Study on Impact of Embodied Energy and CO₂ Emissions for Prolongation of Building Life Time: Case Study in Japan

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Abstract: In this study, we looked at a method quantifying EEC (embodied energy and CO₂) and the effect when we prolonged the building life time particularly through the durable improvement of the structure. Increasing the covering thickness of concrete for reinforcing bars and the earthquake-resistant strength are methods to increase the durability of the structure. The calculation method to obtain the quantity of concrete and reinforcing bars is provided. The EEC increase is evaluated from the 2005 input-output table in Japan. These results show that EE (embodied energy) in the construction phase is increased by 11% to 20% and EC (embodied CO₂) 17% to 32%. However, annual EE is reduced 66% to 72% and EC 70% to 79%.

Key words: Covering thickness of concrete, earthquake-resistant strength, I-O (input-output) table, embodied energy/CO₂.

1. Introduction

Recently, social demand to reduce the global environmental load has been increased. Of particular note was the 5th assessment report of Working Group I from the IPCC (Intergovernmental Panel on Climate Change) that was announced in 2013, stating that “human influence of climate system is clear” [1]. Emissions of construction-related greenhouse gas accounts for approximately 40% of greenhouse gas emissions in Japan. Therefore, the ZEB (zero-energy building) and ZEH (zero-energy house) have been announced to achieve zero energy consumption and zero CO₂ emissions in buildings or houses during operation. According to the Basic Energy Plan [2] in Japan, a target has been established with standard new houses being ZEH by 2020 and the average for all new constructions being ZEB by 2030. Such a movement is being promoted in all the countries throughout the world as well as in Japan. In the UK, it is planned to make all new houses ZEH in 2016 and all new non-residential buildings ZEB by 2019 [3]. In addition, in the United States, it is planned to make all new houses ZEH by 2020 [4] and new non-residential buildings ZEB by 2030 [5]. When buildings are changed to ZEB/ZEH, the environmental loads related to construction account for a large part of the whole life cycle load. In ordinary buildings, the energy for production is 10% to 15%. However, there are some research papers reporting that it accounts for 40% to 60% in low-energy buildings [6]. Therefore, the reduction of EEC (embodied energy and CO₂) becomes important. When we consider the reduction of EEC, it is effective in prolonging building life time, because the amount of annual EEC in the construction phase becomes small.
In the past, there were not so many studies in conjunction with EEC about prolonging of building life time, but Urushizaki et al. [7] examined the influence on LCCO₂ (lifecycle CO₂) when techniques for prolonging of building life time such as changed covering thickness, concrete standard strength and floor height emerged.

Therefore, in this study, we looked at a method for the quantification of EEC and the effect when we prolonged the life of the buildings, particularly through improvement of the durability of the structure.

2. Building Life Time and Prolonging Method

Prior to this study, the life time of buildings was easy to regulate. The life time of buildings is in regard to the state in which it cannot be used because all or part of the building is in a state of degradation. There are three kinds of degradation, as shown in Table 1, and there are techniques to prolong the life time as shown in the list.

In Japan, the average life time of residential buildings is estimated at approximately 30 years [8]. Further, there is a study report indicating that the life time of concrete buildings is 68 years for residential buildings and 56 years for commercial buildings [9]. Accordingly, the government has been implementing policies to promote long-term quality housing as in “Ultra Long-Term Housing Promotion Project” [10].

3. Calculation Method of EEC to Prolongation of Building Life Time by Increasing Durability of Structure

In this study, we adopted increasing the durability of structures as one of the methods to prolong the building life time. It is necessary to calculate an increment in the quantity of reinforcing bars, steel frames and concrete when increasing the durability of structures to evaluate the effect of prolongation of life time. In this study, to increase building life time from 60 years to 100 years, the covering thickness of concrete for reinforcing bars is increased and there is an increase in earthquake-resistant strength. The calculation method is determined when an increase in such materials is found at the design phase, when the material is subject to change. In addition, in this study, we intend to apply the method for steel reinforced concrete construction.

