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# Comparison of Embodied Energy/$CO_2$ of Office Buildings in China and Japan

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**Abstract:** The embodied energy/$CO_2$ of buildings in China and Japan, which reflects the characteristic industrial efficiency of building materials, is described in this paper. The energy consumption and $CO_2$ intensities for the dominant materials used in buildings are derived from the energy consumption in factories, and the energy consumption to produce equipment is derived from IO (input/output) analysis in order to compare the embodied energy/$CO_2$ for buildings between China and Japan based on the same estimation method. Although the energy consumption of structures in China is two to three times greater than in Japan, the interior finish and air conditioning equipment, for example, are simpler and smaller. As a result, the embodied energy/$CO_2$ of office buildings in China is only 10% to 20% greater than that of Japanese office buildings. Thus, the embodied energy/$CO_2$ of buildings depends on both industrial efficiencies and building design trends of the country.

**Key words:** Embodied energy, embodied $CO_2$, China, Japan, energy/$CO_2$ intensities.

## 1. Introduction

The accuracy of the evaluation of energy consumption and related $CO_2$ emissions associated with buildings has been increasing, and such evaluations are being applied in the design of more energy efficient building envelopes and systems. Thus, the weight of the energy consumption and $CO_2$ emissions due to building construction is increasing, so that methods used to estimate these factors will become increasingly important.

This paper demonstrates a method for comparing the embodied energy/$CO_2$ of buildings in China and Japan. The difference in embodied energy/$CO_2$ of buildings is also shown from the view point of industrial energy efficiency, the quantity of materials used in the buildings, and the design of the buildings in the two countries.

Fig. 1 shows a rough estimation of the total $CO_2$ emissions in various countries, and the corresponding fractions of embodied $CO_2$ due to building construction and public works. This figure is based on the calculation result with world IO (input/output) data and $CO_2$ emissions [1, 2]. The shaded areas indicate the total global embodied $CO_2$. In particular, the fraction of embodied energy is higher in developing countries and often exceeds the building operation energy. As shown in Fig. 1, the embodied $CO_2$ differs among countries depending on the building design, the $CO_2$ intensity of materials, and the quantity of materials used in the building.

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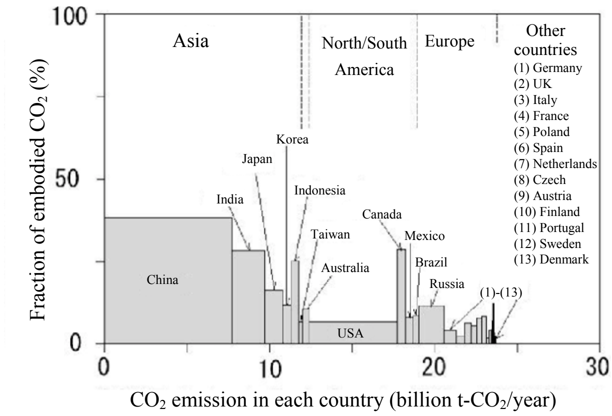


**Fig. 1 Rough estimation of $CO_2$ emissions in various countries and the corresponding fraction of embodied $CO_2$ in 2009 (based on our calculation result with Refs. [1, 2]).** Whole world $CO_2$: 28.7 billion t-$CO_2$/year.

## 2. Input/Output Analysis

### *2.1 Input/Output Analysis*

The embodied energy/$CO_2$ is obtained from the analysis of IO tables. The IO tables of Japan consist of 400 industrial sectors [3], and those of China consist of 30 industrial sectors [4, 5]. Therefore, energy intensities of fundamental building materials, including concrete, steel, wood, and glass are derived from the energy consumption in industrial sectors corresponding to the material and the quantity of the material, which are expressed in terms of MJ/kg or MJ/$m^3$. Energy intensity of equipment, which is expressed in terms of MJ/Yen or MJ/Yuan, is derived from IO analysis. Generally, since materials that have high energy intensity have only a slight influence on other industrial sectors, calculating the energy/$CO_2$ intensity based on energy and the quantity of material consumed in the factory may be sufficiently accurate for estimation of embodied energy and $CO_2$ emissions. Since this calculation method is also applied to embodied energy/$CO_2$ in Japan, it becomes possible to compare the embodied energy/$CO_2$ of buildings in China and Japan using the same methodology. The general domestic production $\boldsymbol{X}$ of each industrial sector can be calculated by Leontief inversion with final demand $\boldsymbol{F_{(D)}}$ as follows:

$$\boldsymbol{X} = \{\boldsymbol{I} - (\boldsymbol{I} - \boldsymbol{M})\mathbf{A}\}^{-1}\{(\boldsymbol{I} - \boldsymbol{M})\boldsymbol{F_{(D)}} + \boldsymbol{F_{(E)}}\} \quad (1)$$

where:

