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The estimation of energy consumption and amount of pollutants due to the construction of buildings

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Abstract

In this paper, the total energy consumption and environmental pollution caused by construction are quantified using the Inter-Industry Relations Table in Japan.

The size of the six buildings which are evaluated in this study vary from 1502 m^2 to 216 000 m^2. The major results are as follows:

- total energy consumption caused by construction of office buildings is 8–12 GJ/m^2 of floor area;
- CO_2 production is 750–1140 kg, SO and SO_2 720–1430 g, NO and NO_2 700–1140 g, dust 70–130 g per m^2 of floor area;
- the construction cost per square meter of floor space is proportional to the energy consumption and production of pollutants;
- structural work is shown to be high in energy consumption and CO_2 exhausted per unit cost of construction; industrial waste exhausted in finishing work is higher than two other categories of the work (structure and equipment); equipment work is shown to be relatively low in energy consumption, CO_2, NO, NO_2 and industrial waste produced.

1. Introduction

The purpose of this study is to quantify the total amount of energy consumption and environmental pollutants caused by the construction of office buildings. Because the construction of an office building is a large-scale project utilizing many different kinds of building materials, the construction of buildings impacts many other industries. In order to quantify the pollutants due to construction, it is necessary to obtain the total amount of domestic goods and services that were used (referred to hereafter as "final domestic product"). For these quantitative analyses, Inter-Industry Relations Tables are used. In the current Inter-Industry Relations Table [1], the industries in Japan have been classified into approximately 400 groups.

2. Analytical calculations using the Inter-Industry Relations Table

The Leontief inverse matrix was used to estimate the total amount of domestic products caused by the construction of office buildings. The model for calculating the total amount of domestic products is the following expression:

$$X=[(\mathbf{I}-(\mathbf{I}-\mathbf{M})\mathbf{A})]^{-1}[(\mathbf{I}-\mathbf{M})Y+E)] \quad (1)$$

where X = production vector = total domestic products (yen/year)
$\mathbf{I}$ = unit matrix
$\mathbf{A}$ = coefficient of input matrix
Y, E = total demand vector and export vector (yen/year)

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Y_i, E_i = final demand and exports of i product (yen/year)

$$\mathbf{M} = \begin{bmatrix} m_1 & & 0 \\ & \ddots & \\ 0 & & m_i \end{bmatrix}$$

$\mathbf{M}_i$ = import of i product (yen/year)

$$\mathbf{m}_i = \mathbf{M}_i \mathbf{C}_i = \frac{\mathbf{M}_i}{\sum_j A_{ij} X_j + Y_i}$$

$\mathbf{C}_i$ = (domestic product + import − export) of i product (yen/year)

To calculate the total amount of total domestic products, it is necessary to subtract transportation costs, storage costs, and profitability from the total price of the construction project because the Inter-Industry Relations Table is based on the costs of the producer. In this paper, the average transportation and storage costs, and average profitability written in the Inter-Industry Relations Table were used, and those were subtracted from the price of the buyer, then vector Y was put into eqn. (1).

The data used in these calculations are from the 1985 Inter-Industry Relations Table which includes over 406 different industries excluding iron and various metals. The estimates for construction are from the period beginning in 1986 and ending in 1988. The construction estimates were then converted to reflect costs in 1985 by using the Construction Price deflator for 1985.

3. Calculating the amount of final production

The data which were used for quantitative analysis by using the Inter-Industry Relations Table were collected from six buildings listed in Table 1, which ranged in size from 1502 to 216 000 m^2.

In Japan, large-scale building structures are mainly steel structures and small buildings have reinforced concrete structures mostly. Therefore the smallest building (no. 1 in Table 1) has a reinforced concrete structure and relatively large-scale buildings (no. 4–6 in Table 1) have steel structures.

The construction costs were separated into four categories: structural work, finishing work, equipment work, and general management work. The cost of each category was itemized and classified further into two categories: (1) material cost (which includes the cost of materials and other items purchased from other categories of industries), (2) labor cost (which includes labor cost and other value added). In Japan, to estimate the cost of the construction, there is a handbook which shows the average material/labor cost data in each category of work (for example, ceiling work, ducting work, etc.) [2]. Thus, average labor/material data corresponding to each work category are used for calculating the required labor cost for the construction and material cost. The cost of materials, thus, is the price to the buyer. To convert this amount into the cost for the producer, the profit margin, transportation cost and storage cost were subtracted using the Inter-Industry Relations Table which includes the average transportation cost, average profit margin and average storage cost for corresponding categories of the industries.

