9.1430%
1984	2158.17000	196.81000	1.34986	181.29300	8.4000%

B. Food, beverage and tobacco industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.03543	9.15527		0.00128	3.6180%
1975	0.06587	15.13670		0.00041	0.6287%
1976	0.06587	15.13670		0.01125	17.0800%
1977	0.60490	95.82520		0.04077	6.7400%
1978	1.00730	146.48400	10.46320	0.02627	2.6070%
1979	1.02168	149.04800	9.93650	0.04448	4.3530%
1980	1.07268	154.41900	8.57883	0.04595	4.2840%
1981	1.24829	177.12400	7.08496	0.06423	5.1450%
1982	2.65301	330.68800	3.21057	0.12207	4.6010%
1983	6.01918	655.39600	2.92588	0.21606	3.5890%
1984	9.86284	989.38000	2.25886	0.40786	4.1350%

C. Textile industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.25690	91.06450		0.01974	7.6820%
1975	0.50037	154.05300		0.01759	3.5150%
1976	1.22004	311.15700		0.15404	12.6200%
1977	1.75907	410.88900		0.19269	10.9500%
1978	2.03770	461.79200	30.78610	0.18320	8.9900%
1979	6.12026	1099.98000	3.26402	0.30203	4.9340%
1980	8.09121	1363.04000	3.22231	0.26055	3.2200%
1981	14.57950	2178.83000	3.99786	0.26910	1.8450%
1982	15.02360	2225.71000	3.94629	0.66955	4.4560%
1983	15.72540	2302.37000	3.60308	0.97832	6.2210%
1984	15.61580	2276.00000	3.33725	1.28894	8.2540%

D. Wood and wood products industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.25690	60.42480		-0.00168	-0.6541%
1975	0.25690	59.63140		-0.00539	-2.0990%
1976	0.25690	59.50930		0.03736	14.5400%
1977	0.25690	58.59380		0.04228	16.4500%
1978	0.26085	59.69240	59.69240	0.03972	15.2200%
1979	0.33067	70.37350	14.07470	0.05656	17.1000%
1980	1.05067	164.73400	7.48791	0.06771	6.4440%
1981	1.04469	161.37700	4.48269	0.08026	7.6820%
1982	1.52400	211.30400	3.52173	0.12285	8.0600%
1983	2.34864	288.02500	3.13071	0.16350	6.9610%
1984	3.67925	394.47000	3.01122	0.22924	6.2300%

E. Paper and pulp industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974					
1975	0.04565	8.91113		0.00111	2.4270%
1976	0.14596	21.57590		0.01278	8.7530%
1977	0.14596	21.33180		0.01539	10.5400%
1978	0.14596	21.42330	21.42330	0.01291	8.8410%
1979	0.17294	24.47510	8.15837	0.01893	10.9400%
1980	0.18654	25.54320	6.38580	0.01904	10.2000%
1981	0.19699	26.33670	5.26733	0.02179	11.0600%
1982	0.55308	57.67820	1.15356	0.04090	7.3940%
1983	0.95907	86.85300	1.31596	0.05933	6.1850%
1984	2.60112	184.14300	1.26125	0.09054	3.4800%

F. Chemical products industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	3.15361	612.79300		0.51136	16.2100%
1975	6.34927	1029.63000		0.34738	5.4710%
1976	13.37400	1780.49000		1.85470	13.8600%
1977	21.29970	2499.08000		2.58435	12.1300%
1978	30.41610	3232.42000	1.22673	2.16535	7.1190%
1979	44.63080	4295.26000	0.67461	3.56587	7.9890%
1980	76.25050	6411.93000	0.46056	3.48258	4.5670%
1981	97.69680	7709.53000	0.36328	4.43563	4.5400%
1982	120.13900	8989.17000	0.32376	8.53932	7.1070%
1983	151.37900	10668.70000	0.29188	12.07190	7.9740%
1984	190.35700	12641.40000	0.28065	17.74870	9.3230%