$\boldsymbol{X}$: domestic output (Yen/year);

$\{\boldsymbol{I} - (\boldsymbol{I} - \boldsymbol{M})\mathbf{A}\}^{-1}$: Leontief competitive import-type inverse matrix (-);

$\boldsymbol{I}$: unit matrix (-);

$\boldsymbol{M}$: import coefficient diagonal matrix;

$$m_i = \boldsymbol{M_i}/\boldsymbol{C_i};$$

$m_i$: import coefficient (-);

$\boldsymbol{M_i}$: import price of *i* product (Yen/year);

$\boldsymbol{C_i}$: domestic demand for *i* product (Yen/year);

$\boldsymbol{A}$: activity (input coefficient) (-);

$\boldsymbol{F_{(D)}}$: domestic final demand value (Yen/year);

$\boldsymbol{F_{(E)}}$: export value (Yen/year).

Since it is possible to obtain the energy consumption and domestic production in each industrial sector, the energy intensity $\boldsymbol{E_i}$ (MJ/Yen) can be derived. The total ultimate energy consumption $\boldsymbol{E_F}$ with final influences by $\boldsymbol{X}$ can be expressed as follows:

$$\boldsymbol{E_F} = \sum_{i=1}^{n} \boldsymbol{X_i} \times \boldsymbol{E_i} \quad (2)$$

where:

*n*: number of industrial sectors in the country;

$\boldsymbol{X_i}$: general domestic product in each industrial sector (Yen);

$\boldsymbol{E_F}$: total ultimate energy consumption (MJ).

### *2.2 Caloric Values and $CO_2$ Emission Factors*

Table 1 shows the caloric values and $CO_2$ emission factors. The caloric values and $CO_2$ emission factors for electricity in Japan are much smaller than in China because nuclear power stations produce 34% of the total consumed electricity in Japan [6].

Ultimate energy consumption and $CO_2$ emission, which are referred to as the energy/$CO_2$ intensity due to the final demand of 1,000 USD for each industrial sector, are shown in Table 2 for China and in Table 3 for Japan.

**Table 1 Caloric values and $CO_2$ emission factors [7].**

| Fuel | Caloric value | $CO_2$ emission | Weight (kg/L) |
|---|---|---|---|
| Coal | 28.9 MJ/kg | 2.5 kg-$CO_2$/kg | - |
| Coke | 30.1 MJ/kg | 3.3 kg-$CO_2$/kg | - |
| Crude oil | 42.4 MJ/kg | 2.9 kg-$CO_2$/kg | 0.90 |
| Gasoline | 46.1 MJ/kg | 3.1 kg-$CO_2$/kg | 0.75 |
| Kerosene | 45.9 MJ/kg | 3.1 kg-$CO_2$/kg | 0.80 |
| Light oil | 46.0 MJ/kg | 3.2 kg-$CO_2$/kg | 0.83 |
| Heavy oil | 43.4 MJ/kg | 3.0 kg-$CO_2$/kg | 0.90 |
| Natural gas | 40.9 MJ/$m^3$ | 2.0 kg-$CO_2$/$m^3$ | - |
| Electricity (China) | 10.9 MJ/kWh | 1.0 kg-$CO_2$/kWh | - |
| Electricity (Japan) | 5.8 MJ/kWh | 0.4 kg-$CO_2$/kWh | - |