3.1 Increasing Durability of the Covering Thickness of Concrete for Reinforcing Bars

When looking at the service life of a structure with reinforced concrete construction, degradation caused by the rusting of reinforcing bars for the concrete is a big factor. The cause of rusting of reinforcing bars is caused by neutralization of the concrete having advanced to the depth of the reinforcing bars.

The definition of the service life is: “a point in time when the steel reinforced concrete construction skeleton is in a condition where many reinforcing bars of the skeleton might generate rust and when the performance of the structure cannot recover even if normal repair or some changes are made is called service life” [11].

Additionally, the progress of the term to neutralize concrete to a certain depth is a relationship almost proportional to the square of the depth [11]. Therefore, if the service time of the structure is standard when the covering thickness is 40 mm, the service time becomes 0.56 times when the thickness is 30 mm and 1.56 times when it is 50 mm. Table 2 shows the covering thickness of standard buildings and buildings with a long service life. When a standard column size is 800 × 800 mm, beam size is 750 × 400 mm, floor slab thickness is 180 mm and wall thickness is 180 mm, the increase in concrete is as follows:

- column: +5.1% (covering thickness is +10 mm);
- beam: +7.8% (covering thickness is +10 mm);
- floor: +11.1% (covering thickness is +10 mm);
- wall: +11.1% (covering thickness is +10 mm).
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Table 1  Type of degradation and methods to prolong life time.

| Type of degradation | Description                                                                 | Methods to prolong life time |
|---------------------|-----------------------------------------------------------------------------|------------------------------|
| Physical degradation| Neutralization of concrete and metal corrosion advancing through aging, and not function | Increasing durability of structure, outer material, equipment and pipes, etc. |
| Functional degradation| Equipment that is highly efficient is developed through innovation, and installed equipment becomes obsolete | Equipment setting and space in which it is easy to retrofit |
| Social degradation | The state in which a building and the equipment become inferior due to change of usage, or profitability as the real estate turns worse, or did not adapt to standards through changes in laws and policies | Skeleton-infill or additional space such as machine room and floor height for future installation |

Table 2  Covering thickness of standard buildings and buildings with a long service life.

| Element type        | Standard*1 | Building with long life time |
|---------------------|------------|-----------------------------|
|                     | Internal side | External side | Internal side | External side |
| Structural element  |            |                            |               |               |
| Column/beam         | 30 mm      | 30 mm                      | 40 mm         | 40 mm         |
| Floor slab (roof)   | 20 mm      | 20 mm                      | 30 mm         | 30 mm         |
| Non-structural element | 20 mm   | 20 mm                      | 30 mm         | 30 mm         |
| Foundation          | 70 mm      | 70 mm                      |               |               |

*1Article 79, Enforcement Ordinance of Building Standard Act.

Table 3  Increasing the rate of the material for each part through increase in earthquake-resistant strength.

| Element                  | Earthquake-resistant strength +50% | Earthquake-resistant strength +25% |
|--------------------------|------------------------------------|------------------------------------|
|                          | Concrete                           | Reinforcing bars                   | Concrete                           | Reinforcing bars                   |
| Column                   | +50%                               | +50%                               | +25%                               | +25%                               |
| Beam                     | +50%                               | +50%                               | +25%                               | +25%                               |
| Floor                    | No change                          | No change                          | No change                          | No change                          |
| Wall                     | No change                          | No change                          | No change                          | No change                          |
| Foundation (equivalent to a pillar and a beam) | +50%                               | +50%                               | +25%                               | +25%                               |

3.2 Prolongation of Life Time through Increase of Earthquake-Resistant Strength

In the earthquake-resistant plans for the government offices building in Japan, even if a major earthquake occurs, the structure is recommended to have its earthquake-resistant strength increased by 50% over standard values to continue use without damage [12]. In addition, the structure is recommended to have its earthquake-resistant strength increased by 25% of standard values for the building to be used without undertaking major repairs to the structure. An additional material increase is calculated based on these recommendations.