G. Petroleum and coal industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.50985	153.06100		0.26599	52.1700%
1975	1.27749	232.54800		0.21287	16.6600%
1976	1.85067	270.72100		0.41738	22.5500%
1977	1.85067	267.39500		0.46088	24.9000%
1978	1.87021	268.68100	20.66770	0.46828	25.0300%
1979	1.89861	267.11300	8.90376	0.54072	28.4700%
1980	2.60510	307.24300	1.98222	0.55535	21.3100%
1981	2.09524	279.00700	1.80005	0.63658	30.3800%
1982	1.47981	236.19100	1.32691	0.66625	45.0200%
1983	1.36345	224.77700	1.13524	0.70060	51.3800%
1984	2.16136	270.27900	1.12149	0.84900	39.2800%

H. Rubber industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974					
1975	0.03043	4.56238		-0.00253	-8.3230%
1976	0.03043	4.53186		0.00259	8.5200%
1977	0.03043	4.63867		0.00367	12.0500%
1978	0.08068	10.36070	1.15119	0.00356	4.4080%
1979	0.11687	14.14490	1.08807	0.00684	5.8480%
1980	0.15051	17.59340	1.09959	0.00738	4.9030%
1981	0.26799	28.82390	1.60133	0.01225	4.5720%
1982	0.75537	69.24440	1.33162	0.02637	3.4910%
1983	2.09831	165.32900	1.42525	0.05447	2.5960%
1984	3.26579	240.73800	1.19770	0.12383	3.7910%

I. Cement, clay and glass industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.32186	71.59420		1.9545E-02	6.0720%
1975	0.35229	75.74460		0.01225	3.4770%
1976	0.51151	98.81590		8.0986E-02	15.8300%
1977	0.66873	120.08700		0.10716	16.0200%
1978	0.84354	142.54800	7.91931	0.09973	11.8200%
1979	1.09622	172.54600	3.13721	0.13666	12.4600%
1980	2.39412	307.03700	2.07458	0.15633	6.5290%
1981	3.10093	371.39900	1.76018	0.21228	6.8450%
1982	4.36208	473.87700	1.61183	0.32770	7.5120%
1983	6.47826	631.16500	1.52088	0.44317	6.8400%
1984	11.68020	971.34400	1.43055	0.65074	5.5710%

J. Iron and steel industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.96754	198.18100		0.25780	26.6400%
1975	6.15161	752.68600		-0.07869	-1.2790%
1976	8.68825	952.02600		0.91121	10.4800%
1977	12.73100	1248.84000		1.25205	9.8340%
1978	14.83580	1379.55000	21.89760	0.83119	5.6020%
1979	19.27710	1657.81000	13.70090	1.24521	6.4590%
1980	21.72570	1802.40000	7.01323	1.40562	6.4690%
1981	25.42120	2011.41000	4.84678	1.86809	7.3480%
1982	25.45330	2006.96000	3.15559	2.73075	10.7200%
1983	29.74750	2232.79000	2.47812	3.27332	11.0000%
1984	29.04350	2174.77000	2.03250	3.95969	13.6300%

K. Non-ferrous metal industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	1.08270	217.52900		-0.04209	-3.8870%
1975	2.18512	368.56100		0.08197	3.7510%
1976	3.13406	483.62700		0.54718	17.4500%
1977	4.31194	615.31100		0.73714	17.0900%
1978	5.87755	772.36900	1.65745	0.74448	12.6600%
1979	8.76855	1052.26000	1.26322	1.11067	12.6600%
1980	17.17510	1763.38000	1.25597	1.30828	7.6170%
1981	63.58720	4852.72000	2.49113	0.58683	0.9228%
1982	67.73600	5045.41000	2.22952	2.34771	3.4650%
1983	74.15920	5410.90000	2.05347	3.99301	5.3840%
1984	83.88680	5982.76000	1.81131	6.38477	7.6110%

L. Fabricated metal product industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	1.45574	351.92900		0.14798	10.1600%
1975	2.23606	486.20600		0.11118	4.9720%
1976	4.93639	891.17400		0.65649	13.2900%
1977	7.58413	1231.69000		0.98164	12.9400%
1978	13.84090	1968.57000	5.19411	1.00012	7.2250%
1979	23.31360	2945.50000	3.31327	1.49150	6.3970%
1980	33.33850	3883.00000	2.44830	1.32372	3.9700%
1981	44.03100	4841.49000	1.99979	2.10238	4.7740%
1982	60.36450	6165.53000	1.87004	3.42427	5.6720%
1983	83.89290	7971.92000	1.72217	4.99002	5.9480%
1984	108.71400	9731.26000	1.65808	7.92874	7.2930%

