Trends in the substitution of production factors to technology – empirical analysis of the inducing impact of the energy crisis on Japanese industrial technology *

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Japan successfully overcame the energy crises of 1973 and 1979, maintaining productivity in the face of drastically increased energy prices, despite the fragile nature of its energy structure. This was due to technological innovation efforts that led to rapid improvement in Japan's industrial technology as a whole.

This paper tries to prove this hypothesis on the basis of an examination of the trends in the substitution of production factors by technology as represented by R&D investment efforts.

Since the first energy crisis in 1973, there have been a number of attempts to identify the possibility of substitutability of energy by other production factors, but none have been successful in taking technology into account.

This paper tackles this subject on the basis of the measurement of the technological knowledge stock and en empirical analysis using a translog cost function incorporating this stock, and shows that over the last two decades all production factors have been substituted by technology in Japan's manufacturing industry or have been moving towards that direction.

1. Introduction

Japan's relatively stable economic growth since the 1970s despite the damaging impact of the energy crises has surprised the world. This paper aims to show that Japan's success owes much to the innovation efforts in reducing energy consumption in production. For this purpose, this paper examines the trends in the substitution of production factors (labor, capital, materials, and energy) to technology (namely, accumulated R&D investment) in the Japanese manufacturing industry over the last two decades, and shows that this substitution is a response to the drastic increase in energy prices after the energy crises.

There have been a number of studies to identify the substitutability of energy by other production factors (see table 1). None, however, have taken technology into account as another production factor. An exception is Jorgenson et al. [23], who used a dummy variable indicating the state of technology. This methodology, however, is hardly satisfactory for analyzing the impact of R&D investment fully.

In this paper, I measure technological knowledge stock and incorporate it into the production function. Although a number of similar efforts have been made in the past (see table 2), they all suffer from two shortcomings. One is the duplication between technological knowledge stock and other production factors, such as R&D personnel included in labor input, and R&D equipment included in capital input (see Griliches [16]). The other is that the data on time lag and lifetime of technology used in these studies to compute technology stock are not based on careful examina-

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tion. To remedy these shortcomings, I use the results of a questionnaire sent to leading Japanese firms [18].

Thus, the objective is threefold; first, to measure technology stock as accurately as possible; second, to estimate a translog cost function incorporating technology stock as one of the factors; and third, to analyze the substitution among production factors based on the estimation results. The structure of the paper is as follows: section 2

Table 1
Major works on measuring substitution among factors in Japanese economy

	Period	Subjects	Substitute	Complement
1. Itoh & Masui [27]	1960–75	Industries	E–L K–L	E–K
2. Economic Planning Agency [8]	1965–83	National level	E–L K–L E–K (1980s)	 E–K (1960s and 1970s)
3. NIRA (Century Research Inst.) [31]	1960–83	Chemicals industry	E–K	E–L K–L E–M
		Iron & steel industry	E–L E–M K–L	E–K
		Pulp & paper industry	E–K K–L	E–L (E–M) (independent)
		Ceramics industry	E–K K–L	E–L E–M
		Automobile industry	E–K	E–L (E–M) (independent) K–L
		Electrical machinery industry	E–K E–M	E–L K–L
4. Economic Planning Agency [8]	1965–87	National level	E–L K–L	E–K
5. Kuroda [24]	1960–79	Chemicals, pulp & paper, automobile, and electrical machinery industries	E–K E–L E–M K–L	
		Iron & steel industry	E–L E–M K–L	E–K
		Ceramics industry	E–K E–M K–L	E–L
		General machinery industry	E–K E–L E–M	K–L

[a] E: Energy, L: Labor, K: Capital, M: Materials.
[b] Substitute: The elasticity is positive. Complement: The elasticity is negative. Independent: The absolute value of the elasticity is less than 0.1.
[c] The studies outside Japan refer to Jorgenson [22], US Department of Energy [36] and others.

explains the methodology; section 3, the model synthesis; section 4, the empirical results; section 5, the implications; and section 6, the conclusion.

2. Method of analysis

2.1. General concept

In order to identify trends in the substitution of production factors to technology, I assume that there exists in the Japanese manufacturing industry a twice differentiable aggregate production function which relates the flow of output Y to the services of five inputs: labor (L), capital (K), materials (M), energy (E) and technology (T); where technology is "endogenous" technological improvement efforts [1] and materials are all other intermediate inputs except energy. On the basis of this function, I have tried to analyze the trends of the changes in the combination of production factors due to the relative price changes among these factors: elasticity of substitution among production factors. The focus of the analysis is to measure how other production factors substitute for *technology* arising from the relative price changes among production factors due to drastic changes in *energy prices* after the energy crises.

2.2. Measurement of technological knowledge stock

In this analysis, determining how to measure "endogenous" technological improvement efforts is essential. I assumed that the trends in technological knowledge stock [2] represented these efforts and I tried to measure this stock using a thorough and consistent approach that avoided duplications with other factors.

In line with the previous approaches [3], I have measured the trends in technological knowledge stock in the Japanese manufacturing industry between 1970 and 1987 on the basis of the following equations:

$$RSTK_t = RDE_{t-m} + (1-\rho) RSTK_{t-1} \tag{1}$$

$$RSTK_0 = RDE_{1-m}/(g+\rho) \tag{2}$$

where $RSTK_t$ is technological knowledge stock in the period t; $RSTK_0$ is technological knowledge stock in the initial period; RDE_t is R&D expenditure in the period t; m is time lag of R&D to commercialization; ρ is rate of obsolescence of technology; and g is increasing rate of RDE in the initial period.

In order to measure technological knowledge stock, it is essential to estimate the reliable up-to-date time lag and rate of obsolescence data. However, as many previous surveys pointed out, there has been no reliable up-to-date survey estimating these factors. [4] Therefore, with the support of AIST, MITI, we prepared a questionnaire for major Japanese firms in April 1990 which included questions related to the time lag of R&D to commercialization and also the lifetime of technology [18]. [5] We received approximately 500 responses (including those from non-manufacturing industries: the received response ratio was approximately 70 percent). Out of the responses, we obtained 360 valid samples for time lag and also 276 for technology lifetime (both for manufacturing industry) as illustrated in tables 3 and 4. Both samples are well-balanced for sectors and stages of technologies (see tables 3 and 4). Therefore, I have estimated the time lag and the technology lifetime in the Japanese manufacturing industry over the 1970s and the 1980s by taking the averages of the valid samples. The average time lags of R&D to commercialization

[1] In this case, "endogenous technological improvement" means technological improvement generated by technological knowledge stock arising from R&D investment efforts, while "exogenous technological improvement" means technological improvement generated by autonomous productivity increases [20].

[2] Stock of technological knowledge possessed by the Japanese manufacturing industry which was generated by R&D investment and contributed to production.

[3] Griliches [16], Goto and Suzuki [14], and others (see section 1).

[4] Goto and Suzuki [14] estimated the time lag by using the Economic Planning Agency's 1982 survey (Questionnaire on Corporate Behavior). They also estimated the rate of obsolescence by using the inverse of the average of life span of patents obtained from the Science and Technology Agency's 1985 survey by assuming that R&D capital depreciates and becomes obsolete over time.

[5] Questions included (i) the time duration of R&D by stages (basic, applied and development research) for specific leading technologies where research and commercialization were undertaken during the 1970s and 1980s, and (ii) the lifetime of specific leading technologies which were in use during the 1970s and 1980s and have been replaced either by new technology or improved technologies and products.

in respective stages were: 5.6 years for basic research to commercialization, 3.6 years for applied research to commercialization and 2.0 years for development research to commercialization (2.7 years for applied and development research to commercialization and 3.3 years for the average of all stages). Existing surveys on time lag by stages are limited: the Institute for Policy Sciences' 1976 survey [19] found that basic research to commercialization was 6.6 years, and applied and development research to commercialization was 3.1 years, and the Economic Planning Agency's 1982 survey [9] found the time lags to be 5.0 years and 2.5 years respectively. My estimates are between the estimates of these two surveys.

The average lifetime of technology was 10.2 years. Assuming that technology depreciates and becomes obsolete over time, the annual rate of obsolescence of technology was estimated at 9.8 percent by taking the inverse of the lifetime of

Table 2
Major works relating to the measurement of technological knowledge stock in Japan's manufacturing industry

Source	Time lag (m: years)				Rate of obsolescence (ρ:%)	Remarks
	B[a]	A[a]	D[a]	T[a]		
1. AIST, MITI [1]				2.4 ⟨2.5⟩[b]		(1962)[b]⟨1955–65⟩[b]
2. Gellman Report [11]	3.5 (invention to market introduction)					doubtful of the reliability because of the limited samples as 34 ⟨1953–73⟩
3. Institute for Policy Sciences [19]	6.6	3.1 (A&D)				(1975)
4. Bosworth [6]					(10)	on the basis of patent data on UK manufacturing industry
5. Economic Planning Agency [9]	5.0	2.5 (A&D)		2.8		(1981) ⟨1970–80⟩
6. Japan Development Bank [20]				3 ⟨3⟩		assumption based on the above estimates in 5. and 4.
7. Economic Planning Agency [8]	4	3	2		7	assumption based on the above estimates in 5. and 6. ⟨1965–84⟩
8. Science and Technology Agency [33]				3.5 ⟨2.4⟩	9.8	on the basis of the period for patent revenues
9. Goto et al. [13]					14* 7–10**	* Japanese chemicals, ** Japanese machinery on the basis of patent data registered in 1968 in Japan
10. Goto and Suzuki [14]				2.8	9.8	assumption based on the estimates in 5. and 8.
11. Suzuki [35]				2.5	10	assumption based on the above data ⟨1965–85⟩

[a] B: Basic research to commercialization, A: Applied research to commercialization, D: Development research to commercialization, T: Total R&D to commercialization.
[b] ⟨ ⟩ in time lag indicates imported technology, ( ) in remarks indicates survey year, ⟨ ⟩ in remarks indicates periods of the subject of survey/analysis.

Table 3
Time lag of R&D to commercialization in the Japanese manufacturing industry in the 1970s and 1980s

Basic research to commercialization	5.6 years (average of 79 samples)
Applied research to commercialization	3.6 years (average of 125 samples)
Development research to commercialization	2.0 years (average of 156 samples)
(Appld. & devlp. res. to commercialization	2.7 years)
(Average of all stages	3.3 years)

[a] Valid samples are technologies which have been undertaken, conducted successively and commercialized, all in the period of the 1970s and 1980s.
[b] The total number of valid samples is 360, as follows:

	Textls., ceramics, paper/pulp	Chemicals	Iron & steel	Machinery	Other manf.	Total
B → C	7	16	9	33	14	79
A → C	11	23	12	52	27	125
D → C	17	28	25	68	28	156
Agr.total	35	67	36	153	69	360

Source: Questionnaire to Major Firms (undertaken in April 1990, supported by AIST, MITI) [18].

technology. This estimate coincides with the Science and Technology Agency's 1985 survey [33] (see table 2).

Using these estimations and the above equations, I have measured the trends in technological knowledge stock in the Japanese manufacturing industry over the period of 1970 to 1987 (see details of data construction and sources in the Appendix). Technological knowledge stock in 1987 was estimated at 29.0 trillion yen in constant 1980 yen terms, which is 6.9 times greater than the stock in 1970 (4.2 trillion yen) and equivalent to 9.3 percent of GNP in 1987 (see tabulated outcome of measurement in the Appendix).