It is assumed that if a column is shear-fractured and a beam is flexure fractured, then the shear strength is proportional to the quantity of structural materials used and the flexure strength is proportional to the second section moment. The results of increasing the rate of the material for each part are shown in Table 3.

3.3 Rate of Increase of Synthetic Materials

It is assumed that the average distribution of the quantity of concrete is 9% of the column, 22% of the beam, 27% of the floor, 19% of the wall, 23% of the base [13] and the increase of the total weight of building is 7.3% from the increase of covering thickness. The increase in the weight by having strengthened earthquake resistance is not included in this value. The total increase rate of material is shown in Table 4.

4. Case Study

4.1 Outline of Building

The case study was conducted for a library that has a steel reinforced concrete construction. The outline of a sample building is shown in Table 5, and some drawings are shown in Figs. 1-4 [14].
Table 4  Increasing material grade for each part by comprehensively prolongation of life time.

| Element                  | Earthquake-resistant strength +50% | Earthquake-resistant strength +25% |
|--------------------------|-----------------------------------|-----------------------------------|
|                          | Concrete                          | Reinforcing bars                  | Concrete                          | Reinforcing bars                  |
| Column                   | +54%                              | +54%                              | +26.8%                            | +26.8%                            |
| Beam                     | +54%                              | +54%                              | +26.8%                            | +26.8%                            |
| Floor                    | +11%                              | +11%                              | +11%                              | +11%                              |
| Wall                     | +11%                              | +11%                              | +11%                              | +11%                              |
| Foundation (equivalent to a pillar and a beam) | +54% | +54% | +26.8% | +26.8% |

Table 5  Outline of a sample building [14].

| Item                           | Detail                                                                 |
|--------------------------------|------------------------------------------------------------------------|
| Intended use                   | Library                                                                |
| Location                       | Japan                                                                  |
| Structure                      | Reinforced-concrete                                                    |
| Number of floors               | 3 stories                                                              |
| Site area                      | 849.37 m²                                                              |
| Gross floor area               | 2,412.99 m²                                                            |
| Electrical equipment           | Receiving high voltage electricity: 125 kVA, lighting and consent, broadcast and telephone equipment, disaster prevention system |
| Air-conditioning equipment    | Air cooled chiller, gas heat-pump-unit, fan coil unit on each floor    |
| Water supply and drainage sanitation | System for direct connection to water supply, sanitary facilities, city gas equipment |
| Elevator facilities            | 750 kg × 1 unit                                                        |

Fig. 1  1st floor plan (units in mm) [14].

Fig. 2  3rd floor plan (units in mm) [14].
4.2 Weight of Major Materials

The capacity and weight of the building structure are obtained from cost data [14] as shown in Table 6. The weight of building structure is 1,664 kg/m².

4.3 Material Increase by Prolongation of Life Time

Table 7 shows the material increase by prolongation of life time, which is calculated in Table 4 in Section 3. The standard building life time is 60 years and the prolonged life time is 100 years. The results show that the concrete increase is 39% and reinforcing bars is 42% in the case of earthquake-resistant strength +50%, and the concrete increase is 21% and reinforcing bars is 22% in case of earthquake-resistant strength +25%.

4.4 Calculation Method of EEC

4.4.1 Intensity of EEC

The intensities of energy consumption and CO₂ emissions, which are calculated from the 2005 input-output table in Japan, are used for EEC calculation. Major construction materials are shown in Table 8.