**Table 2 Energy/$CO_2$ intensity in China.**

| No. | Industrial sector | Energy intensity (MJ/1,000 USD) | $CO_2$ intensity (kg-$CO_2$/1,000 USD) |
|---|---|---|---|
| 1 | Agriculture | 18,244 | 1,517 |
| 2 | Coal mining and processing | 72,456 | 6,278 |
| 3 | Crude petroleum and natural gas products | 82,382 | 6,032 |
| 4 | Metal ore mining | 28,685 | 2,468 |
| 5 | Non-ferrous mineral mining | 33,329 | 2,839 |
| 6 | Manufacture of food and tobacco processing | 24,268 | 2,055 |
| 7 | Textile goods | 31,851 | 2,701 |
| 8 | Wearing apparel leather, furs, down, etc. | 22,959 | 1,935 |
| 9 | Sawmills and furniture | 29,451 | 2,501 |
| 10 | Paper and products, printing, etc. | 36,827 | 3,158 |
| 11 | Petroleum processing and coking | 54,440 | 4,181 |
| 12 | Chemicals | 56,610 | 4,721 |
| 13 | Nonmetal mineral products | 63,416 | 5,437 |
| 14 | Metals smelting and pressing | 95,208 | 8,650 |
| 15 | Metal products | 49,698 | 4,405 |
| 16 | Machinery and equipment | 34,019 | 3,007 |
| 17 | Transport equipment | 38,787 | 3,395 |
| 18 | Electric equipment and machinery | 37,903 | 3,329 |
| 19 | Electric and telecommunication equipment | 18,078 | 1,549 |
| 20 | Instruments, cultural and office machinery | 18,050 | 1,577 |
| 21 | Maintenance and repair of equipment | 0 | 0 |
| 22 | Other manufacturing products | 44,057 | 3,806 |
| 23 | Scrap and waste | 0 | 0 |
| 24 | Electricity, steam and hot water supply | 89,851 | 7,761 |
| 25 | Gas production and supply | 214,762 | 18,368 |
| 26 | Water production and supply | 57,704 | 5,072 |
| 27 | Construction | 40,705 | 3,515 |
| 28 | Transport and warehousing | 48,917 | 3,746 |
| 29 | Wholesale and retail trade | 21,887 | 1,828 |
| 30 | Services | 22,470 | 1,876 |

1 USD = 6.5 Yuan, 1 USD = 84 Yen.

**Table 3 Energy/$CO_2$ intensity in Japan.**

| No. | Industrial sector | Energy intensity (MJ/1,000 USD) | $CO_2$ intensity (kg-$CO_2$/1,000 USD) |
|---|---|---|---|
| 1 | Agriculture | 2,932 | 210 |
| 2 | Mining | 3,775 | 269 |
| 3 | Manufacture of food products | 2,125 | 151 |
| 4 | Textile goods | 2,400 | 170 |
| 5 | Pulp/paper product | 4,422 | 319 |
| 6 | Chemicals | 6,176 | 434 |
| 7 | Petroleum refinery and coal products | 13,574 | 1,219 |
| 8 | Ceramic, stone and clay products | 5,992 | 453 |
| 9 | Steel products | 5,320 | 406 |
| 10 | Non-ferrous metal products | 3,136 | 221 |
| 11 | Metal products | 2,517 | 182 |
| 12 | General industrial machinery | 1,765 | 127 |
| 13 | Electrical equipment | 1,580 | 112 |
| 14 | Transport equipment | 2,044 | 146 |
| 15 | Precision equipment | 2,323 | 162 |
| 16 | Other industrial machinery | 3,437 | 237 |
| 17 | Construction | 1,997 | 146 |
| 18 | Electricity/gas, steam/hot water supply | 27,316 | 1,882 |
| 19 | City water/waste disposal services | 3,404 | 240 |
| 20 | Wholesale/retail trade | 1,046 | 74 |
| 21 | Financial service/insurance | 601 | 42 |
| 22 | Real estate business | 317 | 22 |
| 23 | Transport | 7,629 | 546 |
| 24 | Telecommunication/broadcasting | 935 | 66 |
| 25 | Public administration | 1,525 | 107 |
| 26 | Education/research | 1,465 | 103 |
| 27 | Medical service/health/social welfare | 2,044 | 143 |
| 28 | Other public service | 1,226 | 86 |
| 29 | Business service | 934 | 66 |
| 30 | Personal service | 1,870 | 131 |
| 31 | Office supplies | 3,169 | 226 |
| 32 | Activities not elsewhere classified | 1,932 | 138 |

## 3. Calculation Results

### *3.1 Fraction of Embodied and Operation Energy and $CO_2$ Emissions of Buildings*

Fig. 2 shows the calculation result of the fraction of ultimate embodied $CO_2$ due to the construction of buildings and civil engineering in China in 2000, as well as the $CO_2$ emissions due to operation of residential houses. In China, 18.1% of total $CO_2$ emissions are due to the construction of buildings, and 10.4% is due to the operation of residential houses. Thus, in China, the embodied $CO_2$ is greater than the $CO_2$ emissions required for operations.