2.3. Assessment of technological knowledge stock

In order to assess the statistical significance and consistency of the measured technological knowledge stock as a production factor together with other services of input (labor; L, capital; K, materials; M, and energy; E) to production (Y), I estimated the following simple Cobb–Douglas type production function for the Japanese manufacturing industry between 1970 and 1987 taking all of these services of input into account.

$$Y = AL^{b1}K^{b2}M^{b3}E^{b4}T^{b5},$$

Table 4
Lifetime of technology in the Japanese manufacturing industry in the 1970s and 1980s

Replaced by new technology	13.5 years (average of 119 samples)
Replaced by improved technology/products	7.7 years (average of 157 samples)
Total	10.2 years (average of 276 samples)

[a] Valid samples are technologies which survived in the 1970s and 1980s.
[b] The total number of valid samples is 276 as follows:

	Textls., ceramics, paper/pulp	Chemicals	Iron & steel	Machinery	Other manf.	Total
by new tech.	12	29	11	40	27	119
by impr.tech.	8	24	11	79	35	157
Total	20	53	22	119	62	276

Source: Questionnaire to Major Firms (undertaken in April 1990, supported by AIST, MITI) [18].

Table 5
Significance of technological knowledge stock of the Japanese manufacturing industry in a production function (1970–87)[a,b]
Model: $Y/T = A[(L-L_r)/T]^{b1}[(K-K_r)/T]^{b2}[(M-M_r)/T]^{b3}[(E-E_r)/T]^{b4}$
$T: m = 3.3$ year,s $\rho = 9.8\%$

Time period	DFE [c]	$b1$	$b2$	$b3$	$b4$	adj.R^2	D.W.	F
1970–87	13	0.35 (4.91*)	0.38 (5.76*)	0.31 (3.17*)	−0.12 (−2.86**)	0.999	1.16#	3694
[1970–87	12	0.36 (5.40*)	0.38 (6.47*)	0.38 (3.91*)	−0.16 (−3.19*)	0.996	2.07	995]
[1970–84	10	0.35 (7.33*)	0.51 (8.92*)	0.19 (2.47***)	−0.12 (−3.91*)	0.999	2.10	6432]
1971–85	10	0.35 (9.10*)	0.43 (9.00*)	0.34 (4.54*)	−0.16 (−5.75*)	0.999	1.86	7094
1972–86	10	0.35 (5.14*)	0.34 (4.55*)	0.43 (3.55*)	−0.18 (−3.52*)	0.999	1.13#	1733
[1972–86	9	0.34 (2.99**)	0.34 (4.71*)	0.44 (3.47*)	−0.17 (−1.89****)	0.988	1.35	266]
[1973–87	10	0.37 (4.80*)	0.33 (5.22*)	0.45 (4.20*)	−0.19 (−3.29*)	0.997	1.51	1219]
1974–87	9	0.36 (4.37*)	0.32 (4.78*)	0.42 (3.19*)	−0.18 (−2.26***)	0.994	1.39	567

[a] Figures in parentheses indicate t-value; *: significant at the 1% level, **: significant at the 2% level, ***: significant at the 5% level, ****: significant at the 10% level.
[b] Indications in square brackets indicate Cochrun–Orcutt treatment in order to deal with autocorrelations indicated by # marks on D.W. statistics.
[c] DFE: degree of freedom.

where A is the scale factor and T is the technological knowledge stock. Following Griliches's postulate, in order to avoid duplication between technological knowledge stock and other production factors, I have calculated the factor inputs by deducting respective services of input for R&D (L_r, K_r, M_r, and E_r) from L, K, M and E (see data construction, sources and also tabulated outcome of the calculation in the Appendix). [6] Using the above factors input and technological knowledge stock, first, I assessed the estimation by means of rolling regressions using 10 degrees of freedom with the criteria of adjusted R^2, D.W., F, and t-statistics. Results of the estimation are summarized in table 5, which indicates that all satisfy the above criteria and are considered to be statistically significant.

[6] Average duplication ratios between technological knowledge stock and other production factors in the Japanese manufacturing industry between 1970 and 1987 are L_r/L: 2.2 percent, K_r/K: 17.2 percent, M_r/M: 0.5 percent, and E_r/E: 0.9 percent.
Suzuki, based on his survey of leading electrical machinery firms in Japan, pointed out that capital stock duplication was more than 15 percent [35].

The above estimation suggests that the measured technological knowledge stock described in the foregoing section satisfies statistical significance and consistency. [7]

Second, in order to inspect the significance of time lag (m: 3.3 years for the average of all stages) and the rate of obsolescence of technology (ρ: 9.8 percent) used in the above measurement, I made a comparative assessment with the same criteria by estimating production functions using technological knowledge stock with the following assumptions (see fig. 1):

(i) $m = 3.0$ years and 3.5 years with $\rho = 9.8\%$, and
(ii) $\rho = 9.5\%$ and 10.0% with $m = 3.3$ years.

The results are summarized in table 6, which indicates that the former estimations are statistically more significant than the estimations using the above assumptions. This comparative assess-

[7] Although statistically significant, elasticity of energy shows negative which, under a normal situation, apears inplausible and needs further empirical analysis of the special condition after the energy crises.

ment suggests the significance of the estimated time lag and rate of obsolescence of technology.

Third, in order to see whether the technological knowledge stock (T) has played a significant role in maintaining consistency with other production factors and provided a better explanation than API (autonomous productivity increase), I estimated production functions including API in the above production function in addition to, or instead of T as:

$$Y = A\,e^{\lambda t}(L-L_r)^{b1}(K-K_r)^{b2}(M-M_r)^{b3}\times(E-E_r)^{b4}T^{b5},\text{ or}$$

$$Y = A\,e^{\lambda t}L^{b1}K^{b2}M^{b3}E^{b4}$$

(where t indicates the time trend: 1970, 1971,... 1987).

The results of a comparative assessment with the foregoing criteria are summarized in table 7 and these indicate that the estimates using API become statistically insignificant.

The above estimates suggest that technological knowledge stock (T) has been playing a significant role in maintaining consistency with other production factors, and provided a better explanation than API in the production function.

Fourth, in order to inspect Griliches's postulate, I estimated the production function using the technological knowledge stock and other production factors without deducting the respective services of input for R&D (without eliminating double counting) and made a comparative assessment with the foregoing criteria. The results are summarized also in table 7, which indicates that

Table 6
Comparative assessment of time lag and the rate of obsolescence of technology in the Japanese manufacturing industry (1970–87)[a]
Model: $Y/T = A[(L-L_r)/T]^{b1}[(K-K_r)/T]^{b2}[(M-M_r)/T]^{b3}[(E-E_r)/T]^{b4}$
$T: m = 3.0$–3.5 years, ρ: 9.5–10.0%

Time period	m	ρ	$b1$	$b2$	$b3$	$b4$	adj.R^2	D.W.	F
1970–87	3.3	9.8	0.35	0.38	0.31	−0.12	0.999	1.16#	3694
			(4.91∗)	(5.76∗)	(3.17∗)	(−2.86∗∗)			
			0.36	0.38	0.38	−0.16	0.996	2.07	995
			(5.40∗)	(6.47∗)	(3.91∗)	(−3.19∗)			
	3.0	9.8	0.31	0.40	0.35	−0.11	0.999	1.12#	3272
			(4.25∗)	(5.71∗)	(3.35∗)	(−2.39∗∗∗)			
			0.35	0.39	0.41	−0.17	0.995	2.08	864
			(5.03∗)	(6.44∗)	(4.13∗)	(−3.13∗)			
	3.5	9.8	0.34	0.39	0.31	−0.12	0.999	1.16#	3371
			(4.50∗)	(5.70∗)	(3.00∗)	(−2.62∗∗∗)			
			0.35	0.38	0.40	−0.17	0.996	2.08	981
			(5.15∗)	(6.48∗)	(3.89∗)	(−3.14∗)			
	3.3	9.5	0.33	0.39	0.32	−0.12	0.999	1.19#	3500
			(4.44∗)	(5.70∗)	(3.05∗)	(−2.56∗∗∗)			
			0.34	0.39	0.41	−0.17	0.996	2.05	1051
			(5.00∗)	(6.50∗)	(3.91∗)	(−3.12∗)			
	3.3	10.0	0.34	0.38	0.31	−0.12	0.999	1.16#	3539
			(4.79∗)	(5.71∗)	(3.16∗)	(−2.78∗∗∗)			
			0.36	0.38	0.39	−0.17	0.996	2.07	970
			(5.31∗)	(6.46∗)	(3.92∗)	(−3.17∗)			
1973–87	3.3	9.8	0.37	0.33	0.45	−0.19	0.997	1.51	1219
			(4.80∗)	(5.22∗)	(4.20∗)	(−3.29∗)			
	3.0	9.8	0.35	0.34	0.49	−0.20	0.997	1.49	1093
			(4.44∗)	(5.12∗)	(4.61∗)	(−3.25∗)			
	3.5	9.8	0.36	0.33	0.47	−0.20	0.997	1.53	1183
			(4.59∗)	(5.15∗)	(4.17∗)	(−3.28∗)			
	3.3	9.5	0.35	0.34	0.48	−0.20	0.997	1.54	1197
			(4.46∗)	(5.14∗)	(4.15∗)	(−3.18∗)			
	3.3	10.0	0.36	0.33	0.46	−0.20	0.997	1.51	1174
			(4.71∗)	(5.18∗)	(4.20∗)	(−3.26∗)			

[a] See footnotes of table 5.

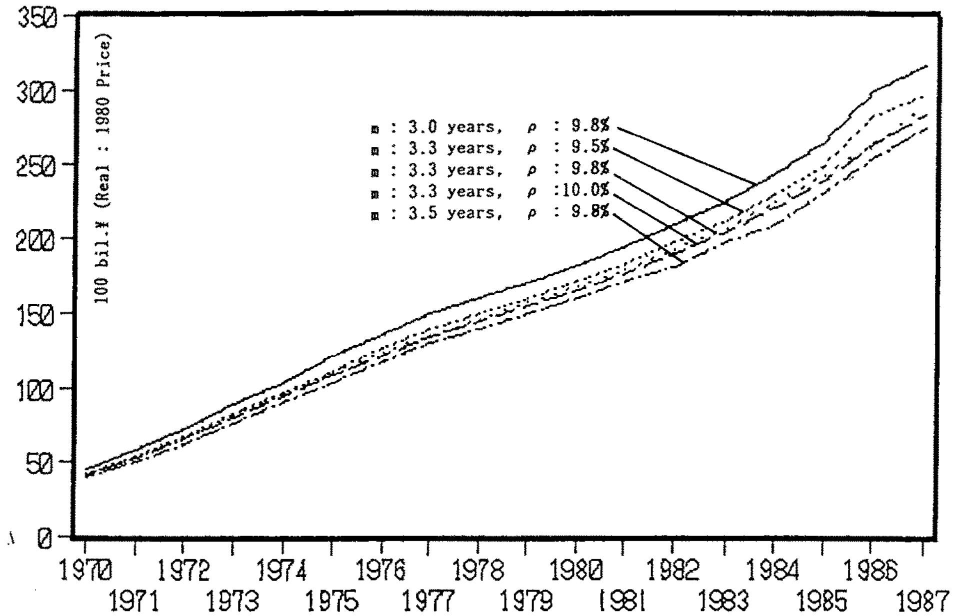

Fig. 1. Trends in technological knowledge stock with varieties of time lags and the rate of obsolescence of technology in the Japanese manufacturing industry (1970–87).