The quantity and price for major materials such as steel, concrete and various energy resources which are consumed in each industrial sector are written in the Inter-Industry Relations Table, therefore it is possible to obtain unit price of major materials. In this paper, the amount of expenses for major materials such as steel and concrete are compensated by using the unit price in the Inter-Industry Relations Table and used quantity of materials, because, if the unit price differs in contract forms in each building, the consumption of quantity of materials may differ.

For other materials, the amount of expense was directly classified into the value added and expense to other industry sectors except the building construction sector, using work classification sheets (which includes average labor/materials data).

The costs for general management were calculated by taking the difference between the amount of the contract and the net construction cost. In this paper, the cost for general management was broken down into many categories such as mail and telegraph costs, advertising expenses, and office supplies by analyzing financial statements [3]. The labor cost is ranked first and covers over 57% of the total general management cost. These costs were then put into corresponding categories by industry.

Thus, the total demand was calculated and put into eqn. (1) to calculate the total domestic products.

Table 2 shows the domestic production which was calculated using eqn. (1). Data from 406 different industry categories was integrated into twelve categories shown in Table 2. (Exchange rate at January 4, 1993 is about 124 yen/US$.)

The direct value added in Table 2 varies from 42% to 53% of the total price. In Japan, mean direct value added is 44% for non-wooden, non-residential buildings and 52% for wooden residential houses [4]. Final value added in all industrial sectors which is influenced by the construction of the building is

TABLE 1. Building statistics

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Building use	Office	Office	Office	Office	Office	Office
Total floor space (m^2)	1502	2802	3500	22 861	88 049	216 000
Number of floors	4 A. G. 1 B.	8 A. G. 1 B.	8 A. G. 1 B.	18 A.G. 1 B.	31 A. G. 5 B.	25 A.G. 1 B.
Building structure	RC	SRC + S	SRC	S	S	S
Air-conditioning system	Air source HP (package + duct system)	Air source HP multi air-conditioning system	Air source HP multi air-conditioning system	Gas absorption refrigeration and heating (air-conditioner + FCU)	District heating and cooling (air-conditioner + convector)	District heating and cooling (air-conditioner + FCU)
Concrete (m^3/m^2)	0.830	0.282	0.565	0.351	0.504	0.449
Reinforcement (kg/m^2)	137.80	17.67	56.50	29.60	45.66	41.30
Steel frame (kg/m^2)	0	133.70	87.51	172.80	113.10	110.13
Total steel (kg/m^2)	137.80	151.37	144.01	202.40	158.76	151.43

TABLE 2. Domestic production required for building construction per m^2 (unit: 1000 yen)

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Agriculture and forestry, marine, mining, food	9.9	4.8	6.1	3.7	6.1	3.6
Textile, paper, wood products	7.8	6.1	9.1	13.5	11.3	8.2
Chemical, oil, coal products	41.0	30.9	29.4	26.7	20.8	21.8
Ceramic, clay products	20.1	24.4	27.5	24.7	15.1	13.5
Steel, nonferrous metals	74.6	58.5	71.0	70.6	77.0	55.8
Metal goods	48.6	31.0	48.6	26.8	23.7	13.2
Electricity, shipping, precision instrument, etc.	49.2	38.0	36.4	45.0	27.1	18.8
Other manufacturing	9.4	6.9	7.7	7.0	6.4	4.5
Electric power, gas, water, wastes	6.3	5.1	5.7	5.9	4.7	3.9
Trade, finance, insurance real estate	15.8	12.7	12.6	15.1	12.1	8.2
Transportation	15.4	10.4	11.9	10.6	11.1	6.5
Others, service, etc.	15.4	11.6	13.0	13.3	10.4	8.4
Domestic category total	313.5	240.5	278.9	262.6	225.8	166.4
Indirect value added (A)	196.8	154.6	172.0	164.7	139.0	101.1
Domestic production	510.3	395.0	450.9	427.3	364.8	267.5
Direct value added (B)	184.1	157.1	147.1	162.4	155.9	136.8
Construction cost (C)	409.3	337.5	347.3	356.3	319.7	258.7
B/C	0.45	0.47	0.42	0.46	0.49	0.53
(A+B)/C	0.93	0.92	0.92	0.92	0.93	0.92

between 92–93% of the construction price, therefore 7–8% of the construction price is paid for imported materials in Japan.

