Life Cycle Energy and Cost Analysis of Thin Flooring Panels with Enhanced Thermal Efficiency

Sungho Lee¹, Jinkyu Joo² and Sunkuk Kim*³

¹Researcher, Department of Architecture Engineering, Kyung Hee University, Republic of Korea
²Professor, Graduate School of Construction Engineering and Industry, Kyonggi University, Republic of Korea
³Professor, Department of Architecture Engineering, Kyung Hee University, Republic of Korea

Abstract

Ondol is the popular house heating system in Korea onto which hardwood flooring is laid. However, the low heat conductivity of the wooden flooring decreases heating efficiency. To address this issue, a thin flooring panel was developed. For practical applications, this material's performance, life cycle energy, and costs must be evaluated. Therefore, the purpose of this study is to analyze the life cycle energy and cost of the developed flooring with enhanced thermal efficiency. The energy analysis focuses on heating energy consumption in the maintenance phase, while the cost analysis focuses on the installation, repair, and replacement costs. As a result of this study, energy consumption was 7.2% lower and cost was 9.62% lower compared with the conventional wooden panel.

Keywords: ondol; life cycle energy; life cycle cost; thin flooring panel; energy reduction

1. Introduction

Buildings consume energy and resources as they go through the construction, operation and maintenance (O&M), and demolition phases. Several studies on energy consumption during a building’s lifecycle divide lifecycle into the construction, O&M, and demolition phases, among which the O&M phase accounts for the greatest energy consumption (Kim et al., 2011; Lee and Lee, 2010; Lee and Yang, 2009; Li and Guo, 2012; Ramesha et al., 2010; Zheng et al., 2011). According to data from Statistics Korea, apartment buildings account for more than 40% of the total area of building permission (National statistical office, 2014). Since Korea has four distinct seasons, the energy consumption for air-conditioning and heating to maintain an indoor environment is high (Baek et al., 2010; Joo et al., Kim and Lee, 2003; 2012; Lee et al., 2002). Moreover, 94% of petroleum (the major energy source of heating) is being imported from overseas (LA times, 2012). Thus, a plan to reduce energy for heating in the construction industry must be discussed, as shown in Fig.1.

Ondol heating, a kind of radiant floor heating is the main form of heating being used in housing units in Korea (Kim and Kim, 2005; Kim et al., 2011; Park and Kim, 2011). Ondol is applied with a low-temperature radiant floor heating system that provides a pleasant indoor thermal environment even at relatively low room temperature, and it is proven superior in terms of energy saving (Kim et al., 2003; Kim et al., 2009; Song, 2003; Song, 2004; Won et al., 2001). According to a Seoul Housing Corporation report, since heat conductivity decreases due to wood insulation properties, management difficulties have occurred in surface-enhanced wooden panels, which are one of the main panels used in the Korean ondol heating system (Son et al., 2013; Yang, 2010). The thickness of the flooring panel is reduced to improve heat conductivity, resulting in the development of a thin flooring panel (TFP).

However, to apply the developed panels on site, cost-efficiency due to lowered energy consumption in the construction and O&M phases should be examined. Previous studies on the life cycle cost (LCC) analysis

*Contact Author: Sunkuk Kim, Professor, Kyung Hee University, 1732 Deogyeong-dearo, Giheung-gu, Yongin-si, Gyeonggi-do, 446-701, Republic of Korea
Tel: +82-31-201-2922 Fax: +82-31-203-0089
E-mail: kimsukk@khu.ac.kr
(Received April 2, 2014; accepted November 1, 2014)
of construction projects did not take into account the economic efficiency due to energy reduction (Zheng et al., 2011; Lee and Lee, 2010; Lee and Yang, 2009; Lee et al., 2011; Yi and Komatsu, 2010).