F-value became drastically worse, t-values of E become insignificant and L and K have worsened. The D.W. ratio has changed to increase autocorrelation. These suggest double counting among factors and verifies Griliches's postulate.

All of the above assessments suggest the significance and consistency of measured technological knowledge stock.

Table 7
Comparative assessment of possible production functions for the Japanese manufacturing industry (1970–87)[a]
Model A: $Y/T = A[(L-L_r)/T]^{b1}[(K-K_r)/T]^{b2}[(M-M_r)/T]^{b3}[(E-E_r)/T]^{b4}$
Model B: $Y/T = A\,e^{\lambda t}[(L-L_r)/T]^{b1}[(K-K_r)/T]^{b2}[(M-M_r)/T]^{b3}[(E-E_r)/T]^{b4}$
Model C: $Y = A\,e^{\lambda t}L^{b1}K^{b2}M^{b3}E^{b4}$
Model D: $Y/T = A(L/T)^{b1}(K/T)^{b2}(M/T)^{b3}(E/T)^{b4}$

Time period	Model	λ	b1	b2	b3	b4	adj.R^2	D.W.	F
1970–87	A	–	0.35	0.38	0.31	−0.12	0.999	1.16#	3694
			(4.91*)	(5.76*)	(3.17*)	(−2.86**)			
		[–	0.36	0.38	0.38	−0.16	0.996	2.07	995]
			(5.40*)	(6.47*)	(3.91*)	(−3.19*)			
	B	0.009	0.38	0.30	0.31	−0.04	0.999	1.05#	2768
		(0.42+)	(3.77*)	(1.57*****)	(3.05**)	(−0.21+)			
		[0.033	0.52	0.07	0.42	0.09	0.996	1.86	904]
		(2.60***)	(6.35*)	(0.57+)	(5.07*)	(0.85+)			
	C	0.03	0.55	0.02	0.38	0.19	0.997	0.99#	1263
		(3.17*)	(2.93**)	(0.17+)	(3.54*)	(2.29***)			
		[0.02	0.51	0.12	0.40	0.05	0.994	1.42	534]
		(2.74**)	(3.49*)	(1.22+)	(4.72*)	(0.62+)			
	D	–	0.28	0.28	0.45	−0.09	0.999	0.91#	2864
			(3.17*)	(4.16*)	(4.13*)	(−1.87****)			
		[–	0.29	0.32	0.44	−0.10	0.991	1.68	452]
			(3.51*)	(5.39*)	(4.35*)	(−1.65*****)			

[a] See footnotes of table 5.
[b] *****: Significant at the 20% level, +: not significant.

3. Model synthesis: Translog cost function

In order to measure the elasticities of substitution among production factors, I have assumed a translog type cost function for the Japanese manufacturing industry over the period of 1970 to 1987. This can measure changes in substitution elasticities without setting a transcendental assumption for alternate substitutes.

First of all, the production function is generally seen in the following way:

$$Y=f(L, K, M, E, T) \tag{3}$$

Next, the following cost function (*LKMET* cost function) exists corresponding to the production function in (3):

$$C=C(Y, P_l, P_k, P_m, P_e, P_t), \tag{4}$$

where C is gross cost, and P_l, P_k, P_m, P_e and P_t are prices of labor, capital, materials, energy, and technology respectively. [8]

The cost function (4) is brought near $\ln Y = \ln P_l = \ln P_k = \ln P_m = \ln P_e = \ln P_t = 0$, and when Taylor expansion is made to the secondary term in connection with $\ln Y$, $\ln P_l$, $\ln P_k$, $\ln P_m$, $\ln P_e$ and $\ln P_t$, we will be able to obtain the following formula:

$$\begin{aligned}\ln C = {} & \ln A_0 + \ln Y + A_l \ln P_l + A_k \ln P_k \\ & + A_m \ln P_m + A_e \ln P_e + A_t \ln P_t \\ & + \ln P_l(B_{ll} \ln P_l + B_{ln} \ln P_k \\ & \quad + B_{lm} \ln P_m + B_{le} \ln P_e + B_{lt} \ln P_t) \\ & + \ln P_k(B_{kl} \ln P_l + B_{kk} \ln P_k \\ & \quad + B_{km} \ln P_m + B_{ke} \ln P_e + B_{kt} \ln P_t) \\ & + \ln P_m(B_{ml} \ln P_l + B_{mk} \ln P_k \\ & \quad + B_{mm} \ln P_m + B_{me} \ln P_e + B_{mt} \ln P_t) \\ & + \ln P_e(B_{el} \ln P_l + B_{ek} \ln P_k + B_{em} \ln P_m \\ & \quad + B_{ee} \ln P_e + B_{et} \ln P_t) \\ & + \ln P_t(B_{tl} \ln P_l + B_{tk} \ln P_k \\ & \quad + B_{tm} \ln P_m + B_{te} \ln P_{et} B_{tt} \ln P_t) \end{aligned} \tag{5}$$

Under the assumptions of the symmetrical nature of coefficients and of the linear homogeneity of the cost function, the following restrictions are imposed on coefficients in (5):

$$\begin{aligned} & A_l + A_k + A_m + A_e + A_t = 1 \\ & B_{ll} + B_{lm} + B_{lk} + B_{le} + B_{lt} = 0 \\ & B_{kl} + B_{kk} + B_{km} + B_{ke} + B_{kt} = 0 \\ & B_{ml} + B_{mk} + B_{mm} + B_{me} + B_{mt} = 0 \\ & B_{el} + B_{ek} + B_{em} + B_{ee} + B_{et} = 0 \\ & B_{tl} + B_{tk} + B_{tm} + B_{te} + B_{tt} = 0 \\ & B_{ij} = B_{ji} \qquad (i, j = L, K, E, M, T) \end{aligned} \tag{6}$$

When $\ln P_l$, $\ln P_k$, $\ln P_m$, $\ln P_e$ and $\ln P_t$ are used here to differentiate (5) and Sheppard's adjustment $[(\partial C/\partial P_i) = x_i,\ x_i = L, K, M, E, T]$ is adopted, the following equation is obtained:

$$\begin{aligned} M_l &= \frac{\delta \ln C}{\delta \ln P_l} = \frac{P_l}{C} \cdot \frac{\delta C}{\delta P_l} = \frac{P_l L}{C} \\ &= A_l + 2(B_{ll} \ln P_l + B_{lk} \ln P_k \\ &\quad + B_{lm} \ln P_m + B_{le} \ln P_e + B_{lt} \ln P_t) \\ M_k &= \frac{\delta \ln C}{\delta \ln P_k} = \frac{P_k}{C} \cdot \frac{\delta C}{\delta P_k} = \frac{P_k K}{C} \\ &= A_k + 2(B_{kl} \ln P_l + B_{kk} \ln P_k \\ &\quad + B_{km} \ln P_m + B_{ke} \ln P_e + B_{kt} \ln P_t) \\ M_m &= \frac{\delta \ln C}{\delta \ln P_m} = \frac{P_m}{C} \cdot \frac{\delta C}{\delta P_m} = \frac{P_m M}{C} \\ &= A_m + 2(B_{ml} \ln P_l + B_{mk} \ln P_k \\ &\quad + B_{mm} \ln P_m + B_{me} \ln P_e + B_{mt} \ln P_t) \\ M_e &= \frac{\delta \ln C}{\delta \ln P_e} = \frac{P_e}{C} \cdot \frac{\delta C}{\delta P_e} = \frac{P_e E}{C} \\ &= A_e + 2(B_{el} \ln P_l + B_{ek} \ln P_k \\ &\quad + B_{em} \ln P_m + B_{ee} \ln P_e + B_{et} \ln P_t) \\ M_t &= \frac{\delta \ln C}{\delta \ln P_t} = \frac{P_t}{C} \cdot \frac{\delta C}{\delta P_t} = \frac{P_t T}{C} \\ &= A_t + 2(B_{tl} \ln P_l + B_{tk} \ln P_k \\ &\quad + B_{tm} \ln P_m + B_{te} \ln P_e + B_{tt} \ln P_t). \end{aligned} \tag{7}$$

The left-hand side in eqn. (7) is the share (cost share) of each production factor to total cost, while the right-hand side is the price (factor price) of each production factor.

[8] All R&D related factors are included in T and P_t, exclusive of other production factors and prices. See details of data construction and sources in the Appendix.

I have estimated eqn. (7) by employing the cost share and factor cost series under the restriction of eqn (6).

Elasticity of substitution among production factors (σ_{ij}) can be measured by Allen partial elasticity of substitution (AES) which, in a translog cost function, can be calculated as follows (Uzawa [37]; Berndt-Wood [5]):

$$\sigma_{ij} = \frac{B_{ij} + M_i^2 - M_i}{M_i} \quad (i, j = L, K, M, E, T) \quad (i = j)$$
$$\sigma_{ij} = \frac{B_{ij} + M_i \cdot M_j}{M_i M_j} \quad (i, j = L, K, M, E, T) \quad (i \neq j). \tag{8}$$

The price elasticities of demand (ϵ_{ij}) for production factors follow directly from the elasticities of substitution:

$$\epsilon_{ij} = M_j \sigma_{ij} \quad (i, j = L, K, M, E, T) \tag{9}$$

On the basis of the above equations, by using technological knowledge stock as a technology factor, I have tried to identify the trends in the substitution of production factors to technology with regard to Japan's manufacturing industry over the period of 1970 to 1987.

4. Trends in the substitution of production factors to technology

4.1. Estimation and assessment

By incorporating the technological knowledge stock in the model described in section 3, avoiding duplication as described in section 2. I have made an analysis of the trends in the substitution of production factors for the Japanese manufacturing industry over the period of 1970 to 1987, a time period which includes two energy crises.

The focus of the analysis was to analyze how Japan's manufacturing industry was able to sustain stable production levels despite increasing constraints of production factors due to the energy crises; especially to measure how such a challenge was done by substituting production factors (L, K, M, E) for technology (T).

First, I calculated the cost shares and prices of labor, capital, materials, energy and technology (see data construction, sources and also the tabulated outcome of the calculation in the Appendix).

The outcomes of the calculations suggest that over the period of 1970 to 1987, cost shares of technology increased steadily (1.1 percent in 1970 to 2.3 percent in 1987), [9] especially after 1976, which resulted in technological knowledge stock taking a leading role in the Japanese manufacturing industry production. The price of energy (real price) rose sharply after the energy crises in 1973 and 1979 in parallel with the sharp increase in the international oil prices, which suggests that energy prices of the Japanese manufacturing industry were very susceptible to trends in international oil prices. [10]

The rise of energy prices influenced other production factors by affecting prices, quantities and/or costs. The rise of energy prices influenced the rise in the price of labor, [11] while the price of technology and capital showed a sharp decrease (the price of materials was rather independent) [12]. On the other hand, this rise resulted in a rapid increase in technology and capital.

[9] R&D intensity: R&D expenditure (technology cost)/value added increased from 2.9 percent in 1970 to 6.1 percent in 1987.