M. General machinery industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	1.14312	250.61000		0.17402	15.2200%
1975	2.32246	427.12400		0.09668	4.1620%
1976	6.31325	916.50400		0.78297	12.4000%
1977	12.86600	1577.39000		1.25450	9.7500%
1978	16.82280	1937.93000	3.62908	0.93887	5.5800%
1979	22.41850	2424.13000	1.97566	1.66631	7.4320%
1980	35.12600	3441.04000	1.00351	1.96343	5.5890%
1981	57.77110	5085.21000	0.82606	2.80951	4.8630%
1982	82.29270	6680.42000	0.81948	4.85858	5.9040%
1983	108.25800	8309.20000	0.84589	6.55823	6.0570%
1984	149.80900	10702.50000	0.90036	10.77820	7.1940%

N. Electric and electronics machinery industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	2.96758	766.23500		0.22898	7.7160%
1975	6.32641	1380.49000		0.10396	1.6430%
1976	12.52950	2398.32000		1.78427	14.2400%
1977	23.38250	3899.17000		2.79061	11.9300%
1978	37.83860	5711.43000	1.90254	2.84712	7.5240%
1979	55.82540	7814.21000	1.02147	4.27788	7.6620%
1980	124.19700	14927.70000	1.49922	4.29237	3.4560%
1981	198.51800	22053.30000	1.61622	6.23948	3.1430%
1982	299.84700	30695.90000	1.67664	13.71710	4.5740%
1983	450.63100	43151.20000	1.72750	24.49400	5.4350%
1984	732.41300	64623.10000	1.82227	46.29890	6.3210%

O. Transportation machinery industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	7.57287	1456.73000		0.79792	10.5300%
1975	10.87470	1918.52000		0.65613	6.0330%
1976	26.86980	3838.13000		4.00459	14.9000%
1977	53.90460	6537.05000		6.42674	11.9200%
1978	80.04640	8795.04000	6.68825	5.07037	6.3340%
1979	124.63100	12309.60000	3.44613	7.51916	6.0330%
1980	177.07700	16259.20000	2.24451	8.51625	4.8090%
1981	245.49300	21102.20000	1.85775	12.47960	5.0830%
1982	364.36000	28532.80000	1.70691	20.64950	5.6670%
1983	472.71700	34791.30000	1.60922	29.33930	6.2060%
1984	625.09700	43224.20000	1.55064	47.43020	7.5870%

P. Precision machinery industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	2.12938	509.61300		0.17546	8.2400%
1975	2.66582	585.86100		0.10714	4.0190%
1976	3.42416	708.93900		0.65241	19.0500%
1977	5.43301	992.50800		0.91420	16.8200%
1978	7.88544	1304.93000	4.32000	0.92324	11.7000%
1979	11.00040	1665.50000	1.56400	1.31798	11.9800%
1980	16.92760	2305.54000	1.42900	1.46592	8.6590%
1981	24.68910	3047.27000	1.33800	1.85131	7.4980%
1982	35.99590	3947.88000	1.26400	2.53089	7.0310%
1983	50.91610	5090.03000	1.22300	3.70633	7.2790%
1984	76.04870	6864.90000	1.13500	5.37573	7.0680%

Q. Other manufactring industry

year	R stock of I.R in 1980 billion yen	L_R labor force augmentation by I.R	E_R equivalent workers per I.R	B_R benefits of I.R in 1980 billion yen	R_R rate of return of I.R stock
1974	0.28347	48.95020		0.10149	35.8000%
1975	0.73588	108.64300		-0.06868	-9.3330%
1976	1.54152	199.82900		0.05447	3.5330%
1977	2.27021	275.87900		0.09852	4.3390%
1978	2.46682	297.11900	21.22280	0.05780	2.3430%
1979	3.09339	359.13100	4.98793	0.13183	4.2610%
1980	4.74288	512.45100	2.31878	0.13760	2.9010%
1981	6.09790	636.71900	1.71161	0.23844	3.9100%
1982	10.04940	964.11100	1.46745	0.49522	4.9270%
1983	14.57690	1323.00000	1.43329	0.86425	5.9280%
1984	19.53350	1692.38000	1.33573	1.48217	7.5870%