Considering the cost savings due to energy reduction during the O&M lifecycle phase, outcomes compared to existing LCC analyses may differ (Na et al., 2011; Song et al., 2011). Likewise, existing studies on the estimation of life cycle energy (LCE) do not consider LCC when calculating the energy consumption of a building's lifecycle reduction (Lee and Lee, 2010; Lee and Yang, 2009; Choi et al., 2010; Zheng et al., 2011). This implies that the cost relevant to LCC has been increased, demonstrating low economic efficiency although energy consumption per unit basis is low. Thus, considering resources (material cost, labor cost, and overhead charge) and energy input during the lifecycle phases as the panels used as finishing materials for ondol change in terms of LCC and LCE is critical. Therefore, the purpose of this study is to analyze the life cycle energy and cost of the developed flooring with enhanced thermal efficiency. The LCE/LCC analysis model verified in this study is used as a material development tool that not only satisfies the LCC of apartment buildings, but also minimizes energy consumption. In order to calculate the LCE and cost of TFP used as finishing materials of ondol in apartment buildings, and to compare it with conventional wooden panels (CWP), this study focuses on energy analysis at the operation phase and on cost at the construction and maintenance phases.

This study analyzes the energy and cost reduction effects of the TFP with enhanced thermal efficiency. As illustrated in Fig.2., this study is intended to estimate the energy and cost generated per phase by dividing the lifecycle of a building into a construction phase and an O&M phase, and ultimately compares the application of TFP and CWP to apartment buildings.

2. Preliminary Study
2.1 Thin Flooring Panel

For TFP, the surface of plywood is decorated with sliced veneer so that a solid color or colorful pattern appears, and a silica nano particle dispersion coating method is adopted to improve the wear and scratch resistance of the sliced veneer (Son et al., 2013). The line that is vertical to a base is formed with multiple slits inclined to 25 degrees in order to prevent bending of the lower surface. As shown in Fig.3., the sides of each surface are applied with the standard flooring panel (4×75×600 mm) that is formed with a tongue-and-groove joint. Three new technologies are applied to TFP. First, a silica nano particle dispersion coating technology is adopted to form a surface that is highly resistant to scratches or dents, to protect from ultraviolet radiation, and to prevent decolonization. Second, flooring panels are joined by inserting the joints formed at both sides of the flooring panels, or separately furnished joint materials are inserted in the grooves, in order to increase the durability of the panel-to-panel connection. Third, multiple slits are formed in the lower part of flooring panels to prevent bending or twist that may occur on flooring panels when thermal heating is turned on. Unlike other surface-enhanced flooring panels (7-7.5 mm), it is comparatively thin so as to improve heat conductivity.

2.2 Literature Survey

LCE analysis accounts for all energy inputs to a building during its life cycle. The system boundaries of this analysis include the energy use of the manufacture, use, and demolition phases. The manufacture phase includes manufacturing and transportation of building materials and technical installations used in erection and renovation of a building. The operation phase encompasses all activities related to the use of a building over its life span. These activities include maintaining comfortable conditions inside the building, water use, and powering appliances. Finally, the demolition phase includes destruction of the building and transportation of dismantled materials to landfill sites and/or recycling plants (Ramesha et al., 2010). This study excludes the demolition phase.

3. Lifecycle Energy and Cost Analysis
3.1 Procedure of Lifecycle Energy and Cost Analysis

TFP resource analysis for a building’s lifecycle is...
composed of energy and cost analyses. To do so, it is linked to the actual resource database (DB) and the CO₂ emission DB provided by the Greenhouse Gas Inventory and Research Center of Korea which adopts the guidelines of IPCC2006. Fig.4. demonstrates a concept of calculating resources and energy consumption throughout the lifecycle of an apartment building when finishing materials (CWP, TFP) are applied to ondol in terms of LCC and LCE. Cost analysis consists of installation and maintenance costs of finishing materials. The installation cost at the construction phase includes panel material cost, labor cost for installation, and overhead. Like the construction phase, the cost in the maintenance phase is calculated by taking into account the material cost, labor cost, and overhead according to the long-range repair and replacement plan for finishing materials. The energy consumption of CWP and TFP at the operation phase is estimated by investigating the energy use of apartment buildings for CWP, and by experimenting with energy efficiency at the Korea Conformity Laboratory for TFP. This cost is referred to as operation cost. This process is adopted to compare LCE and LCC of both CWP and TFP. The procedure illustrated in Fig.5. is applied to identify the cost and energy consumption of CWP and TFP in this study.