[10] Trends in energy prices in the Japanese manufacturing industry (P_e) showed close correlation with the trends for international oil prices (IOP) as follows:

$P_e = 62.30 + 0.47$ IOP(1970–87) R^2 0.884 D.W.1.00
(3.55) (11.14)

[11] The 1975 White Paper on the Japanese Economy [8] found that the sharp increase in the international oil prices due to the first energy crisis increased Japan's price of energy sharply: this caused a dramatic increase in prices of commodities and this drastic increase resulted in the rise in the price of labor (wages).

The 1976 White Paper [8] analyzed the ratio of contribution of the increase in prices of commodities to the rise in the wages in the period 1970–76 as follows: 1970: 25.4%, 1971: 21.3%, 1972: 20.6%, 1973: 20.2%, 1974: 49.0%, 1975: 62.2% and 1976: 54.5%.

[12] Correlations between energy prices and prices of production factors in the Japanese manufacturing industry (1970–87)

				R^2	D.W.
Labor price	$P_l = 65.21$ (9.38)	$+4.51$ (9.10)	P_e	0.828	1.32
Capital price	$P_k = 5.49$ (23.97)	-0.14 (-8.45)	P_e	0.805	0.98
Materials price	$P_m = 1.50$ (19.29)	-0.01 (-1.70)	P_e	0.100	1.09
Technology price	$P_t = 4.12$ (9.81)	-0.13 (-4.30)	P_e	0.508	0.35

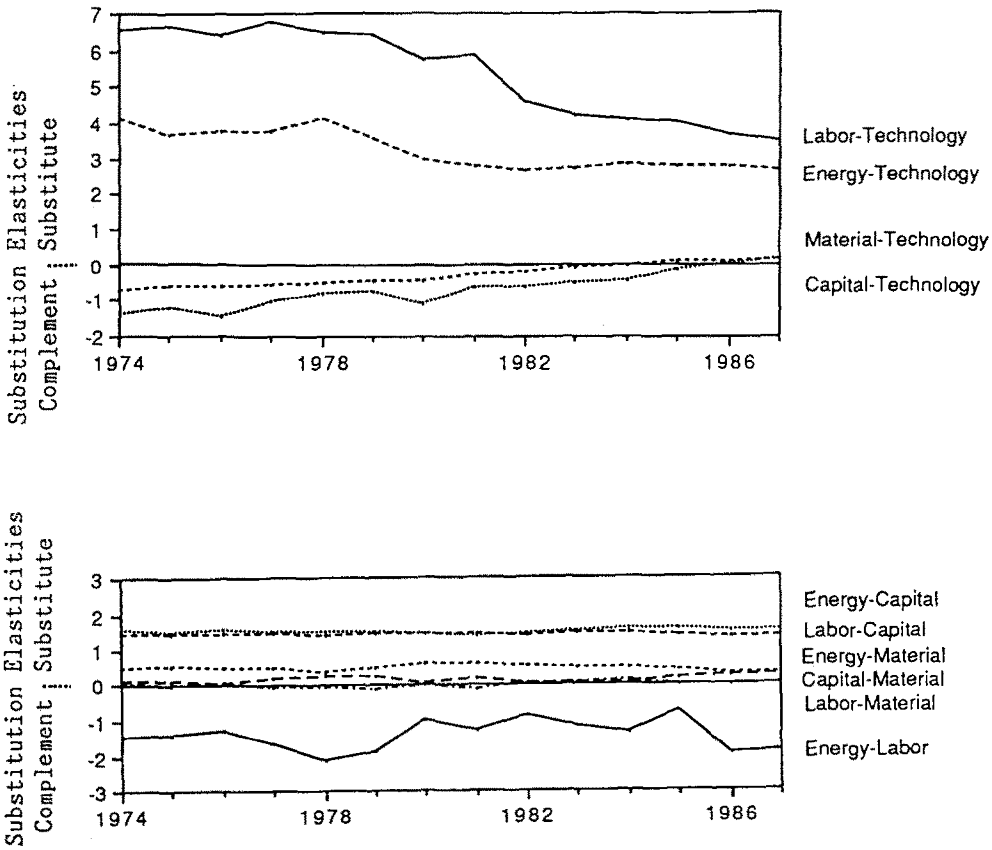

Fig. 2. Trends in the substitution of production factors to technology in the Japanese manufacturing industry (1974–87).

These trends suggest that, of the production factors of the Japanese manufacturing industry, technology and capital moved directly to be free from energy constraints, while labor moved to be free from energy constraints by shifting to technology and/or capital.

Next, using the above cost shares and prices of production factors, by means of the equations described in section 3, I estimate the translog cost function (*LKMET* cost function) for the Japanese manufacturing industry over the period of 1970 to 1987, with linear homogeneity in prices imposed.

Table 8
Cost share and price equation for the Japanese manufacturing industry (1970–87)[a]

$M_l = 0.1471$	$+0.0996 \ln P_l$	$+0.0091 \ln P_k$	$-0.0892 \ln P_m$	$-0.0277 \ln P_e$	$+0.0082 \ln P_t$
(98.15)	(12.86)	(1.71)	(−10.30)	(−6.97)	(6.87)
$M_k = 0.1591$	$+0.0091 \ln P_l$	$+0.0273 \ln P_k$	$-0.0837 \ln P_m$	$+0.0058 \ln P_e$	$-0.0035 \ln P_t$
(34.84)	(1.71)	(7.72)	(−7.93)	(1.16)	(−2.47)
$M_m = 0.5952$	$-0.0892 \ln P_l$	$-0.0837 \ln P_k$	$+0.2093 \ln P_m$	$-0.0260 \ln P_e$	$-0.0104 \ln P_t$
(234.24)	(−10.30)	(−7.93)	(12.14)	(−5.62)	(−6.73)
$M_e = 0.0831$	$-0.0277 \ln P_l$	$+0.0058 \ln P_k$	$-0.0260 \ln P_m$	$+0.0455 \ln P_e$	$+0.0023 \ln P_t$
(27.97)	(−6.97)	(1.16)	(−5.62)	(12.59)	(2.78)
$M_t = 0.0156$	$+0.0082 \ln P_l$	$-0.0035 \ln P_k$	$-0.0104 \ln P_m$	$+0.0023 \ln P_e$	$+0.0033 \ln P_t$
(23.96)	(6.87)	(−2.47)	(−6.73)	(2.78)	(5.31)

[a] Numbers in parentheses indicate *t*-ratios.

In table 8, I present estimates of the function. Table 8 shows almost all estimated parameters statistically significant at the 1 to the 5 percent level except parameters B_{lk} (B_{kl}) and B_{ke} (B_{ek}) (they are at the 10 percent to 20 percent level). [13]

Third, on the basis of the estimated function, I computed the estimated Allen partial elasticities of substitution as shown in table 9 and fig. 2, in order to measure factor substitution possibilities.

Table 9
Trends in Allen partial elasticity of substitution in the Japanese manufacturing industry (1970–87)

Year	L–T	K–T	M–T	E–T	E–L
1970	7.712	−0.998	−0.732	6.765	−4.006
1971	7.084	−0.966	−0.733	6.700	−3.639
1972	6.468	−0.807	−0.651	6.588	−3.712
1973	6.736	−1.036	−0.634	6.489	−3.648
1974	6.562	−1.377	−0.717	4.192	−1.474
1975	6.668	−1.194	−0.609	3.642	−1.414
1976	6.399	−1.446	−0.630	3.814	−1.307
1977	6.787	−1.044	−0.579	3.780	−1.644
1978	6.477	−0.782	−0.515	4.140	−2.154
1979	6.424	−0.745	−0.433	3.608	−1.866
1980	5.781	−1.104	−0.432	3.011	−0.977
1981	5.846	−0.628	−0.289	2.833	−1.288
1982	4.581	−0.608	−0.217	2.724	−0.893
1983	4.233	−0.507	−0.078	2.789	−1.155
1984	4.147	−0.455	−0.025	2.868	−1.360
1985	4.047	−0.146	0.081	2.812	−1.786
1986	3.719	0.049	0.125	2.838	−1.960
1987	3.532	0.151	0.156	2.724	−1.911
Average	5.734	−0.758	−0.384	4.018	−2.012
(1974–87	5.372	−0.702	−0.297	3.270	−1.515)

Year	E–K	E–M	L–K	L–M	K–M
1970	1.736	0.040	1.377	−0.091	0.289
1971	1.741	0.018	1.348	−0.023	0.276
1972	1.769	−0.058	1.325	0.007	0.282
1973	1.855	0.016	1.368	0.014	0.234
1974	1.522	0.432	1.400	0.035	0.097
1975	1.462	0.491	1.428	−0.048	0.112
1976	1.516	0.482	1.436	0.030	0.039
1977	1.461	0.465	1.423	−0.089	0.159
1978	1.507	0.351	1.382	−0.085	0.227
1979	1.459	0.433	1.412	−0.131	0.204
1980	1.430	0.560	1.449	−0.021	0.016
1981	1.380	0.548	1.441	−0.167	0.142
1982	1.420	0.522	1.384	0.031	0.048
1983	1.496	0.466	1.394	0.059	0.040
1984	1.539	0.429	1.399	0.061	0.050
1985	1.518	0.376	1.383	−0.024	0.157
1986	1.511	0.292	1.332	−0.022	0.218
1987	1.482	0.279	1.311	−0.034	0.241
Average	1.542	0.341	1.388	−0.027	0.157
(1974–87	1.479	0.438	1.398	−0.029	0.125)

Table 9 (continued)

Year	L–L	K–K	M–M	E–E	T–T
1970	−0.777	−2.285	−0.058	2.437	−67.800
1971	−1.068	−2.286	−0.067	2.579	−66.906
1972	−1.188	−2.258	−0.075	4.319	−64.840
1973	−1.121	−2.367	−0.058	3.138	−65.574
1974	−1.124	−2.452	−0.073	−4.228	−66.240
1975	−1.026	−2.447	−0.073	−4.444	−64.076
1976	−1.216	−2.455	−0.069	−4.412	−64.807
1977	−0.886	−2.420	−0.072	−4.367	−63.505
1978	−0.923	−2.343	−0.075	−3.664	−61.782
1979	−0.752	−2.374	−0.074	−4.237	−59.842
1980	−1.141	−2.455	−0.080	−4.470	−59.375
1981	−0.698	−2.418	−0.084	−4.482	−55.179
1982	−1.333	−2.453	−0.098	−4.492	−51.909
1983	−1.342	−2.458	−0.086	−4.418	−48.323
1984	−1.324	−2.458	−0.080	−4.247	−46.973
1985	−1.146	−2.407	−0.082	−3.939	−42.945
1986	−1.228	−2.306	−0.098	−3.389	−40.239
1987	−1.254	−2.240	−0.109	−3.424	−38.302
Average	−1.086	−2.382	−0.078	−2.541	−57.145
(1974–87	−1.099	−2.406	−0.082	−4.158	−54.536)

[a] L: labor, K: capital, M: materials, E: energy, T: technology.

Fourth, by using the above estimated values, I also computed the price elasticities of demand in order to estimate the magnitude of the interactions among production factors induced by the changes in respective prices. Table 10 and fig. 3 present the estimated price elasticities which are summarized in table 11.