![Fig. 3 Section (units in mm) [14]](image1)

![Fig. 4 East side view [14]](image2)

Table 6 Capacity and weight of building structure.

|                      | Concrete* | Reinforcing bars |
|----------------------|-----------|------------------|
|                      | m³        | Ratio            | kg      | kg/m³  |
| Column               | 208       | 12%              | 41,007  | 197    |
| Beam                 | 402       | 23%              | 69,656  | 173    |
| Floor                | 379       | 22%              | 24,957  | 66     |
| Wall                 | 235       | 14%              | 25,279  | 108    |
| Foundation           | 505       | 29%              | 50,800  | 101    |
| Total                | 1,729     | 100%             | 211,700 | 122    |

Weight of building structure 4,016 t and 1,664 kg/m²

*Specific weight of concrete is 2,200 kg/m³.

Table 7 Material increase by prolongation of life time.

|                        | Earthquake-resistant strength +50% | Earthquake-resistant strength +25% |
|------------------------|------------------------------------|------------------------------------|
|                        | Concrete               | Reinforcing bars | Concrete               | Reinforcing bars |
|                        | Increasing rate (%) m³ | Increasing rate (%) kg | Increasing rate (%) m³ | Increasing rate (%) kg |
| Column                 | 54                    | 112               | 22,144               | 27               | 56               | 27               | 11,072           |
| Beam                   | 54                    | 217               | 37,614               | 27               | 109              | 27               | 18,807           |
| Floor                  | 11                    | 42                | 2,745                | 11               | 42               | 11               | 2,745            |
| Wall                   | 11                    | 26                | 0                    | 11               | 26               | 0                | 0                |
| Foundation             | 54                    | 273               | 27,432               | 27               | 136              | 27               | 13,716           |
| Total                  | 670                   | 89,935            | 369                  | 46,340           |
| (increasing rate)      | (39%)                 | (42%)             | (21%)                | (22%)            |
| Increasing weight      | 1,563 t               | 857 t             |
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Table 8  Intensities of energy consumption and CO₂ emissions of major materials (listing only major industrial sectors from all the 401 industry sectors).

| Industrial No. | Industrial sector               | Per consumer price of millions of Yen | Energy (MJ) | CO₂ (kg-CO₂) | Quantity of material |
|---------------|--------------------------------|----------------------------------------|-------------|--------------|---------------------|
| 30            | Gravel and quarrying           | 52,153                                 | 3,626       | 287.5 t      |                     |
| 31            | Crushed stones                 | 52,030                                 | 3,640       | 593.1 t      |                     |
| 87            | Timber                         | 13,621                                 | 952         | 22.68 m³     |                     |
| 88            | Plywood                        | 22,697                                 | 1,599       | 7.0 m³       |                     |
| 120           | Thermo-setting resins          | 94,869                                 | 6,570       | 1.884 t      |                     |
| 121           | Thermoplastic resins           | 267,594                                | 18,347      | 6.002 t      |                     |
| 146           | Sheet glass and safety glass   | 36,902                                 | 2,636       | -            |                     |
| 147           | Glass fiber and glass fiber products | 71,691                       | 4,842       | -            |                     |
| 149           | Cement                         | 315,036                                | 80,992      | 124.4 t      |                     |
| 150           | Ready mixed concrete           | 81,093                                 | 16,745      | 62.60 m³     |                     |
| 151           | Cement products                | 43,193                                 | 5,994       | -            |                     |
| 152           | Ceramic                        | 54,376                                 | 3,500       | -            |                     |
| 162           | Hot rolled steel               | 189,779                                | 18,271      | 13.47 t      |                     |
| 163           | Steel pipes and tubes          | 119,963                                | 11,182      | 6.158 t      |                     |
| 175           | Electric wires and cables      | 22,562                                 | 1,611       | 0.645 Conductor-t |                   |
| 182           | Metal products for construction| 63,388                                 | 5,577       | -            |                     |
| 183           | Metal products for architecture| 35,353                                 | 2,878       | -            |                     |
| 189           | Boilers                        | 22,980                                 | 1,832       | -            |                     |
| 193           | Refrigerators and air conditioning apparatus | 23,502    | 1,808       | -            |                     |
| 194           | Pumps and compressors          | 27,127                                 | 2,238       | -            |                     |
| 215           | Electric transformers          | 21,509                                 | 1,727       | -            |                     |
| 216           | Relay switches and switch boards | 22,878                              | 1,780       | -            |                     |
| 223           | Electric lighting fixtures and apparatus | 24,345    | 1,770       | 284.3 p      |                     |
| 226           | Air conditioning equipment for consumer use | 21,210  | 1,577       | 11.13 p      |                     |
| 276           | Residential construction (wooden) | 19,921                            | 1,707       | 6.318 m²     |                     |
| 277           | Residential construction (non-wooden) | 29,055                       | 2,704       | 5.527 m²     |                     |
| 278           | Non residential construction (wooden) | 21,103                       | 1,835       | 7.749 m²     |                     |
| 279           | Non residential construction (non-wooden) | 29,644                        | 2,704       | 6.844 m²     |                     |
| 280           | Repair of constructions        | 27,466                                 | 2,436       | -            |                     |
| 375           | Building maintenance services  | 7,753                                  | 548         | -            |                     |
| 377           | Civil engineering and construction services | 11,234                         | 801         | -            |                     |