Each item for the procedure described above is as follows:

1. Select a panel that is to be used as the finishing material of ondol.
2. Calculate the panel installation cost using the price information and Korean estimate data.
3. Calculate the maintenance cost to sustain a pleasant indoor environment for occupants by considering the long-range repair and replacement plan, price information, and estimate data.
4. Calculate the operation cost for indoor heating by applying CO₂ emissions from heating apartment buildings and from energy sources, such as diesel.
5. Sum the values of (2), (3), and (4) to estimate the cost and energy consumption throughout the building's lifecycle.

(6) Lastly, compare the calculated values to check the lifecycle energy and cost per panel.

3.2 Lifecycle Energy and Cost Analysis

For lifecycle energy and cost analysis, the installation cost in the construction phase, the maintenance cost in the maintenance phase, and the energy consumption in the operation phase are utilized. The lifecycle cost \( C_{\text{life}} \) consists of installation cost \( C_{\text{inst}} \), maintenance cost \( C_{\text{main}} \), and operation energy cost \( C_{\text{energy}} \) as shown in eq. (1).

\[
C_{\text{life}} = C_{\text{inst}} + C_{\text{main}} + C_{\text{energy}}
\]  

The estimate data, price information, and wage unit price are used to calculate an installation cost \( C_{\text{inst}} \). The installation cost is composed of material cost \( C_m \), labor cost \( C_l \), and overhead charge \( C_o \) as shown in eq. (2). The material cost is calculated by multiplying the unit price of a panel \( P_u \) obtained from the price information) by the installation area \( A_i \) as shown in eq. (3). The labor cost uses the standard of estimate
on flooring panels \( (E) \) as well as the wage unit price \( (C_w) \) and installation area \( (A_i) \) as shown in eq. (4). The overhead charge is calculated on the assumption that percentage of tools and consumables \( (P) \) is added to the material and labor costs as shown in eq. (5).

\[
C_{\text{inst}} = C_m + C_l + C_o
\]

(2)

\[
C_m = A_i \times P_w
\]

(3)

\[
C_l = A_i \times E_r \times C_c
\]

(4)

\[
C_o = (C_m \times C_o) \times P
\]

(5)

The standard estimate data, price information, wage unit price, and long-range repair and replacement plan are used to calculate the maintenance cost \( (C_{\text{main}}) \). A long-range repair and replacement plan is a scheme to repair and replace materials and equipment that comprise a building.

The maintenance cost \( (C_{\text{main}}) \) is estimated by multiplying the installation cost \( (C_{\text{inst}}) \) by the replacement and repair ratio during the lifecycle of a building as shown in eq. 6. The number of replacements \( (N_p) \) is calculated by dividing the life span of a building \( (L_m) \) with the material service life \( (L_m) \) and then rounding up to the nearest integer, excluding the initial installation as shown in eq. 7. The number of repairs \( (N_{pr}) \) is estimated by dividing the material service life \( (L_m) \) with the repair cycle \( (R_c) \) and then multiplying the calculated value by the repair rate \( (R_r) \), which results in a ratio that represents the cost to repair flooring panels for a set period of time as shown in eq. 8.

\[
C_{\text{main}} = C_{\text{inst}} \times (N_p + N_{pr})
\]

(6)

\[
N_p = \text{Int}((L_m - L_m - 1), 0)
\]

(7)

\[
N_{pr} = (L_m - R_c) \times R_r
\]

(8)