A cost function is well-behaved if it is concave in input prices and if its input demand functions are strictly positive. I have checked the fitted cost shares based on the parameter estimates of *LKMET* cost function and found that the positivity conditions were satisfied at each annual observation. Concavity of the cost is satisfied if the Hessian matrix is negative, and this postulation is satisfied in the translog cost function when the Allen partial elasticities of substitution (σ_{ii}: $i = L, K, M, E, T$) is negative [24]. I have checked the estimated σ_{ii} (table 9) and found that all σ_{ii} were negative except σ_{ee} for the period 1970–73. Energy demand before the first energy crisis in late 1973 continued to sharply increase (the aver-

[13] In order to identify the extent of bias due to double counting between technological knowledge stock and *L*, *K*, *M*, and *E*, I tried to estimate the translog cost function without eliminating double counting. However, due to difficulty of the fittability of the model, I could not obtain any fittable estimate with regard to this case.

age annual increase rate in the 1970–73 period was 9.8 percent) despite the slight increase in its own price (average increase rate in real terms in the same period was 0.2 percent). The above σ_{ee} estimates for the period 1970–1973 reflect this behavior which provides such statistics as against concave conditions.

Table 10
Trends in price elasticities of demand in the Japanese manufacturing industry (1970–87)
Labor

Year	ϵ_{ll}	ϵ_{lk}	ϵ_{lm}	ϵ_{le}	ϵ_{lt}
1970	−0.100	0.256	−0.057	−0.172	0.073
1971	−0.150	0.251	−0.014	−0.155	0.068
1972	−0.174	0.252	0.004	−0.148	0.066
1973	−0.160	0.236	0.009	−0.152	0.067
1974	−0.187	0.211	0.022	−0.110	0.064
1975	−0.142	0.219	−0.030	−0.117	0.070
1976	−0.180	0.202	0.019	−0.107	0.066
1977	−0.118	0.231	−0.055	−0.130	0.072
1978	−0.124	0.245	−0.052	−0.141	0.072
1979	−0.097	0.242	−0.080	−0.141	0.076
1980	−0.164	0.203	−0.013	−0.095	0.069
1981	−0.089	0.234	−0.101	−0.122	0.078
1982	−0.210	0.208	0.018	−0.083	0.067
1983	−0.212	0.203	0.035	−0.094	0.068
1984	−0.207	0.203	0.037	−0.102	0.069
1985	−0.165	0.226	−0.014	−0.123	0.076
1986	−0.183	0.244	−0.013	−0.123	0.075
1987	−0.189	0.253	−0.019	−0.121	0.076
Average	−0.158	0.229	−0.016	−0.124	0.071
(1974–87	−0.161	0.223	−0.017	−0.114	0.071)

Capital

Year	ϵ_{kl}	ϵ_{kk}	ϵ_{km}	ϵ_{ke}	ϵ_{kt}
1970	0.178	−0.426	0.183	0.074	−0.009
1971	0.189	−0.425	0.171	0.074	−0.009
1972	0.194	−0.430	0.173	0.071	−0.008
1973	0.195	−0.409	0.148	0.076	−0.010
1974	0.210	−0.370	0.060	0.114	−0.011
1975	0.198	−0.375	0.069	0.121	−0.013
1976	0.213	−0.345	0.024	0.123	−0.015
1977	0.189	−0.391	0.098	0.115	−0.011
1978	0.187	−0.414	0.139	0.097	−0.009
1979	0.182	−0.407	0.125	0.109	−0.009
1980	0.209	−0.344	0.010	0.138	−0.013
1981	0.183	−0.392	0.085	0.132	−0.008
1982	0.218	−0.369	0.028	0.132	−0.009
1983	0.220	−0.358	0.024	0.122	−0.008
1984	0.219	−0.357	0.030	0.116	−0.008
1985	0.200	−0.396	0.094	0.105	−0.003
1986	0.199	−0.422	0.127	0.095	0.001
1987	0.198	−0.432	0.137	0.094	0.00
Average	0.199	−0.392	0.096	0.106	−0.008
(1974–87	0.202	−0.384	0.075	0.115	−0.008)

Table 10 (continued)

Materials

Year	ϵ_{ml}	ϵ_{mk}	ϵ_{mm}	ϵ_{me}	ϵ_{mt}
1970	−0.012	0.054	−0.037	0.002	−0.007
1971	−0.003	0.051	−0.042	0.001	−0.007
1972	0.001	0.054	−0.046	−0.002	−0.007
1973	0.002	0.040	−0.037	0.001	−0.006
1974	0.005	0.015	−0.045	0.032	−0.007
1975	−0.007	0.017	−0.045	0.041	−0.006
1976	0.004	0.005	−0.043	0.040	−0.006
1977	−0.012	0.025	−0.044	0.037	−0.006
1978	−0.011	0.040	−0.046	0.023	−0.006
1979	−0.017	0.035	−0.045	0.032	−0.005
1980	−0.003	0.002	−0.049	0.055	−0.005
1981	−0.021	0.023	−0.051	0.053	−0.004
1982	0.005	0.007	−0.057	0.048	−0.003
1983	0.09	0.006	−0.051	0.038	−0.002
1984	0.010	0.007	−0.049	0.033	−0.001
1985	−0.003	0.025	−0.050	0.026	0.002
1986	−0.003	0.040	−0.058	0.018	0.003
1987	−0.005	0.046	−0.062	0.018	0.003
Average	−0.003	0.027	−0.047	0.028	−0.004
(1974–87	−0.003	0.021	−0.049	0.035	−0.003)

Energy

Year	ϵ_{el}	ϵ_{ek}	ϵ_{em}	ϵ_{ee}	ϵ_{et}
1970	−0.518	0.324	0.025	0.105	0.064
1971	−0.511	0.325	0.011	0.110	0.065
1972	−0.543	0.337	−0.035	0.173	0.068
1973	−0.521	0.314	0.010	0.132	0.065
1974	−0.222	0.231	0.265	−0.315	0.041
1975	−0.196	0.225	0.302	−0.369	0.038
1976	−0.194	0.214	0.299	−0.358	0.039
1977	−0.219	0.237	0.287	−0.345	0.040
1978	−0.289	0.268	0.215	−0.240	0.046
1979	−0.242	0.250	0.266	−0.317	0.043
1980	−0.141	0.201	0.340	−0.436	0.036
1981	−0.164	0.224	0.331	−0.428	0.037
1982	−0.141	0.214	0.306	−0.418	0.039
1983	−0.183	0.219	0.279	−0.359	0.044
1984	−0.213	0.244	0.261	−0.319	0.047
1985	−0.258	0.250	0.228	−0.272	0.052
1986	−0.292	0.276	0.172	−0.213	0.057
1987	−0.288	0.287	0.159	−0.216	0.058
Average	−0.285	0.256	0.207	−0.226	0.049
(1974–87	−0.217	0.237	0.265	−0.328	0.044)

On the basis of the above assessment, I concluded that the estimated *LKMET* cost function was well-behaved in Japan's manufacturing industry over the period 1970–87, especially for the period 1974–78 (excluding the period 1970–73 when the concavity condition with regard to energy prices was not satisfied).

Table 10 (continued)

Technology					
Year	ϵ_{tl}	ϵ_{tk}	ϵ_{tm}	ϵ_{te}	ϵ_{tt}
1970	0.997	−0.185	−0.461	0.290	−0.641
1971	0.994	−0.180	−0.455	0.285	−0.644
1972	0.949	−0.153	−0.398	0.266	−0.664
1973	0.963	−0.178	−0.400	0.271	−0.656
1974	0.986	−0.207	−0.440	0.312	−0.651
1975	0.923	−0.183	−0.373	0.303	−0.670
1976	0.950	−0.203	−0.391	0.309	−0.665
1977	0.903	−0.169	−0.356	0.299	−0.677
1978	0.870	−0.138	−0.314	0.272	−0.690
1979	0.826	−0.127	−0.265	0.271	−0.705
1980	0.833	−0.155	−0.262	0.293	−0.709
1981	0.742	−0.102	−0.174	0.271	−0.737
1982	0.721	−0.091	−0.127	0.254	−0.757
1983	0.670	−0.074	−0.047	0.227	−0.776
1984	0.649	−0.066	−0.015	0.215	−0.783
1985	0.584	−0.024	0.049	0.194	−0.803
1986	0.555	0.009	0.073	0.178	−0.815
1987	0.533	0.029	0.089	0.172	−0.823
Average	0.814	−0.122	−0.237	0.260	−0.715
(1974–87	0.768	−0.107	−0.182	0.255	−0.733)

Table 11

Average of price elasticities of demand in the Japanese manufacturing industry (1974–87)

Change in prod. factors	Labor	Capital	Mater.	Energy	Techno.
Price change					
P_l	−0.161	0.202	−0.003	−0.217	0.768
P_k	0.223	−0.384	0.021	0.237	−0.107
P_m	−0.017	0.075	−0.049	0.265	−0.182
P_e	−0.114	0.115	0.035	−0.328	0.255
P_t	0.071	−0.008	−0.003	0.044	−0.733

4.2. Interpretation

By using the estimated *LKMET* cost function, I have tried to interpret the behavior of *LKMET* factors. In this I have – based on the above conclusion, in order to interpret the behavior of

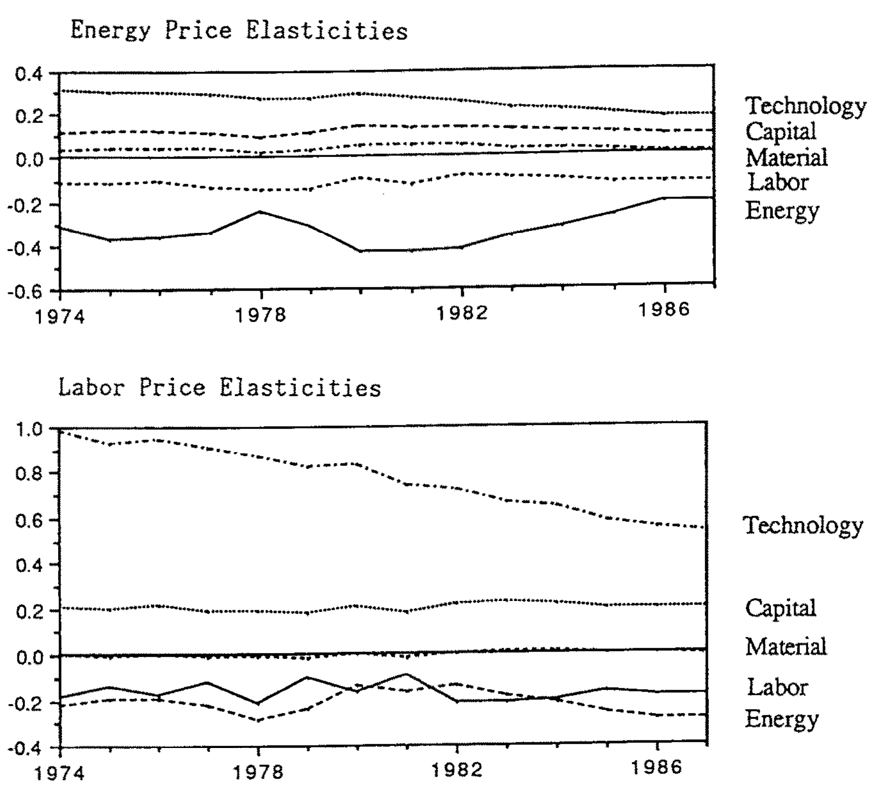

Fig. 3. Trends in the price elasticities of demand in the Japanese manufacturing industry (1974–87).