Fig. 3 shows the fraction of $CO_2$ emissions in Japan [8]. In Japan, 5% and 14% of total $CO_2$ emissions are due to building construction and the operation of residential houses, respectively. Including civil engineering, 16% and 32% of total $CO_2$ emission are embodied $CO_2$ due to construction and building operation, respectively. Generally, embodied energy/$CO_2$ tends to vary according to economic circumstances in the country more than operation energy/$CO_2$. The embodied energy due to construction in developing countries is greater than that in developed countries because the first step in the development of the country is the construction of

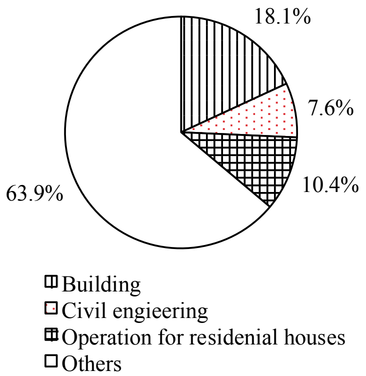


**Fig. 2 Result of fraction of $CO_2$ emissions in China in 2000.**

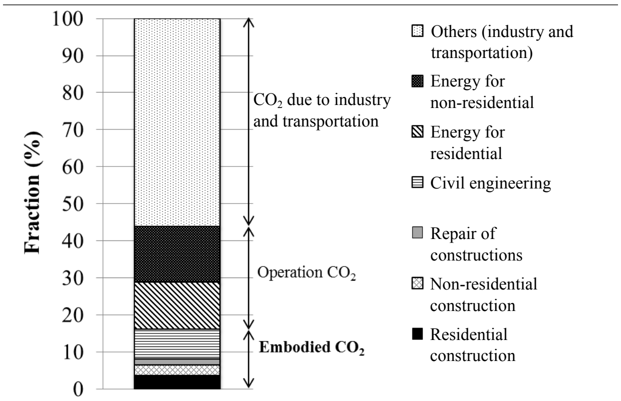


**Fig. 3 Result of fraction of $CO_2$ emissions in Japan in 2000 [8].**

buildings and public works.

### *3.2 Embodied Energy and Embodied $CO_2$ of Building Materials*

The embodied energy/$CO_2$ of dominant building materials is derived from energy consumption in corresponding industrial sectors and the quantity of produced materials in both China and Japan. Tables 4 and 5 list the calculation results of the embodied energy/$CO_2$ in China and Japan, respectively. Table 6 shows the comparison of embodied energy/$CO_2$ of building materials between China and Japan. The efficiencies of manufacturing appear to influence the embodied energy/$CO_2$ of building materials.

The embodied energy/$CO_2$ changes yearly according to the manufacturing efficiency of the country. Tables 7 and 8 show the intensities of the embodied energy/$CO_2$ due to construction of various types of buildings and structures in Japan. The embodied energy/$CO_2$ per unit floor area of buildings in 1975 was 1.5 times greater than that in 2000, although, in 1975, buildings were simpler than they were in 2000. Tables 9 and 10 compare the energy/$CO_2$ intensities of building materials in 1975 and in 2000, where the energy consumption for the production of cement and crude steel have decreased by more than half. The energy consumption for building materials, which depends on the efficiency of factories, appears to decrease according to the level of development of the country, and the embodied energy can also be decreased. There are no similar data of 1975 in China. However, it is expected that the energy/$CO_2$ intensities of building materials in China would follow similar trend.