Table 9  Intensity of concrete, reinforcing bars and non-residential construction.

| Industrial No. | Industrial sector                      | Per unit | Unit         |
|---------------|---------------------------------------|----------|-------------|
| 150           | Ready mixed concrete                  | 1,295    | 267 m³      |
| 162           | Hot rolled steel                      | 14.1     | 1.36 kg     |
| 279           | Non residential construction (non-wooden) | 4,331    | 395 m³      |

4.4.2 EEC Increase through Prolongation of Life Time

The intensities of concrete and reinforcing bars per unit are shown in Table 9 based on Table 8. Table 10 shows the results of EEC increase.

4.4.3 Effectiveness of Prolongation of Life Time

EEC of the building with long life time is compared with standard buildings and the effect is quantified. Since EEC of structures does not affect the operating phase, the evaluation is conducted by the value of EEC in the construction phase. In addition, the EEC of a standard building is calculated from the intensity of “non-residential construction (non-wooden)” sector as
shown in Table 9 multiplied by total building area. EEC of prolongation of building life time is obtained by adding EEC of the standard building and EEC of the increase in structure in prolongation of life time. The annual EEC is shown in Table 11 and Fig. 5. These results show that EE (embodied energy) in construction phase is increased by 20% and EC (embodied CO₂) is 32% in case of earthquake-resistant strength +50%. However, annual EE is reduced to 72% and EC to 79%. On the other hand, in case of earthquake-resistant strength +25%, EE in construction phase is increased by 11% and EC 17%. However, annual EE is reduced to 66% and EC to 70%.

4.4.4 Effectiveness of Cost
In order to determine the additional cost of prolongation of life time, increasing material quantity and cost of concrete and reinforcing bars and formwork are estimated for a sample building [14]. The result shows that 3% to 9% is added to the original

| Table 10  EEC increase by prolongation of life time. |
|-----------------------------------------------|
| Earthquake-resistant strength +50%             |
| Quantity | Unit  | Energy (MJ) | CO₂ (t-CO₂) |
|----------|-------|-------------|-------------|
| Concrete | 670   | m³          | 867,928     | 179         |
| Reinforcing bars | 89,935 | kg         | 1,267,109   | 122         |
| Total    |       |             | 2,135,038   | 301         |
| Earthquake-resistant strength +25%            |
| Quantity | Unit  | Energy (MJ) | CO₂ (t-CO₂) |
|----------|-------|-------------|-------------|
| Concrete | 369   | m³          | 478,008     | 99          |
| Reinforcing bars | 46,340 | kg       | 652,885     | 63          |
| Total    |       |             | 1,130,893   | 162         |