APPENDIX-4

Gross and Net Benefits of NC Machine Tools by Industry

A. Whole manufacturing industry

year	V value added in 1980 billion yen	G_N gross benefits of NC mach. in 1980 billion yen	N_N net benefits of NC mach. in 1980 billion yen	G_N/N gross rate of return of NC mach. stock in %	N_N/N gross rate of return of NC mach. stock in %
1970	39572.6	26.3426	20.8711	153.0000	121.2210
1971	41769.1	40.8017	29.2189	122.0700	87.4166
1972	45751.1	53.7160	36.2904	111.4560	75.2994
1973	52012.9	80.7800	58.8337	102.1560	74.4023
1974	51903.6	106.8060	74.5937	95.0579	66.3891
1975	48744.4	117.2490	81.1421	86.7983	60.0687
1976	53644.4	140.2260	106.6380	82.9856	63.1083
1977	56576.6	171.1050	135.3680	75.6311	59.8347
1978	60389.7	212.0780	168.4430	69.9622	55.5675
1979	64452.7	301.8980	243.6260	66.5355	53.6930
1980	70232.3	408.7090	318.3800	60.2426	46.9284
1981	73415.6	527.0350	392.9150	55.4036	41.3045
1982	77653.4	627.8910	456.7870	51.8470	37.7183
1983	83871.5	728.3740	560.2190	48.1748	37.0530
1984	93567.5	894.0190	699.2130	46.0656	36.0279

L. Fabricated metal products industry

year	V value added in 1980 billion yen	G_N gross benefits of NC mach. in 1980 billion yen	N_N net benefits of NC mach. in 1980 billion yen	G_N/N gross rate of return of NC mach. stock in %	N_N/N gross rate of return of NC mach. stock in %
1970	2596.9	1.4106	1.0647	155.0050	116.9960
1971	2618.7	2.6864	1.9730	152.0540	111.6720
1972	2977.7	3.3123	2.2347	130.0260	87.7230
1973	3762.4	4.6984	3.3209	112.4110	79.4544
1974	3105.0	8.0398	6.1666	135.3750	103.8320
1975	2352.0	10.3989	8.1940	145.6420	114.7610
1976	2426.2	12.6750	10.4696	141.9130	117.2200
1977	2729.2	13.9639	11.6274	116.7720	97.2336
1978	3064.2	16.7775	13.9229	104.7100	86.8948
1979	3256.9	24.1335	20.1054	100.6260	83.8305
1980	3272.7	35.8390	29.5261	99.9407	82.3366
1981	3469.5	48.0591	38.6957	95.5808	76.9587
1982	3718.6	57.1244	44.9121	89.2393	70.1615
1983	3861.6	66.6265	53.3832	83.3698	66.7984
1984	3911.6	85.8777	69.9597	83.7157	68.1984

M. General machinery industry

year	V value added in 1980 billion yen	G_N gross benefits of NC mach. in 1980 billion yen	N_N net benefits of NC mach. in 1980 billion yen	G_N/N gross rate of return of NC mach. stock in %	N_N/N gross rate of return of NC mach. stock in %
1970	3732.9	18.1920	15.4129	231.8580	196.4370
1971	3893.3	30.7214	24.9427	201.6880	163.7500
1972	3834.9	40.4740	31.6284	184.2820	144.0070
1973	4014.4	68.8626	57.6398	191.0960	159.9520
1974	4235.5	97.5675	82.0416	190.5490	160.2270
1975	3942.4	107.8170	90.0059	175.1450	146.2110
1976	4339.1	124.3350	107.0240	161.4650	138.9840
1977	4887.5	132.6280	114.6860	128.6420	111.2390
1978	5145.1	162.1080	140.4220	117.3490	101.6510
1979	5934.3	224.5610	194.2590	108.6010	93.9469
1980	7507.4	284.5730	236.4950	92.0431	76.4926
1981	8357.2	377.3390	306.5030	87.0437	70.7035
1982	8842.2	475.5850	384.1080	86.1736	69.5985
1983	9087.9	561.6360	464.3710	81.5132	67.3966
1984	10156.7	720.9380	604.6810	81.5146	68.3697