The annual heating energy consumption \( (Q) \), diesel unit price \( (C_d) \) and diesel energy heating unit \( (D_{\text{coh}}) \) are used to calculate the operation energy cost \( (C_{\text{energy}}) \) as shown in eq. 9. The operation energy cost \( (C_{\text{energy}}) \) is estimated by converting the energy consumption during the life span of a building \( (E_{\text{ops}}) \) as shown in eq. 10.

\[
C_{\text{energy}} = E_{\text{ops}} \times D_{\text{coh}} \times C_d
\]

(9)

\[
E_{\text{ops}} = \sum_{i=1}^{N_{\text{cycle}}} Q_i
\]

(10)

For cost conversion, the diesel unit price \( (C_d) \) that is used as the heating energy source and the diesel energy heating unit \( (D_{\text{coh}}) \) are used. For annual heating energy consumption values, the apartment housing management information system \( (www.k-apt.net) \) can be used.

4. Case Study
4.1 Analysis Conditions

For this research, a housing unit with 100 m² of floor area was selected. This type of housing unit accounts for approximately one quarter of all apartment units in Korea, and the total area of the heating system applied with the flooring panel was 80.9 m² as shown in Fig.6. For reference, the case apartment unit analyzed in this paper adopted the district heating method using diesel for energy source. Table 1. shows the detailed conditions for energy and cost analyses.

![Fig.6. Plan of a Housing Unit Used in Case Study](image)

Table 1. Plan of a Housing Unit Used in Case Study

| Zone                  | Area (m²) | Panels installed |
|-----------------------|-----------|------------------|
| Bedroom 1             | 20.7      | O                |
| Bedroom 2             | 10.9      | O                |
| Bedroom 3             | 8.1       | O                |
| Living and kitchen    | 41.2      | O                |
| Bathroom              | 4.9       | X                |
| Service area          | 3.2       | X                |
| Total                 | 100       |

Table 1. Analysis Conditions

| Description                        | Unit | CWP  | TFP  |
|------------------------------------|------|------|------|
| Installation area \( (A_i) \)      | m²   | 80.9 | 80.9 |
| Unit price of panel \( (P_w) \)     | USD/m² | 48.50 | 41.23 |
| Labor productivity rate \( (E_r) \) | Man-day/m² | 0.038 | 0.038 |
| Unit labor cost \( (C_l) \)         | USD/man-day | 92.31 | 92.31 |
| Percentage of tools and consumables \( (P) \) | % | 10 | 10 |
| Life span of a building \( (L_m) \) | Years | 30 | 30 |
| Material service life \( (L_m) \)   | Years | 20 | 20 |
| Repair cycle \( (R_c) \)            | Years | 5  | 5   |
| Repair rate \( (R_r) \)             | %    | 5  | 5   |
| Diesel unit price \( (C_d) \)       | USD/L | 1.64 | 1.64 |
| Energy efficiency                  | %    | 100| 92.80 |

4.2 Energy and Cost Analyses of CWP

The CWP installation cost is calculated by using the conditions described in Table 1. When the panels are installed on a surface of 80.9 m², Eq. (3) is used to calculate the material cost, which is USD 3,924.72. The labor cost calculated with eq. (4) is USD 283.79, and the overhead charge calculated with eq. (5) is USD 420.75. Therefore, the total installation cost calculated with eq. (2) is USD 4,628.26.

The maintenance cost is estimated with the same conditions specified in Table 1. Equations 6-8 are used for calculation, and the total cost is USD 5,785.32. Ten apartment complexes in metropolitan cities were selected from the apartment housing management information system \( (www.k-apt.net) \) to calculate the energy consumption of CWP, and CO₂ emissions per monthly heating were investigated. The result was converted into CO₂ emissions from heating per unit
area. Fig.7. shows the relevant diagram. Monthly energy consumption soars constantly from November to April when heating systems are used, increasing CO\(_2\) emissions. There are no CO\(_2\) emissions from heating from May to October.