**Table 4 Result of embodied energy/$CO_2$ of building materials in China.**

| Material | Embodied energy | $CO_2$ |
|---|---|---|
| Wood | 1,267,412 kJ/$m^3$ | 114.7 kg-$CO_2$/$m^3$ |
| Steel | 41,058 MJ/t | 4.03 t-$CO_2$/t |
| Cement | 4,508 MJ/t | 0.42 t-$CO_2$/t |
| Aluminum | 42,380 MJ/t | 3.91 t-$CO_2$/t |
| Brick | 4,103 MJ/t | 0.38 t-$CO_2$/t |
| Glass | 13,707 MJ/t | 1.27 t-$CO_2$/t |

**Table 5 Result of embodied energy/$CO_2$ of building materials in Japan.**

| Material | Embodied energy | $CO_2$ |
|---|---|---|
| Wood | 573,581 kJ/$m^3$ | 40.3 kg-$CO_2$/$m^3$ |
| Steel | 11,289 MJ/t | 1.10 t-$CO_2$/t |
| Cement | 2,044 MJ/t | 0.18 t-$CO_2$/t |
| Aluminum | 40,070 MJ/t | 3.13 t-$CO_2$/t |
| Brick | 3,409 MJ/t | 0.25 t-$CO_2$/t |
| Glass | 12,619 MJ/t | 0.91 t-$CO_2$/t |

**Table 6 Comparison of embodied energy/$CO_2$ between China and Japan (calculated from Tables 4 and 5).**

| Material | China/Japan | |
|---|---|---|
| | Energy | $CO_2$ |
| Wood | 2.2 | 2.8 |
| Steel | 3.6 | 3.7 |
| Cement | 2.2 | 2.3 |
| Aluminum | 1.1 | 1.3 |
| Brick | 1.2 | 1.5 |
| Glass | 1.1 | 1.4 |

These values are calculated as a division of a value of Japan by a value of China, e.g., 1,267,412 (kJ/$m^3$)/573,581 (kJ/$m^3$) = 2.2 (wood).

**Table 7 Embodied energy of buildings in 1975 and 2000 in Japan [9].**

| Year | Energy ($GJ/m^2$) | | Ratio |
|---|---|---|---|
| | 1975 | 2000 | 1975/2000 |
| Wooden residential house | 4.7 | 3.6 | 1.3 |
| Non-wooden residential house | 8.2 | 5.1 | 1.6 |
| Wooden non-residential house | 3.1 | 3.0 | 1.0 |
| Non-wooden non-residential house | 7.2 | 4.9 | 1.5 |

**Table 8 Embodied $CO_2$ of buildings in 1975 and 2000 in Japan [9].**

| Year | $CO_2$ (kg-$CO_2/m^2$) | | Ratio |
|---|---|---|---|
| | 1975 | 2000 | 1975/2000 |
| Wooden residential house | 390 | 300 | 1.3 |
| Non-wooden residential house | 595 | 420 | 1.4 |
| Wooden non-residential house | 260 | 260 | 1.0 |
| Non-wooden non-residential house | 690 | 435 | 1.6 |

**Table 9 Embodied energy of building materials in 1975 and 2000 in Japan [9].**

| Year | Energy (GJ) | | Ratio |
|---|---|---|---|
| | 1975 | 2000 | 1975/2000 |
| Log ($GJ/m^3$) | 1.0 | 0.9 | 1.2 |
| Cement (GJ/t) | 5.0 | 1.6 | 3.2 |
| Crude steel (GJ/t) | 22.7 | 9.0 | 2.5 |

**Table 10 Embodied $CO_2$ of building materials in 1975 and 2000 in Japan [9].**

| Year | $CO_2$(kg-$CO_2$) | | Ratio |
|---|---|---|---|
| | 1975 | 2000 | 1975/2000 |
| Log ($GJ/m^3$) | 91 | 58 | 1.6 |
| Cement (GJ/t) | 345 | 120 | 2.9 |
| Crude Steel (GJ/t) | 1,770 | 780 | 2.3 |

**Table 11 Floor areas of office buildings in China and Japan.**

| Office No. | Floor area ($m^2$) |
|---|---|
| Office A in China | 947 |
| Office B in China | 1,513 |
| Office C in China | 2,130 |
| Office D in China | 1,019 |
| Office E in Japan | 1,145 |

## 4. Embodied Energy/$CO_2$ of Office Buildings in China and Japan

### *4.1 Calculation Methods*

The calculation method is as follows:

- The energy intensities and $CO_2$ intensities shown in Tables 4 and 5 are used for the dominant building materials;
- The energy intensities and $CO_2$ intensities in Tables 2 and 3 are used for other materials and equipments;
- The energy/$CO_2$ for margin and transport from gate to site is obtained by IO analysis.