| Table 11  EEC per year per total floor area. |
|-----------------------------------------------|
| Type of building                              |
| Building life time                           |
| Year   | Energy (MJ/m²) | Ratio (%) | CO₂ (kg-CO₂/m²) | Ratio (%) | Energy (MJ/m²) | Ratio (%) | CO₂ (kg-CO₂/m²) | Ratio (%) |
| Reference building                           |
| 60  | 4,333          | 100       | 395             | 100       | 72.2          | 100       | 6.58            | 100       |
| Building with long life time                 |
| earthquake-resistant strength +50%          |
| 100 | 5,218          | 120       | 520             | 132       | 52.2          | 72        | 5.20            | 79        |
| Building with long life time                 |
| earthquake-resistant strength +25%          |
| 100 | 4,802          | 111       | 462             | 117       | 48.0          | 66        | 4.62            | 70        |

| Table 12  Cost increase by prolongation of life time. |
|-----------------------------------------------|
| Item       | Sub item | Cost [14] (Yen) | Quantity | Earthquake-resistant strength +50% | Earthquake-resistant strength +25% |
|           |          |                 |          | Quantity increase | Cost increase (Yen) | Quantity increase | Cost increase (Yen) |
| Temporary work | -       | 31,570,000      | -        | -                   | -                   | -                   | -                   |
| Structure   | Concrete | 24,610,000      | 1,729 m³ | 670 m³              | 9,540,000           | 369 m³              | 5,260,000           |
|             | Reinf.   | 24,790,000      | 212 t    | 90 t                | 10,540,000          | 46 t                | 5,430,000           |
|             | Formwork | 47,090,000      | -        | -                   | 8,980,000*          | -                   | 5,470,000*          |
|             | Others   | 10,320,000      | -        | -                   | -                   | -                   | -                   |
| Finishing   | -        | 94,190,000      | -        | -                   | -                   | -                   | -                   |
| Equipment   | -        | 103,630,000     | -        | -                   | -                   | -                   | -                   |
| Total       | -        | 336,200,000     | -        | -                   | 365,260,000         | -                   | 346,890,000         |

*It is assumed that cost of formwork is proportional to the quantity of concrete.
cost of the building as shown in Table 12.

5. Conclusions

We can draw conclusions from the results above:

(1) In this research, the technique to improve the durability of the building structure is provided as a method through the prolongation of building life time. Increasing the covering thickness of concrete for reinforcing bars and the earthquake-resistant strength is used to increase the durability of the structure. The calculation method to obtain the quantity of concrete and reinforcing bars is provided;

(2) Two cases are assumed for an increase of earthquake-resistant strength. One is to increase the strength by 50% to continue use without damage if a major earthquake occurs. The other is to increase strength by 25% to use a building without undertaking major repairs to the structure;

(3) The material increase of a sample building is evaluated applying the calculation method. The results show that the concrete increase is 36% and reinforcing bars is 39% in the case of an earthquake-resistant strength ±50%, and the concrete increase is 21% and reinforcing bars is 22% in the case of an earthquake-resistant strength ±25%;

(4) The EEC increase is evaluated from the 2005 input-output table in Japan. These results show that EE in the construction phase is increased from 11% to 20% and EC from 17% to 32%. However, annual EE is reduced from 66% to 72% and EC from 70% to 79%;

(5) On the other hand, the additional cost is 3% to 9% of the original cost of the building;

(6) In this study, to prevent the neutralization of concrete, the covering thickness of concrete for reinforcing bars is considered. However, it is said that certain elements such as the adjustment of the water cement ratio, the kind of cement, surface finishing materials and maintenance affect the progress of neutralization.

Numerous buildings are being constructed in individual countries. Construction demand is particularly high in developing countries. When constructing buildings, it is important to construct them from the viewpoint of longer life time in order to achieve reduced CO₂ emissions in the future, even if the costs increase to a certain extent. For individual governments, it would be effective for policy-making to facilitate quantitative discussions provided in this article on effects of EEC reduction achieved through longer life time.

Acknowledgments

The present study was supported in part by the IBEC (Institute for Building Environment and Energy Conservation).

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