4. Calculating the total amount of resources used

Table 3 shows the total amount of materials used in constructing a building. The raw materials in different categories were calculated by using the Inter-Industries Relations Table and Table of Materials.

Iron ore is mainly used for structural work and limestone is mainly used for structural and finishing work. Iron ore and limestone consumption is about proportional to that of cement.

Resources of power plants are classified into three categories: nuclear which represents approximately 26% of power in Japan, fuel which represents approximately 61%, and hydraulic which represents approximately 13% in Japan. This paper deals with only fuel, thus nuclear and hydraulic power are excluded for the calculation.

Primary energy of 8–12 GJ is necessary to construct one square meter of floor area. Energy consumptions of building no. 1 with reinforced concrete and no. 6, a large-scale building, are small. Energy consumption for finishing work is larger than structural work in cases nos. 1–5.

5. The amount of pollutants exhausted: CO_2, SO, SO_2, NO, NO_2, dust

5.1. CO_2

The amount of CO_2 was calculated by calculating the consumption of oil, coal, and liquefied natural gas (Table 4).

For cement, the amount of CO_2 produced was estimated using data which showed that 0.3 t of CO_2 will be produced for every ton of cement production due to the limestone dissolution. Table 4 shows total CO_2 production from the construction from all six buildings. The total amount of CO_2 was estimated to be 750–1140 kg per square meter. The analysis found that the production of CO_2 was proportional to the amount of energy consumed.

5.2. SO, SO_2, NO, NO_2, and dust

The production of SO, SO_2, NO, NO_2, and dust was estimated based on the assumption that the amount of these gases is proportional to the domestic production of industries based on the category. The production of these gases in each industry sector (20 aggregated sectors in total) has been arranged in Japan [5]. Thus, the amount of SO, SO_2, NO, NO_2 was higher in the category of transportation. The result is shown in Table 5.

The amount of pollutants was calculated from the Inter-Industry Relations Table and the Table of Released Gases. For the production of NO and NO_2, the industry category of transportation was higher than the other industries. The pollutants – SO, SO_2, NO, NO_2 – were produced proportionally.

TABLE 3. Main resources required for building construction per m^2

		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Amount of main resource							
Wood (0.001 m^3)		57	49	93	61	58	90
Iron ore (kg)		358	314	345	409	425	326
Limestone (kg)		433	515	563	453	252	267
Gravel, stone (kg)		1728	622	1313	812	915	1102
Coal for coke making (kg)		156	135	146	173	172	140
Coal (kg)		51	45	52	41	30	28
Heavy oil (l)		92	86	77	93	68	55
Gas oil (l)		27	20	23	20	21	13
Volatile oil, kerosene (l)		33	22	24	20	20	12
LNG City gas (m^3)		26	22	25	25	20	15
Naphtha (l)		72	61	55	43	26	32
Coke (kg)		142	127	137	166	167	128
Utility power (kWh)		431	351	398	412	321	243
Cement (kg)		258	250	311	172	116	127
Amount of resource by items of construction work							
Iron ore (kg)	Structure	244	178	185	224	207	192
	Finishing, etc.	70	96	130	118	115	68
	Equipment	45	40	30	67	103	66
	Expenses	0	0	0	0	0	0
	Total	359	314	345	409	425	326
Limestone (kg)	Structure	209	87	151	106	150	116
	Finishing, etc.	206	415	391	313	75	126
	Equipment	18	13	21	34	27	25
	Expenses	0	0	0	0	0	0
	Total	433	515	563	453	252	267
Utility power (kWh)	Structure	100	68	73	79	69	71
	Finishing, etc.	240	202	262	210	153	104
	Equipment	87	78	60	120	96	65
	Expenses	4	3	3	3	3	3
	Total	431	351	398	412	321	243
Energy consumption (MJ)	Structure	4560	3030	3380	3750	3600	3340
	Finishing, etc.	5680	5400	6590	5530	4340	2880
	Equipment	1740	1600	1150	2540	2540	1750
	Expenses	80	60	60	50	50	60
	Total	12060	10090	11180	11870	10530	8030

Thus, the amount of SO and SO_2 ranged from 720 g to 1430 g, the amount of NO and NO_2 ranged from 700 g to 1140 g, and the amount of dust ranged from 70 g to 130 g per square meter of floor area. Also, as the amount of energy consumed increased, the amount of dust and pollutants increased proportionally.