### *4.2 Buildings*

The embodied energy/$CO_2$ of four office buildings in China and one office building in Japan are calculated. The corresponding floor areas are shown in Table 11.

The structures of these office buildings are reinforced concrete. The plans of Office A in China and Office E in Japan are shown in Figs.4 and 5, respectively. The offices in China are located in northeast China and Office E is located in Tokyo.

Table 12 shows the quantities of materials per unit floor area used in Office A in China and Office E in Japan, where the quantity of steel used for Office E in Japan is three times greater than that for Office E in China because earthquake countermeasures must be taken in Japan. Offices in Japan use concrete, whereas bricks are widely used in China. Since double glazing is common in northern China, the use of glass is more extensive in China than in Japan.

### *4.3 Embodied Energy and $CO_2$ of Buildings*

Tables 13 and 14 show the embodied energy/$CO_2$ classified by construction work in Office A in China and office E in Japan. The embodied energy/$CO_2$ for the skeleton of Office A is three times greater than that for office E, where the skeleton is constructed from concrete, brick, and steel. The embodied energy/$CO_2$ for the foundation, the skeleton, and finish elements are greater in China, and embodied energy/$CO_2$ for other elements, especially HVAC, electrical, and sanitary elements, are lower for office A in China, because equipment used in offices in China is simpler than that used in Japan. One reason for this is the use of district heating systems in China and less demand for cooling. Figs. 6 and 7 show embodied energy/$CO_2$ of Offices A-E

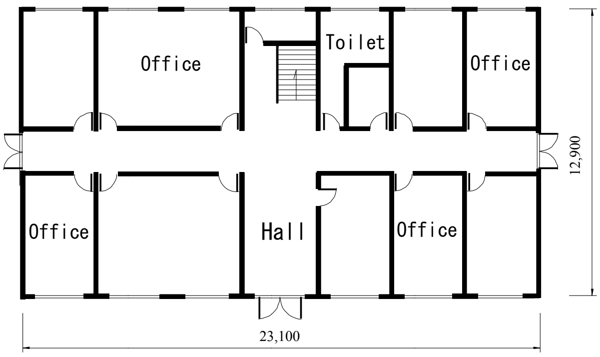


**Fig. 4 Floor plan of Office A in China (units in mm).**

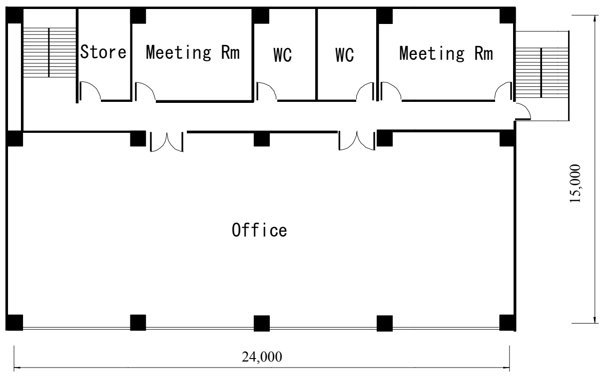


**Fig. 5 Floor plan of Office E in Japan (units in mm).**

**Table 12 Quantity of building materials per unit floor area in offices in China and Japan.**

| Materials | China | Japan |
|---|---|---|
| Concrete ($m^3$) | 0.554 | 0.676 |
| Steel (kg) | 31.8 | 89.8 |
| Wood ($m^2$) | 0.019 | 0.111 |
| Brick (kg) | 0.662 | - |
| Glass ($m^3$) | 0.275 | 0.183 |

**Table 13 Embodied energy classified by building element.**

| Work | Office A in China ($MJ/m^2$) | Office E in Japan ($MJ/m^2$) | Ratio (A/E) |
|---|---|---|---|
| Foundation | 377 | 350 | 1.08 |
| Skeleton | 5,089 | 1,756 | 2.90 |
| Interior finish | 416 | 1,494 | 0.28 |
| Finish work | 1,583 | 865 | 1.83 |
| HVAC* | 142 | 1,195 | 0.12 |
| Electric work | 89 | 384 | 0.23 |
| Sanitary | 110 | 412 | 0.27 |
| Transport, trade | 672 | 932 | 0.72 |
| Total | 8,478 | 7,388 | 1.15 |

*Heating, ventilation and air conditioning.