Based on the survey, CO\(_2\) emissions are converted into diesel consumption, energy consumption, and cost using Equations 9-10 in order to identify the annual energy consumption and cost as shown in Table 2. that shows the test results of CWP provided by the government-authorized test institution. The carbon emission from diesel in order to replace CO\(_2\) with the diesel is \(2.084 \times 10^{-3} \text{TCO}_2/L\), the energy consumption of diesel for energy conversion is 9,200 kcal/L, and the diesel price for cost conversion is 1.64 USD/L (Korea Institute of Construction Technology, 2004). Table 3. shows the annual energy consumption and cost applied for the 100 m\(^2\) apartment by using the data of Table 2. The annual energy use for heating is 5,046,658 J, and the cost of operation energy consumption is USD 900.41.

4.3 Energy and Cost Analysis of TFP

The operation cost of TFP is calculated by applying the conditions set in Table 1. When the panels are installed on a surface of 80.9 m\(^2\), the material cost is USD 3,335.16, the labor cost is USD 283.79, the overhead charge is USD 361.90, and the installation cost is USD 3,980.84. The operation cost is also calculated by applying Table 1. and Equations 6-8, which results in a total of USD 4,777.01. The energy consumption of TFP is calculated by multiplying the energy consumption of CWP and the energy efficiency of TFP.

In order to analyze the energy efficiency of TFP, as shown in Fig.8., the hot water supply amount changes according to the time CWP and TFP were measured by testing in the Korea Conformity Laboratory. For testing, hot water supply and a constant temperature/humidity were maintained. A hot water supply system was applied to the floor heating system with PE-Xa piping (outer diameter of 20 mm, thickness of 1.9 mm) arranged at intervals of 200 mm. The mortar finish was applied to the surface of the floor. The hot water was supplied at 2 L/min, the size of the testing room was 2,000 (W) × 2,000 (D) × 1,000 (H) mm, and the temperature and humidity were 20°C and 80%, respectively. The testing room was built according to Article 2009-1217 of the Ministry of Land, Transport, and Maritime Affairs (KS L 9016) that followed the ISO regulations. The results are shown in Table 4.

As a heat source, two boilers (11.6 KW = 10,000 Kcal) were operated for 3 hours and then stopped for 3 hours four times a day for testing. The heating water temperature under testing was set as 80°C, and the gas consumption and indoor air temperature were measured until reaching the desired indoor temperature of 22°C. The flow rate in the return pipe was measured every 30 seconds for gas consumption and every 1-minute for indoor temperature. As a result, the accumulated gas consumption was 1.6562 (m\(^3\)·N) for CWP and 1.5366 (m\(^3\)·N) for TFP, which represented a 7.2% energy reduction.

The energy efficiency verified though it can be applied to the annual heating energy and cost per household of CWP to calculate the annual energy and cost of TFP as shown in Table 5. The annual TFT energy consumption for heating is 4,683,299 J, and the operation cost is USD 835.58.

4.4 Comparison of the Lifecycle Energy and Cost

The installation, maintenance, and operation costs of both CWP and TFP were converted into total costs. The deflator of Korean construction cost index was considered as the discount rate to calculate the LCC of TFP and CWP. As illustrated in Fig.9., TFP is superior to CWP in terms of both energy efficiency and cost. The initial installation cost of TFP is 87% of that required to install CWP. Furthermore, the energy efficiency of TFP improved by 7.2%, reducing energy usage during the operation phase. And the LCC of CWP is around 20,661 USD, and that of TFP is around 18,673 USD, reducing the LCC by 9.62% compared to that of CWP. As time elapses, the difference of accumulated cost ratio per panel use decreases (from
This is because the annual operation and maintenance costs decrease every year compared to the total accumulated cost. However, the annual accumulated cost increases.