6. Industrial waste

The amount of industrial waste released is shown in Table 6. The table of amount of industrial waste in each industrial sector has also been arranged. In this paper, the quantity of industrial waste was calculated with reference to the table of amount of industrial waste [6], assuming that industrial waste released in each industrial sector is proportional to the quantity of production. The amount of industrial waste is 230–380 kg per square meter in which 64% is due to finishing work. The waste level was calculated using the Inter-Industry Relations Table which did not include the commercial or service sectors so industrial waste released from commercial and service sectors is not included; however, because

TABLE 4. Amount of CO_2 generated by building construction per m^2 (unit: kg)

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Amount generated by fuel						
Coal	140	124	143	112	82	77
Crude oil·heavy oil	259	217	239	263	172	139
Gas oil	82	61	70	58	57	35
Volatile oil·kerosine	81	52	59	50	51	30
City gas·LNG	57	46	52	54	42	32
Coke	447	397	427	519	520	398
Cement	77	75	98	62	35	33
Total	1144	971	1083	1109	959	749
Amount generated by construction work						
Structure	449	275	345	352	331	347
Finishing, etc.	536	529	648	525	392	219
Equipment	152	161	84	227	230	176
Expenses	7	6	6	5	6	7
Total	1144	971	1083	1109	959	749

TABLE 5. Amount of SO, SO_2, NO, NO_2 and dust by building construction per m^2 (unit: g)

		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Amount generated by construction work							
SO,	Structure	241	166	177	177	190	164
SO_2	Finishing, etc.	947	761	1014	741	526	378
	Equipment	232	186	168	318	238	171
	Expenses	12	10	10	8	9	11
NO,	Structure	337	168	235	201	243	207
NO_2	Finishing, etc.	635	681	782	630	492	321
	Equipment	156	140	105	219	195	159
	Expenses	9	7	8	6	7	8
Dust	Structure	24	15	21	17	19	18
	Finishing, etc.	79	71	91	73	46	38
	Equipment	18	16	13	26	22	14
	Expenses	1	1	1	1	1	1
Amount generated by industrial class							
SO,	Transportation	187	160	184	165	168	117
SO_2	Others	1245	963	1185	1127	795	607
NO,	Transportation	647	535	617	545	562	352
NO_2	Others	490	461	513	511	375	343
Total							
SO, SO_2		1432	1123	1369	1244	963	724
NO, NO_2		1137	996	1130	1056	937	695
Dust		122	103	126	117	88	71

the amount of pollutants is relatively low for these sectors, this is not significant.

To estimate the industrial waste, 74% of the final domestic products is used. 26% of final domestic products cannot be taken into consideration to estimate the amount of industrial waste, because these final domestic products are commercial, insurance and taxes, which lack industrial waste data in the table.

7. Energy and pollutants intensity

Figure 1 shows the relationship between the construction cost and the amount of energy consumed,

TABLE 6. Amount of industrial waste by building construction per m² (unit: kg/m²)

		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Sludge	Structure	41.4	20.2	29.2	23.8	25.2	24.0
	Finishing, etc.	123.2	136.8	157.3	131.7	83.0	69.6
	Equipment	26.4	23.8	19.6	38.5	32.4	27.6
	Expenses	2.1	1.6	1.8	1.3	1.6	1.3
Waste acid	Structure	10.3	7.7	7.3	7.8	6.6	6.7
Waste alkali	Finishing, etc.	65.1	47.1	69.5	45.3	32.7	24.0
Waste oil	Equipment	15.4	13.0	11.4	23.8	14.7	13.8
Waste plastic	Expenses	0.2	0.1	0.1	0.1	0.1	0.2
Scrap, etc.	Structure	3.6	1.8	3.3	2.2	2.4	2.8
	Finishing, etc.	8.5	7.2	10.2	9.4	6.5	6.1
	Equipment	1.9	1.4	1.3	2.3	3.0	1.7
	Expenses	0.2	0.2	0.2	0.2	0.2	0.2
Residue	Structure	30.1	16.6	19.8	19.9	13.3	18.3
Slag	Finishing, etc.	27.7	38.8	46.4	40.7	34.3	20.7
Dust, etc.	Equipment	8.8	8.2	6.5	14.2	16.9	10.2
Others	Expenses	0.1	0.1	0.1	0.1	0.1	0.1
Total		365.0	324.6	384.0	362.4	273.0	227.2