N. Electric and electronics machinery industry

year	V value added in 1980 billion yen	G_N gross benefits of NC mach. in 1980 billion yen	N_N net benefits of NC mach. in 1980 billion yen	G_N/N gross rate of return of NC mach. stock in %	N_N/N gross rate of return of NC mach. stock in %
1970	757.4	4.1642	3.7411	277.5470	249.3430
1971	980.1	4.9232	4.0264	169.0230	138.2340
1972	1623.7	4.8604	3.5412	115.7290	84.3170
1973	2314.8	5.8216	4.1940	84.4829	60.8627
1974	2733.5	6.3426	3.9787	64.7779	40.6351
1975	2179.7	8.5066	5.7192	72.2647	48.5855
1976	2872.3	10.5715	8.0677	71.7927	54.7888
1977	3561.7	11.5905	9.2753	58.7904	47.0469
1978	4185.2	14.2255	11.5760	53.8522	43.8223
1979	5502.9	18.1247	14.7590	45.8388	37.3265
1980	7663.2	22.0827	16.5024	37.3517	27.9129
1981	9033.1	30.0595	21.5533	36.2617	26.0004
1982	10686.5	37.9338	27.7349	35.9446	26.2805
1983	14423.4	43.8423	36.0935	33.2757	27.3945
1984	19358.3	59.6163	51.5301	35.2503	30.4691

[illegible]. Transportation machinery industry

year	V value added in 1980 billion yen	G_N gross benefits of NC mach. in 1980 billion yen	N_N net benefits of NC mach. in 1980 billion yen	G_N/N gross rate of return of NC mach. stock in %	N_N/N gross rate of return of NC mach. stock in %
1970	4291.6	6.2629	5.3813	223.3590	191.9180
1971	4220.3	9.7786	7.9258	179.6390	145.6020
1972	4262.7	14.2469	11.4598	181.5160	146.0060
1973	5115.0	18.5508	15.0224	144.0510	116.6520
1974	6156.1	18.4972	13.5110	101.0860	73.8370
1975	5721.8	22.2438	16.7418	101.1120	76.1023
1976	6747.6	24.9710	19.5788	90.7412	71.1468
1977	6940.3	29.2084	23.8262	79.2755	64.6674
1978	6898.3	32.3818	26.2013	65.5936	53.0742
1979	6989.9	43.3221	35.2397	58.6268	47.6891
1980	7962.2	54.8933	42.7853	49.6824	38.7238
1981	8201.2	75.4050	57.1960	48.6734	36.9196
1982	8050.8	92.1340	68.8088	46.7145	34.8880
1983	9013.9	102.0840	80.7178	41.4588	32.7814
1984	9792.0	123.0510	98.9960	38.9321	31.3214

F. Precision machinery industry

year	V value added in 1980 billion yen	G_N gross benefits of NC mach. in 1980 billion yen	N_N net benefits of NC mach. in 1980 billion yen	G_N/N gross rate of return of NC mach. stock in %	N_N/N gross rate of return of NC mach. stock in %
1970	366.3	1.0882	0.9075	152.5550	127.2210
1971	377.6	2.0914	1.9211	151.0290	138.7300
1972	403.9	2.7503	2.3914	137.7470	119.7720
1973	668.0	3.1818	2.2308	97.1245	68.0963
1974	842.1	4.0058	2.8976	86.0560	62.2491
1975	548.3	6.5509	7.5143	117.0590	134.2730
1976	623.9	7.7404	9.1304	110.5700	130.4260
1977	818.6	8.3877	9.1160	89.4914	97.2612
1978	915.1	10.2811	11.0245	81.8664	87.7864
1979	1123.8	12.7061	11.3958	67.5937	60.6233
1980	1433.1	16.7030	13.1752	59.4273	46.8757
1981	1592.4	22.2301	16.0749	56.4080	40.7894
1982	1620.0	28.3130	19.6772	56.4319	39.2194
1983	1853.5	34.3593	23.7614	54.8543	37.9349
1984	1983.2	48.6084	38.2225	60.4563	47.5389