### 5. Conclusion

Buildings consume energy and resources as they go through their lifecycles of construction, operation and maintenance, and demolition phases. Globally, the construction industry is consuming tremendous amounts of energy and resources, accounting for 30% of energy consumption and 40% of raw material consumption. CO$_2$ emissions are increasing rapidly in Korea with the rapid development of industry and the economy. Moreover, 94% of petroleum (the major energy source of heating) is imported. Thus, a plan to reduce energy for heating in the construction industry must be discussed.

![Comparison of the LCE Cost of TFP and CWP](image)

Table 2. Energy Cost of CWP for Heating Apartment Buildings Per Unit Floor Area

| Description | Unit | 2011.01 | 2011.02 | 2011.03 | 2011.04 | 2011.05 | 2011.06 | 2011.07 |
|-------------|------|---------|---------|---------|---------|---------|---------|---------|
| CO$_2$ emission | kg-CO$_2$/m$^2$ | 2.480 | 2.938 | 1.963 | 1.583 | 0.763 | 0.178 | 0.041 |
| Diesel | L/m$^2$ | 1.19 | 1.41 | 0.94 | 0.76 | 0.37 | 0.09 | 0.02 |
| Energy | J/m$^2$ | 10,950 | 12,968 | 8,667 | 6,986 | 3,368 | 785 | 180 |
| Cost | USD/m$^2$ | 1.95 | 2.31 | 1.55 | 1.25 | 0.60 | 0.14 | 0.03 |

Table 3. Annual Energy Cost of CWP Per Housing Unit (100m$^2$ of Floor Area)

| Description | Unit | 2011.01 | 2011.02 | 2011.03 | 2011.04 | 2011.05 | 2011.06 | 2011.07 |
|-------------|------|---------|---------|---------|---------|---------|---------|---------|
| CO$_2$ emission | kg-CO$_2$/m$^2$ | 0.028 | 0.004 | 0.100 | 0.506 | 0.848 | 11.432 |
| Diesel | L/m$^2$ | 0.01 | 0.00 | 0.05 | 0.24 | 0.41 | 5.49 |
| Energy | J/m$^2$ | 122 | 18 | 442 | 2,234 | 3,745 | 50,467 |
| Cost | USD/m$^2$ | 0.02 | 0.00 | 0.08 | 0.40 | 0.67 | 9.00 |

Table 4. Experiment Results for Heat and Energy Efficiency

| Contents | Test results | Difference |
|----------|--------------|------------|
| Accumulated gas consumption | 1.6562 (m$^3$·N) | 1.5366(m$^3$·N) | ∆7.2% |
| Time to reach the design temperature | 1 hour 15 minutes | 1 hour 4 minutes |
| Indoor air temperature change | ∆11.6 | ∆11.0 |

Table 5. Annual Energy Cost of TFP Per Housing Unit (100m$^2$ of Floor Area)

| Description | Unit | 2011.01 | 2011.02 | 2011.03 | 2011.04 | 2011.05 | 2011.06 | 2011.07 |
|-------------|------|---------|---------|---------|---------|---------|---------|---------|
| Energy | J | 1,016,187 | 1,203,423 | 804,343 | 648,327 | 312,533 | 72,818 | 4,683,299 |
| Cost | USD | 181.30 | 214.71 | 143.51 | 115.67 | 55.76 | 12.99 | 835.58 |

13% initially to 9.7% in the final phase). This is because the annual operation and maintenance costs decrease every year compared to the total accumulated cost. However, the annual accumulated cost increases.
Therefore, this study aims to analyze the LCE and cost of a building with flooring developed for maximal energy efficiency. The results include the LCE efficiency of TFP and the LCC required for installation, maintenance, and operation.

As a result, TFP provides a 7.2% energy reduction compared to CWP. Moreover, 363,359 J of energy is saved throughout the lifecycle, which translates into a cost savings of USD 66.14/year, or USD 1944.88 for the whole lifecycle of a building. Energy consumption is reduced in different phases, saving USD 647.41 in the construction phase, USD 1,008.31 in the maintenance phase, and USD 1,944.88 in the operation phase. This totals cost savings of USD 3,600.60, which is a 9.7% improvement.