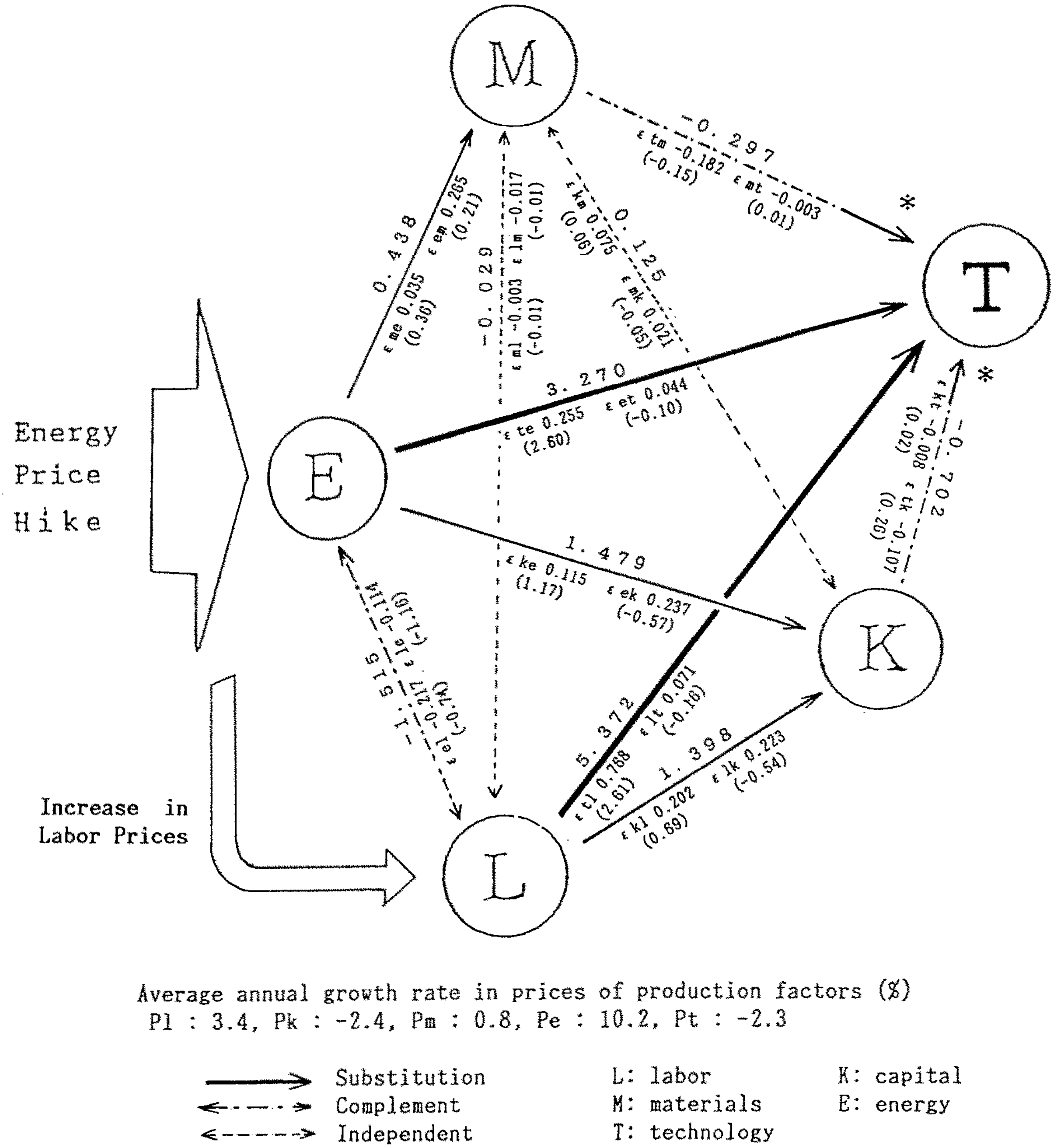

Fig. 4. Schematic of trends in the substitution of production factors to technology in the Japanese manufacturing industry (1974–87). Figures in the upper line indicate average of Allen partial elasticity of substitution. ϵ indicates average of price elasticity of demand. Figures in parentheses indicate the magnitude of transaction by using the multiplicated index of average price elasticity and increasing rate in prices. * indicates increasing trends towards substitution.

all factors in the "well-behaved period" (period when the cost function is well-behaved under the condition that all concavity conditions were satisfied) – interpreted the outcomes of the estimated Allen partial elasticities of substitution and also the estimated price elasticities of demand focusing on the period 1974–87 (elasticities for the period 1970–87 are presented in tables 9 and 10 which are almost the same as those of 1974–87). I found several important results as outlined below.

(i) A sharp increase in energy prices after the oil crises (a 10.2 percent average annual rate of increase in real terms for 1974–87) induced a significant increase in labor prices (similarly 3.4 percent) a slight increase in materials prices (0.8 percent), and corresponding decreases in the prices of capital (−2.4 percent) and technology (−2.3 percent).

(ii) Changes in energy prices had a strong impact on energy demand (average price elasticities of demand ϵ_{ee} was −0.33) and technology demand (ϵ_{te} 0.26), followed by impacts on capital (ϵ_{ke} 0.12) and labor (ϵ_{le} −0.11), while the impact on materials was slight (ϵ_{me} 0.04).

(iii) Changes in labor prices had an extremely strong impact on technology demand (ϵ_{tl} 0.77) followed by energy (ϵ_{el} −0.22), capital (ϵ_{kl} 0.20), and labor (ϵ_{ll} −0.16), while the impact on materials was slight (ϵ_{ml} −0.003).

(iv) Energy and technology displayed substantial substitutability (σ_{et} 3.27, ϵ_{te} 0.26, ϵ_{et} 0.04). Although this substitutability decreased slightly from around 1978, it became stable from around 1980 (just after the second energy crisis).

(v) Labor and technology also displayed substantial substitutability (σ_{lt} 5.37, ϵ_{tl} 0.77, ϵ_{lt} 0.07). This also decreased slightly from around 1981.

(vi) Materials and technology displayed slight complementability. However, they moved steadily towards substitutability and changed to substitutes from around 1985 (σ_{mt} −0.30, ϵ_{tm} −0.18, ϵ_{mt} −0.003).

(vii) Capital and technology also displayed slight complementability. However, they also moved steadily towards substitutability and changed to substitutes from around 1986 (σ_{kt} −0.70, ϵ_{tk} −0.11, ϵ_{kt} −0.008).

(viii) Energy and labor displayed complementability through the period (σ_{le} −1.52, ϵ_{el} −0.22, ϵ_{le} −0.11).

(ix) Energy and capital as well as labor and capital displayed stable substitutability through the period (σ_{ke} 1.48, ϵ_{ek} 0.24, ϵ_{ke} 0.12; σ_{kl} 1.40, ϵ_{lk} 0.22, ϵ_{kl} 0.20).

(x) Energy and materials are slightly substitute (σ_{me} 0.44), while materials and labor as well as materials and capital are almost independent (σ_{lm} −0.03, σ_{km} 0.13).

On the basis of the above findings, in order to identify the directions of substitution, the magnitude of transaction between production factors was calculated by using a simple multiplicated index (D_{ij}) of average price elasticity of demand and the increasing rate in prices (%). As a result, the following indications were obtained as illustrated in fig. 4.

(i) Energy substituted to technology (D_{te} 2.60, D_{et} −0.10).
(ii) Labor substituted to technology (D_{tl} 2.61, D_{lt} −0.16).
(iii) Energy substituted to capital (D_{ke} 1.17, D_k −0.57).
(iv) Labor substituted to capital (D_{kl} 0.69, D_{lk} −0.54).
(v) Energy slightly substituted to materials (D_{me} 0.36, D_{em} 0.21).
(vi) Materials and capital have been moving from a complement to a substitute for technology (D_{tm} −0.15, D_{mt} 0.01, and D_{tk} 0.26, D_{kt} 0.02 on average between 1974–87: D_{tm} 0.03, D_{mt} −0.02, and D_{tk} 0.17, D_{kt} −0.01 on average between 1979–87).

5. Implications of empirical results

In light of the foregoing findings, I have reached the following conclusions, and these verify the hypothesis mentioned at the beginning of this paper.

Triggered by the sharp increase in energy prices due to the two energy crises;

(i) Energy has been substituted by technology and also, to some extent, by capital. This can be confirmed by looking at the intensive R& D efforts that sought freedom from energy constraints [14] and also the sharp increase in energy saving investments [15] in the Japanese

[14] The share of expenditure for energy R&D out of total R&D expenditure by the Japanese manufacturing industry increased from 2.2 percent in 1976 to 8.2 percent in 1980. Source: Report on the Survey of Research & Development (Management & Coordination Agency).

[15] The shares of energy saving investment out of total investment in major Japanese industries were extremely small in 1970. However, they increased sharply in 1980 as follows: cement 46 percent, iron and steel 9 percent, paper and pulp and petrochemical 7 percent. Source: Japan Development Bank.

manufacturing industry after the first energy crisis in 1973.

(ii) Sharp increases in energy prices resulted in an increase in labor prices which has induced technology to be substituted for labor. This can be confirmed by looking at the significant increase in R&D on robotics for manufacturing process. [16]

(iii) Although capital and material have been complementary with technology, they have been shifting towards substitution by technology. These trends in Japan's manufacturing industry can be typically confirmed by looking at incidations that R&D expenditure has been exceeding capital investment. [17]

(iv) Thus, all of the production factors have been, directly or indirectly, substituting to technology or have been shifting towards that direction as illustrated in fig. 4.

These empirical results prove my hypothesis.

6. Concluding remarks

The above results suggest that induced technology has been changing energy and other coefficients dramatically. However, in my previous analysis inspecting the significance and consistency of technological knowledge stock by using a simple Cobb–Douglas type production function, I depended on fixed coefficients. Therefore, in concluding, I would like to briefly propose the production function illustrated in table 12 in the case of using a Cobb–Douglas type production function, which shows statistically more significant over the whole time period and explains the drastic change in energy and other coefficients due to technological innovation efforts aiming for freedom from energy constraints.

In that Cobb–Doublas type production function, the energy and labor coefficients, especially the energy coefficient, are defined as a function of the change in technological knowledge stock $(\Delta T/T)$ [18] and an increase in this stock contributes significantly to a decrease in dependency on energy. This also provides substantiation of both the significance as well as the consistency of technological knowledge stock and also of my hypothesis.

Appendix – Data construction, sources and outcomes of the calculation for input data

A.1. General concept

Production: $Y = f(L, K, M, E, T)$,
Gross cost: $C = c(Y, P_l, P_k, P_m, P_e, P_t) = GLC + GCC + GMC + GEC + GTC$,
where GLC is gross labor cost, GCC is gross

[16] Production of advanced robotics for manufacturing use has shown a sharp increase from 14 billion yen in 1976 to 300 billion yen in 1985. Source: Japan Industrial Robotics Association.

[17] Ratio of R&D expenditure to capital investment in the Japanese manufacture industry.
Manufacturing industry total: 1982; 64%, 1987; 76%.
Automobile industry: 1982; 77%, 1987; 100%.
Source: White Paper on Industrial Technology (1988) [29].

[18] The capital and materials coefficients are also defined as a function of the change in technological knowledge stock, however, influences of that change on these coefficients are small.