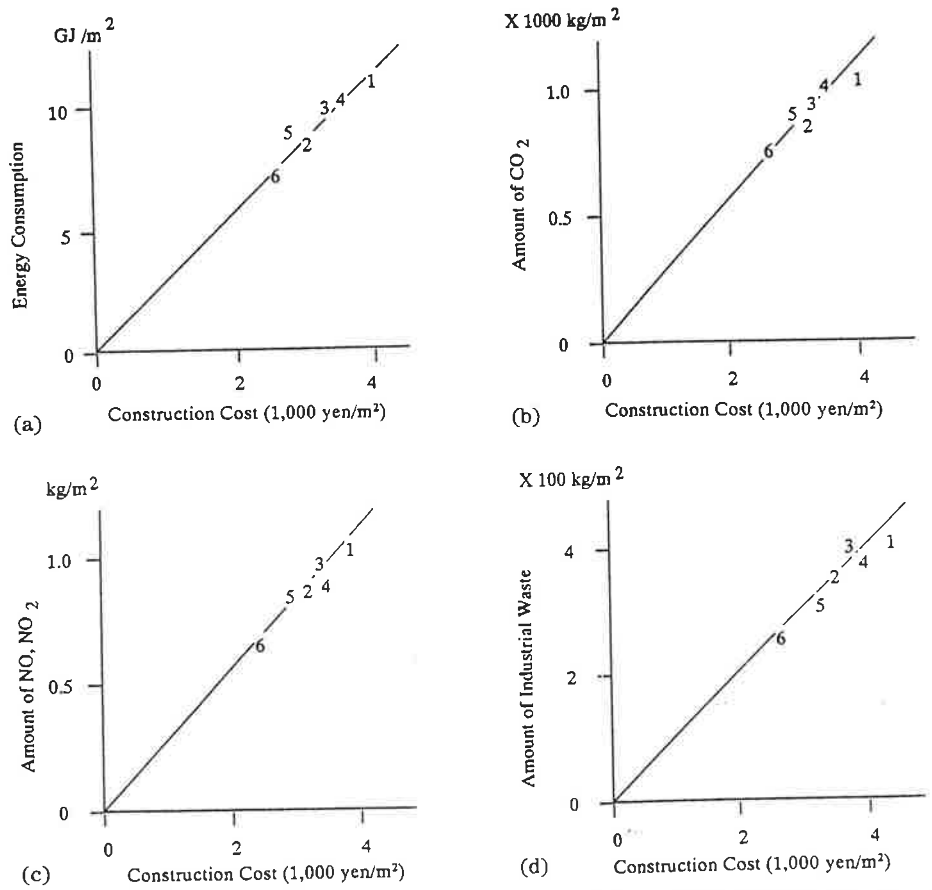

Fig. 1. Relationship between the construction cost and the amount of energy consumption, CO_2, NO, NO_2, or industrial waste per unit floor area (numbers in the graphs correspond to buildings 1–6). (a) Energy consumption. (b) Amount of CO_2. (c) Amount of NO, NO_2. (d) Amount of industrial waste.

and the amount of pollutants and industrial waste produced. The energy consumption, amount of NO, NO_2, CO_2 and industrial waste production are proportional to the construction cost per square meter.

Figures 2, 3, and 4 show the relationship between the amount of CO_2, NO, NO_2 and industrial wastes in each categories of the work versus energy consumption. The amount of pollutants produced is shown to be proportional to energy consumption in each category of construction work (structure, finishing, and equipment). The amount of CO_2 production per energy consumption in each category is almost the same. But the amount of NO, NO_2, industrial waste per energy consumption varies in each category.

Figure 5 shows the energy consumption of structural, finishing, and equipment work versus construction cost. The energy consumption for structural work is higher than the other two categories of the work.

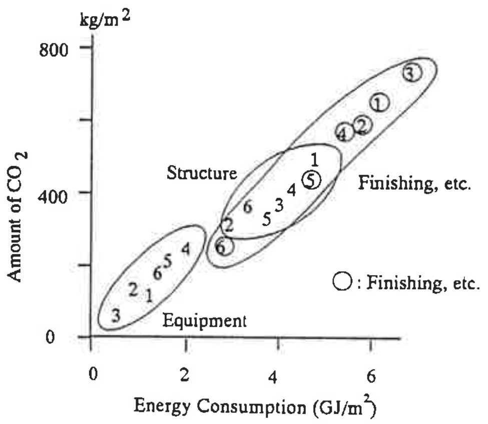

Fig. 2. Relationship between the energy consumption and the amount of CO_2 discharged by the construction work (numbers in the graph correspond to buildings 1–6).