**Table 14 Embodied $CO_2$ classified by building element.**

| Work | Office A in China (kg-$CO_2$/$m^2$) | Office E in Japan (kg-$CO_2$/$m^2$) | Ratio A/E |
|---|---|---|---|
| Foundation | 35 | 27 | 1.31 |
| Skeleton | 471 | 154 | 3.05 |
| Interior finish | 35 | 111 | 0.32 |
| Finish work | 139 | 63 | 2.21 |
| HVAC | 12 | 86 | 0.14 |
| Electric work | 8 | 27 | 0.29 |
| Sanitary | 9 | 31 | 0.31 |
| Transport, trade | 52 | 67 | 0.77 |
| Total | 761 | 566 | 1.35 |

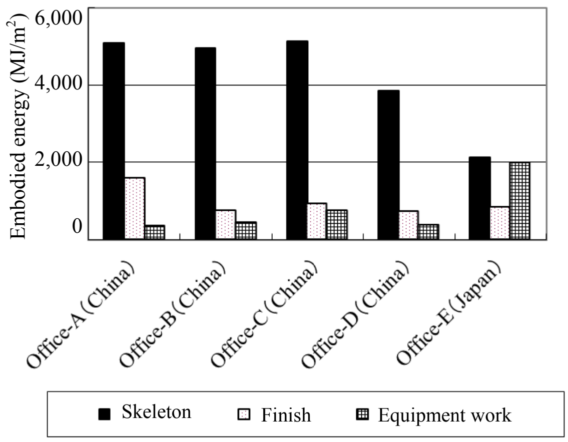


**Fig. 6 Embodied energy of office buildings in China and Japan.**

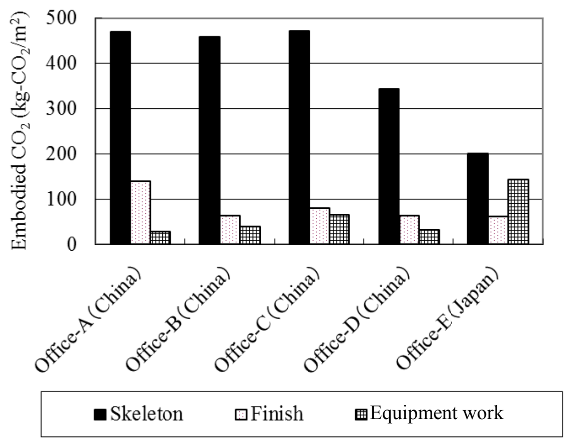


**Fig. 7 Embodied $CO_2$ of office buildings in China and Japan.**

in China and Japan. The embodied energy/$CO_2$ per unit floor area of Offices A-D in China is almost the same and the fraction for the skeleton is dominant.

The embodied energy/$CO_2$ of equipment installation is almost the same as for the skeleton in Office E in Japan. This is because equipment installation is more complicated in Japan because of the need for cooling systems and complicated ceiling system with lighting etc.. These results for embodied energy/$CO_2$ in China and Japan show that embodied energy/$CO_2$ due to building construction depends on both industrial efficiency and building design.

## 5. Conclusions

This paper describes embodied energy/$CO_2$ due to building construction in China and Japan using the same calculation method.

The energy and $CO_2$ intensities of industrial sectors are obtained by IO analysis.

The embodied energy/$CO_2$ of dominant building materials is obtained from the energy consumption and the quantity of material produced.

The embodied energy/$CO_2$ of office buildings is shown and compared between China and Japan.

The embodied energy/$CO_2$ due to building construction depends on both the industrial efficiency and the building design of the country such as earthquake resistance and so on.

Generally, it is effective to reduce embodied energy/$CO_2$ by using low embodied energy/$CO_2$ materials as well as reducing the quantity of materials used in buildings [10]. However, prolongation of building life-span is significant important and effective measure to reduce annual embodied energy/$CO_2$ even if embodied energy/$CO_2$ is slightly increased at present time.

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