Table 12
Production function with dynamic elasticities for the Japanese manufacturing industry (1970–87) [a,b]

$Y = 0.46$	L^{b1}	K^{b2}	M^{b3}	E^{b4}	adj. R^2 0.989	D.W. 1.41
	(2.19)	(4.03)	(3.54)	(4.48)		

$b1 = 0.132/(fl*T)^{0.26}$; $fl = fl(Te/T) = P^{-1.04}$
$b2 = 0.172*(fk*T)^{0.18}$; $fk = fk(Te/T) = P^{-1.00}$
$b3 = 0.767*(fm*T)^{0.04}$; $fm = fm(Te/T) = P^{-2.00}$
$b4 = 0.007/(fe*T)^{0.35}$; $fe = fe(Te/T) = P^{-2.11}$

T, technological knowledge stock; Te, technological knowledge stock of energy R&D; P, international oil prices.
[a] Figures in parentheses indicate t-value.
[b] fl, fk, fm and fe are functions which define the rate of significant contribution of technology to relaxing energy constraints. They are similar to "monthly working hours" for labor and "operating rate" for capital which adjust the availability of production factors and can be represented by a ratio such as Te/T (which reflects trend in international oil prices).

capital cost, GMC is gross materials cost, GEC is gross energy cost, and GTC is gross technology cost. GTC consists of costs for labor (GTC_l), capital(GTC_k) [A1], materials(GTC_m), and energy (GTC_e).
Price: $P_l = GLC/L$, $P_k = GCC/K$, $P_m = GMC/M$, $P_e = GEC/E$, and $P_t = GTC/T$.

I have calculated production factors in the following ways: L is (number of workers) × (working hours), K is (capital stock) × (operating rate), M is total sum of raw, processed and auxiliary materials, and components used for production, E is final energy consumption, and T is technological knowledge stock.

Production factors and costs with regard to labor, capital, materials, and energy contain technology-related factors which are incorporated in T and GTC. Therefore, in order to avoid duplication, I have deducted technology-related factors from L, K, M, E and GLC, GKC, GMC, GEC as follows:

$$Y = f\left[(L - L_r), (K - K_r), (M - M_r), (E - E_r), T\right],$$

$$C = (GLC - GTC_l) + (GCC - GTC_k) + (GMC - GTC_m) + (GEC - GTC_e) + GTC,$$

where L_r is (number of researchers) × (working hours), K_r is (capital stock for R&D) × (operat. rate), M_r is materials for R&D, and E_r is energy for R&D.
Prices are: $P_l = (GLC - GTC_l)/(L - L_r)$, $P_k = (GCC - GTC_k)/(K - K_r)$, $P_m = (GMC - GTC_m)/(M - M_r)$, $P_e = (GEC - GTC_e)/(E - E_r)$, and $PT = GTC/T$.

A.2. Data construction and sources

The data used for the analyses were constructed in accordance with the formulas described in section A.1. by depending on the following sources, all of which are Japanese publications.
(1) Y and C: Annual Report on National Accounts (Economic Planning Agency).
(2) Production factors (except T)
1) L: number of workers: Annual Report on National Accounts and Year Book of Labor Statistics (Ministry of Labor), working hours: Year Book of Labor Statistics. [A2]
2) K: capital stock: Statistics of Enterprises' Capital Stock (Economic Planning Agency), operating rate: Annual Report on Indices on Mining and Manufacturing (MITI). [A2]
3) M: Industrial Statistics (MITI). [A2]
4) E: Energy Balances in Japan (Institute of Energy Economics). [A2]
(3) Gross costs
1) GLC, GKC, GMC, and GEC (1970–85): Input–Output Tables [A2] (Management and Coordination Agency).
2) GLC, GKC, GMC, and GEC (1986 and 1987): because Input–Output Tables for these years were not available, I have estimated based on trends for 1970–85 and also on related statistics of the Annual Report on National Accounts, Industrial Statistics, and Energy Statistics (Institute of Energy Economics). [A2]
3) GTC and its composition:
$GTC = RDE + TIE = GTC_l + GTC_k + GTC_m + GTC_e$, where RDE is R&D expenditure, and TIE is payment for technology import.
All data originate from the Report on the Survey of Research and Development (Management and Coordination Agency) except for GTC_e, which comes from the Questionnaire to Major Firms (undertaken in April 1990 supported by AIST, MITI). [A3]
(4) Technological knowledge stock (T).

Considering the differences of time lag of R&D to commercialization (m) depend upon the stages of technology, I have estimated by summing up respective technological stock using the equations described in section 3 as follows:

$$RSTK_t = RSTK(B)_t + RSTK(A)_t + RSTK(D)_t + RSTK(Imp)_t.$$

[A1] Expenditures for tangible fixed assets, information purchases, technology import, travel, communications, and premiums.

[A2] These statistics maintain consistency with the Annual Report on National Accounts.

[A3] Both the Report on the Survey of Research and Development and the Questionnaire to Major Firms maintain consistency with the Annual Report on National Accounts by multiplying survey returns of each stratum by the reciprocal of the sample fraction.

Table A1
Structure of technology import in the Japanese manufacturing industry

1. Ratio of technology import to R&D expenditure in manufacturing industry (%)

1970	1975	1980	1985	1987	
14.5	10.7	8.1	5.2	4.6	[Source 1]

2. Types of imported technology (1973 to 1985)
   (1) Types of payment
   Patentship: 19%, patentship and know-how: 19%, patentship, know-how and technical guidance: 16%, know-how: 14%, know-how and technical guidance: 9%, instruments and equipment: 7%, technical guidance: 5%, others: 11%.
   (2) Character of technology
   Fundamental technology: 35%, improved technology: 22%, accessary technology: 17%, package of these technologies: 26%. [Source 2]
3. Motivations in importing technology (%)

	–1960	1960–1973	1973–1985	1985–(estimate)	
Catch up with tech. level	33	26	20	20	
No advanced tech. at home	51	47	47	42	
Clash with patent	15	26	30	32	
Others	1	1	4	5	
Total	100	100	100	1100	[Source 2]

4. Conditions of contract
   (1) Average of terms of contract (years)

1970	1975	1980	1985	1987	
6.4	5.1	5.6	5.9	6.0	[Source 3]

   (2) Estimated lifetime of imported technology:
   Approximately 2 times that of the contract terms. [Source 4]

Source: 1. Report on the Survey of Research and Development (annual issues: Management and Coordination Agency, Japan).
2. Impact of Technology Import on Japanese Economy, Technology and Society (AIST of MITI [2]).
3. Annual Report on Technology Import (annual issues: Science and Technology Agency, Japan).
4. Changing R&D and Capital Investment (Japan Development Bank [20]).

Table A2
Trends in technological knowledge stock in the Japanese manufacturing industry (1970–87)[a,b]. Real (1980 price); 100 mil yen

	R&D				Tech. import	Total
	Basic research	Applied research	Develp. research	Total		
1970	3,154	12,676	20,186	36,016	6,144	42,160
1971	3,690	14,705	27,990	46,385	6,980	53,365
1972	4,330	17,123	37,092	58,545	7,392	65,937
1973	5,234	20,035	45,553	70,821	10,356	81,177
1974	6,165	23,096	55,223	84,484	10,695	95,178
1975	7,119	25,618	65,308	98,045	11,600	109,645
1976	8,171	27,507	74,343	110,021	13,533	123,554
1977	9,111	28,982	82,648	120,741	15,062	135,803
1978	9,801	30,171	90,815	130,787	15,658	146,445
1979	10,233	31,180	99,131	140,544	16,412	156,956
1980	10,416	32,315	108,150	150,881	17,083	167,964
1981	10,455	33,508	117,498	161,462	18,202	179,664
1982	10,499	34,882	127,639	173,021	19,463	192,484
1983	10,550	36,712	138,762	186,025	20,944	206,969
1984	10,666	39,360	150,654	200,680	23,610	224,289
1985	10,931	42,788	164,514	218,233	24,864	243,097
1986	11,410	46,647	179,877	237,934	27,205	265,139
1987	12,091	50,999	198,544	261,633	27,903	289,536

[a] Time lag to commercialization – basic research: 5.6 years, applied research: 3.6 years, development research: 2.0 years, and imported technology: 3.3 years.
[b] Rate of obsolescence of technology: 9.8%.

Table A3
Structure of internal technology in the Japanese manufacturing industry in 1987

		CNA[b]	Sources
1. Gross technology expenditure	6,382 bill. yen [a]		
(1) R&D expenditure	6,101 (100%)		
1) Labor costs	2,553 (41.8%)	GLC[d]	source 1
2) Expenditure on tangible fixed assets	883 (14.5%)	GCC	source 1
① Machinery, instruments, equipment	627 (10.3)		
② Buildings, land	198 (3.2)		
③ Others	58 (1.0)		
3) Materials	1,270 (20.8%)	GMC	source 1
4) Other expenses	1,395 (22.9%)		
① Information purchases	185 (3.0)	GCC	source 2
② Energy	170 (2.8)	GEC	source 2
③ Miscellaneous (travel, communicat.,premiums,etc.)	1,040 (17.1)	GCC	source 1
(2) Technology import	281 (4.6% of R&D expenditure)	GCC	source 1
2. Number of researchers (num.of pers.engaged in R&D)	446 thousand persons		source 1
3. Capital stock for R&D	3,836 bill. yen[c]	eqn in A.2.	
4. Energy consumption	1100×10^{10} kcal		source 2

[a] Current prices.
[b] Countings in the national account.
[c] Constant prices in 1980.
[d] GLC: gross labor cost, GCC: gross capital cost, GMC: gross materials cost, and GEC: gross energy cost.
[c] Trends in the share of R&D expenditure (%) are as follows (source 1):

	1970	1971	1972	1973	1974	1975	1976	1977	1978
① Labor costs	40.4	43.6	45.7	46.5	51.4	53.4	53.1	52.2	50.9
② Exp.on T.F.A.	21.1	18.5	17.0	16.5	12.8	11.8	10.9	10.9	11.4
③ Materials	20.5	20.4	19.6	17.7	17.6	17.0	17.7	18.3	19.1
④ Other expens.	18.0	17.5	17.7	19.3	18.2	17.8	18.3	18.6	18.6

	1979	1980	1981	1982	1983	1984	1985	1986	1987
① Labor costs	49.5	48.0	45.8	44.9	43.6	42.9	41.2	41.8	41.8
② Exp.on T.F.A.	12.4	13.9	14.5	14.9	14.2	14.8	15.3	14.9	14.5
③ Materials	19.1	18.8	20.2	20.3	20.1	20.9	20.9	20.9	20.8
④ Other expens.	19.0	19.3	19.5	19.9	22.1	21.4	22.6	22.4	22.9

Source: 1. Report on the Survey of Research and Development (annual issues: Management and Coordination Agency, Japan).
2. Questionnaire to Major Firms (undertaken in April 1990 supported by AIST, MITI, Japan) [18].

The right-hand side in the equation is technological knowledge stock in the period t generated by basic research, applied research, development research, and imported technology respectively. In estimating $RSTK(\text{Imp})_t$, first, on the basis of a survey made by AIST of MITI [2] and the Japan Development Bank [20], I analyzed the structure of technology import in Japan's manufacturing industry over the period of the 1970s and 1980s. The outcome of the analysis is summarized in table A1 which suggests that: (a) although dependency on imported technology in Japan's manufacturing industry has been decreasing (ratio of payment for technology import [A4] to R&D ex-

[A4] Most payments for technology import are "soft payments" consisting of payments for patentship, know-how and technical guidance (see table A1).