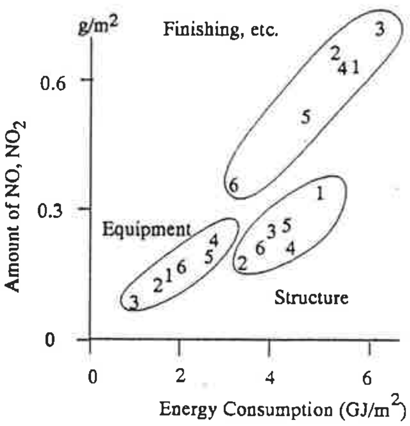

Fig. 3. Relationship between the energy consumption and the amount of NO and NO_2 discharged by the construction work (numbers in the graph correspond to buildings 1–6).

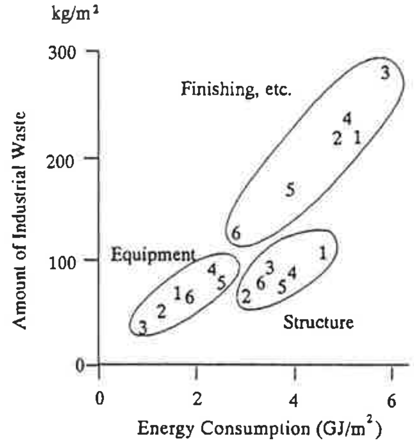

Fig. 4. Relationship between the energy consumption and the amount of industrial waste by the construction work (numbers in the graph correspond to buildings 1–6).

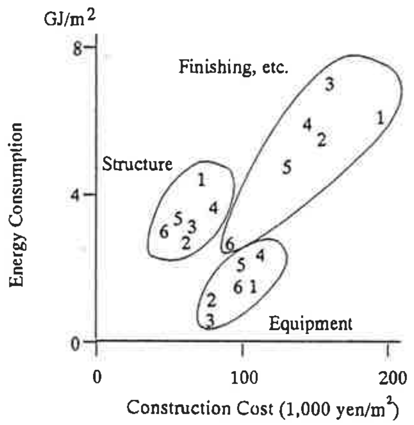

Fig. 5. Relationship between the construction cost per floor area and the energy consumption of the construction work (numbers in the graph correspond to buildings 1–6).

TABLE 7. Amount of energy consumption, CO_2, NO, NO_2, and industrial waste

	Energy consumption (MJ/1000 yen)	CO_2 (kg/ 1000 yen)	NO, NO_2 (g/ 1000 yen)	Industrial waste (kg/ 1000 yen)
Structure	53	5.1	3.8	0.9
Finishing, etc.	35	3.2	4.0	1.4
Equipment	21	1.9	1.8	0.6
Expenses	2	0.2	0.2	0.1
Total	32	3.0	3.1	1.0

Table 7 shows the average values of energy consumption and pollutants released due to the construction of the six buildings. The total amount of energy consumption per unit price is 32 MJ/1000 yen, 3.0 kg/1000 yen for CO_2 production, 3.1 g/

1000 yen for NO and NO_2 production, and 1.0 kg/1000 yen for industrial waste production.

Structural work is shown to be high in energy consumption and CO_2 exhausted per unit cost. Industrial waste exhausted in finishing work is higher than the other two categories of work. Equipment work is shown to be relatively low in energy consumption, CO_2, NO, NO_2 and industrial waste produced.

8. Conclusions

The total consumption of energy and major resources was linked to the production of pollutants and industrial waste due to the construction of office buildings, and calculated using the Inter-Industry Relations Table.

(1) Total energy consumption caused by the construction of office buildings is 8–12 GJ per square meter of floor area.

(2) CO_2 production is 750–1140 kg, SO and SO_2 720–1430 g, NO and NO_2 700–1140 g, dust 70–130 g per square meter of floor area.

(3) The amount of industrial waste per square meter of floor area is 230–380 kg.

(4) The construction cost per square meter of floor space is proportional to the energy consumption and production of pollutants.

(5) The amount of energy consumption per unit price is 32 MJ/1000 yen, 3.0 kg/1000 yen for CO_2 production, 3.1 g/1000 yen for NO and NO_2 production, and 1.0 kg/1000 yen for industrial waste production

(6) Structural work is shown to be high in energy consumption and CO_2 exhausted per unit cost of construction. Industrial waste exhausted in finishing work is higher than the other two categories of work (structure and equipment). Equipment work is shown to be relatively low in energy consumption, CO_2, NO, NO_2 and industrial waste produced.

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