Table A4
Relationship between internal technology and the national account in the Japanese manufacturing industry in 1987

A. Gross cost	(bill. yen: current prices) 1.CNA	2.Gross tech. cost	3. 2./1. (%)	Sources for CNA[a]
Gross labor cost	45,409	2,553	5.6 (4.0)[b]	source 1,2
Gross capital cost	56,897	2,389[c]	4.2 (3.2)	source 1,2
Gross materials cost	162,155	1,270	0.8 (0.5)	source 1,2,3
Gross energy cost	18,087	170	0.9 (0.6)	source 1,2,4
Total	282,548	6,382	2.3 (1.6)	
B. Production factor	1.CNA	2.Technology	3. 2./1. (%)	Sources for CNA[a]
Labor (thous.persons)	14,684	446	3.0 (2.2)	source 1
Capital stock (bill. yen[d])	20,337	3,836	18.9(17.2)	source 1,5
Materials (bill. yen)	151,774	1,270	0.8 (0.5)	source 1,2,3
Energy (10^{10} kcal)	116,766	1,100	0.9 (0.9)	source 4

[a] See table A3 sources for technology.
[b] Figures in parentheses indicate average for 1970–87.
[c] Expenditure on tangible fixed assets: 883, information purchases: 185, miscellaneous expenses: 1040, and technology import: 281.
[d] Constant prices in 1980.
Source: 1. Annual Report on National Accounts (Economic Planning Agency, Japan).
2. Input–Output Tables (Management and Coordination Agency, Japan).
3. Industrial Statistics (MITI, Japan).
4. Energy Statistics (Institute of Energy Economics, Japan).
5. Statistics of Enterprises' Capital Stock (Economic Planning Agency, Japan).

penditure decreased from 14.5 percent in 1970 to 4.6 percent in 1987), imported technology has been incorporated in all stages of indigenous technology from fundamental technology to accessory one as inseparable parts of the technology system, not independent ones, (b) payment for technology import has been changing from a means of catching up with the technological level by paying cheaper cost than own R&D expenditure to a means of avoiding clashes with patents for indispensable technology, therefore, (c) such payment has gained a significant meaning similar to own R&D expenditure in achieving R&D of indispensable technology, and, (d) the average of terms of contract of imported technology is five to six years and its lifetime is estimated to be 10 to 12 years. On the basis of the above analysis, I assumed that, on average, payment for technology import behaved similar to the average of own R&D expenditure in generating technological knowledge stock: $RSTK(\mathrm{Imp})_t = TIE_{t-m} + (1-\rho)RSTK(\mathrm{Imp})_{t-1}$, where m is 3.3 years, [A5] and ρ is 9.8 percent.

Data for R&D expenditure (*RDE*) in respective stages and *TIE*, as well as the increasing rate of *RDE* and *TIE* in the initial period are based on the Report on the Survey of Research and Development. Outcomes of the estimation are presented in table A2.

(5) Technology-related production factors (L_r, K_r, M_r, E_r)

1) L_r: number of researchers: in order to maintain consistency with countings in the national account, I used the number of persons engaged in R&D [A6] from the Re-

[A5] This estimate is longer than AIST, MITI's survey in 1963 [1] (2.5 years) and also Science and Technology Agency's survey in 1985 [2] (2.4 years); however, based on the recognition derived from the above analysis, I used this estimate.

[A6] Persons engaged in R&D consist of researchers, assistant research workers, technicians, and clerical and other supporting personnel.

Table A5
Indices of production and input factors in the Japanese manufacturing industry (1970–87). Real (1970 = 100)

Year	Production	Labor[a]	Capital[a]	Material[a]	Energy[a]	Technology
1970	100.00	100.00	100.00	100.00	100.00	100.00
1971	105.02	98.57	106.84	98.21	105.41	126.58
1972	114.29	98.23	118.83	107.08	108.32	156.40
1973	127.18	101.54	137.13	121.23	124.42	192.54
1974	122.44	95.98	137.54	115.44	122.77	225.75
1975	116.57	88.05	125.56	110.58	110.31	260.07
1976	127.44	90.41	143.61	120.32	114.70	293.06
1977	133.97	89.80	150.45	131.89	113.05	322.11
1978	141.36	89.06	163.03	138.28	112.10	347.35
1979	152.14	89.82	182.34	144.55	115.70	372.28
1980	158.22	91.39	193.64	145.09	110.92	398.39
1981	163.85	91.81	196.52	149.42	104.59	426.15
1982	166.70	91.18	200.05	147.95	99.02	456.55
1983	175.20	93.38	212.84	153.96	94.03	490.91
1984	191.63	96.51	242.10	167.05	100.11	531.99
1985	201.67	96.22	263.95	175.16	99.32	576.60
1986	204.03	95.59	282.15	177.30	95.26	628.88
1987	211.31	94.86	297.14	177.08	96.72	686.75

[a] Services of input for technology are all deducted and included in technology.

port on the Survey of Research and Development, and working hours: on the basis of both Year Book of Labor Statistics [A7] and of the survey on working conditions of researchers in Japan's manufacturing industry (Science and Technology Agency, 1990), [A8] I assumed that average working hours of persons engaged in R&D were the same as average working hours of workers.

2) K_r: Capital stock for R&D: I estimated by using the following equations. $KR_t = (RDE_k)_t + (1 - \rho)KR_{t-1}$, $KR_0 = (RDE_k)1/(g + \rho)$, where RDE_k is R&D expenditure for capital ($= GTC_k$) [A9] which can be obtained annually from the Report on the Survey of Research and Development. I estimated ρ for this by taking the inverse of the average of the lifetime on tangible fixed assets for R&D defined by Corporate Tax Law [A10] assuming that capital stock for R&D depreciates and becomes obsolate over time. Average lifetime was 7 years and the rate of obsolescence of capital stock for R&D was estimated at 14.3 percent. Operating rate: as I depended for the lifetime on the above law, on the basis of the principle underling the law (all production facilities, including R&D facilities, should be dealt with using the same

[A7] The average monthly working hours of employees in Japan's manufacturing industry (number of employees 30 or more) in 1988 was 181.1 hours, consisting of production workers with 181.8, and intellectual workers (researchers, operators and administrators) with 179.9.

[A8] The average monthly working hours of researchers in Japan's manufacturing industry in 1989 was 186.9 hours (including 23.1 hours' research works in the out of fixed working time) which was similar to the average monthly working hours of all workers in Japan's manufacturing industry. Source: Survey on Researchers for the Promotion of Basic and Leading Science and Technology (Institute for Future Technology entrusted by Science and Technology Agency, 1990).

[A9] Average time lag to operation is less than 1 year.

[A10] Legal lifetime of the tangible fixed assets for R&D is, buildings: 10–25 years, constructions and installations: 5–7 years, machinery and instruments: 4–7 years, and equipment and tools: 4 years. By examining the composition of expenditure on tangible fixed assets which can be obtained annually from the Report on the Survey of Research and Development, I estimated the average lifetime of the capital stock for R&D. Source: Corporate Tax Law (MITI).

Table A6
Total production cost and cost shares of production factors in the Japanese manufacturing industry (1970–87)

Year	Total production cost (bill. yen[b])	Cost shares(%)[a]				
		Labor	Capital	Materials	Energy	Technology
1970	80,379	12.93	18.49	63.21	4.29	1.08
1971	84,223	14.03	18.46	62.13	4.26	1.12
1972	93,010	14.66	18.85	61.26	4.02	1.21
1973	119,026	14.29	17.12	63.27	4.18	1.14
1974	148,453	15.03	14.98	61.44	7.46	1.09
1975	146,613	13.84	15.21	61.48	8.31	1.16
1976	168,300	14.84	13.94	61.98	8.11	1.13
1977	180,401	13.29	16.05	61.59	7.90	1.17
1978	187,732	13.43	17.58	61.22	6.55	1.22
1979	207,585	12.85	17.02	61.36	7.48	1.29
1980	242,496	14.40	13.93	60.63	9.75	1.29
1981	252,592	12.70	16.10	60.21	9.55	1.44
1982	257,591	15.74	14.93	58.45	9.31	1.57
1983	264,895	15.82	14.45	49.88	8.14	1.71
1984	286,321	15.66	14.42	60.64	7.51	1.77
1985	296,487	14.43	16.35	60.35	6.90	1.97
1986	283,344	14.92	18.21	58.47	6.28	2.12
1987	282,548	15.17	19.29	56.94	6.34	2.26

[a] Costs for technology are all included in technology cost (not included in other cost factors).
[b] Current prices.

Table A7
Indices of prices of production factors in the Japanese manufacturing industry (1970–87). Real (1970 = 100)

	Labor	Capital	Materials	Energy	Technology
1970	100.00	100.00	100.00	100.00	100.00
1971	109.19	92.81	106.54	99.85	80.91
1972	119.89	89.31	111.84	100.09	71.57
1973	128.14	79.37	104.82	100.69	58.45
1974	147.22	71.45	93.69	176.56	48.11
1975	135.50	72.93	95.42	212.31	41.15
1976	151.46	62.43	91.54	218.94	37.77
1977	138.37	69.79	113.82	227.78	36.38
1978	139.92	69.98	116.69	201.50	35.98
1979	142.60	65.19	119.57	232.61	36.18
1980	176.64	56.53	94.81	321.66	36.78
1981	156.51	64.82	94.12	345.49	38.76
1982	195.64	59.12	93.46	358.74	39.17
1983	195.95	54.88	94.96	344.67	40.56
1984	200.34	51.38	95.89	323.20	41.15
1985	187.69	54.51	94.89	313.36	43.74
1986	184.73	53.40	102.94	306.26	41.95
1987	189.20	53.59	110.43	305.57	40.76
A.A.G.R.[a]					
1970–87	4.3	−3.3	1.0	8.5	−4.8
1974–87	3.4	−2.4	0.8	10.2	−2.3

[a] Average annual growth rate (%).
[b] Prices for technology are all included in technology price (not included in other price factors).

principle), I used the same operating rate as capital stock general. [A11]

3) M_r and E_r: I estimated on the basis of both the Report on the Survey of Research and Development and the Questionnaire to Major Firms.

I present in tables A3 and A4 outcomes of the estimation of the breakdown of GTC and T in 1987 and also average for 1970–87. Looking at table A4 we notice that the GTC_l/GLC ratio in 1987 (5.6 percent) was higher than the L_r/L

[A11] Although I need further empirical survey work on the operating rate of R&D facilities in Japan's manufacturing industry, on average, I can assume a similar operation rate of both capital stock for production and for R&D considering the significant correlation between working hours (which were almost the same between workers engaging in production and researchers as I checked) and operating rate in production facilities:

Operating rate =
−140.58 + 1.33 working hours (1970–87) R^2 0.70
(−3.78) (6.43) D.W. 0.87

ratio (3.0 percent). This was considered due to the higher price (salary) of researchers. On the other hand, the K_r/K ratio (18.9 percent) was extremely higher than the GTC_k/GCC ratio (4.2 percent). This was considered due chiefly to the lower average price of R&D facilities because of shorter lifetime facilities (average legal lifetime of tangible fixed assets for production facilities is longer than 20 years which is more than three times longer than similar assets for R&D).

A.3. Outcomes of the calculation for input data

I present outcomes of the calculation for input data (production, cost and price) avoiding duplications in tables A5–A7.

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