The LCE/LCC the TFP verified in this study will satisfy the LCC of apartment buildings, minimize energy consumption, induce material development, and improve excessive energy and resource consuming construction technologies in the near future.

Acknowledgement

This research was supported by the Ministry of Land, Infrastructure and Transport (MOLIT) of the Korea government and the Korea Agency for Infrastructure Technology Advancement (KAIA) (No. 13AUDP-B068892-01).

References

1) Baek, J., Choi, J. Jang, S. and Park, M. (2010) Simulational Analysis of Adaptive Outdoor Reset Control based on a Fuzzy Target Temperature Gap for a Hydronic Radiant Floor Heating System, Journal of Asian Architecture and Building Engineering, 9(1), pp.251-257.

2) Choi, J., Lee, D., Kwon, G. and Kim, S. (2010) A study on energy consumption and estimation of CO2 form re-bar production, Journal of the Korea institute of ecological architecture and environment, 10(4), pp.101-109.

3) John M.G. U.S. presses China, Japan, South Korea to trim Iran oil imports, Los Angeles Times, January 10, 2012.

4) Joo, J., Zheng, Q., Kim, J., and Kim S. (2012) Optimum energy use to safety indoor air quality needs, Energy and Buildings, 46, pp.62-67.

5) Kim, B., and Lee, J. (2003) A study of the ondol(gudul, floor heating system) and kitchen space in the traditional houses on Jeju Island, International Journal of Human Ecology, 4(1), pp.15-23.

6) Kim, M., Kim, J., Kwon, O., Choi, A. and Jeong, J. (2011) Overall Heat Transfer Coefficient of a Korean Traditional Building Envelope Estimated Through Heat Flux Measurement, Journal of Asian Architecture and Building Engineering, 10(11), pp.263-270.

7) Kim, S. and Kim, H. (2005) Comparison of formaldehyde emission from building finishing materials at various temperatures in under heating system; ONDOL, Indoor Air, 15(5), pp.317-325.

8) Kim, S., Hong, H., Kim, S. and Kim, J. (2011) Method and analysis of a dynamic simulation of Ondol heating, Indoor and Built Environment, 20(1), pp.112-119.

9) Kim, T., Kim, H., Jo, H., Kim, G. and Seo, S. (2009) An experimental study on the analysis and the reduction of defects for Ondol wooden floor coverings in apartment housing, Architectural Institute of Korea, 29(1), pp.503-506.

10) Kim, T., Kim, N., Kim, J. and Sohn J. (2003) A Study on heat retrieving characteristics of the pre-fabricated Ondol system and existing Ondol system according to floor finishing materials, Architectural Institute of Korea, 23(2), pp.845-848.

11) Korea institute of construction technology. (2004) A study on the program development and making unit for building life cycle assessment, Korea institute of construction technology.

12) Lee, J., Yeo, M. and Kim, K. (2002) Predictive Control of the Radiant Floor Heating System in Apartment Buildings, Journal of Asian Architecture and Building Engineering, 1(1), pp.105-112.

13) Lee, K. and Yang, J. (2009) A study on the functional unit estimation of energy consumption and carbon dioxide emission in the construction materials, Journal of the architectural of Korea, 25(6), pp.43-50.

14) Lee, Y. and Lee, K. (2010) Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building, Energy and Buildings, 42(2), pp.230-242.

15) Lee, Y., Jeong, C., Yeo, M. and Kim, K. (2011) Design of the radiant floor heating panel considering heating load of residential building, Architectural Institute of Korea, 27(9), pp.349-357.

16) Li, C. and Guo, S. (2012) Life Cycle Cost Analysis of Maintenance Costs and Budgets for University Buildings in Taiwan, Journal of Asian Architecture and Building Engineering, 11(1), pp.87-94.

17) Na, Y., Nam, E. and Yang, I. (2010) Life Cycle Cost Analysis of Air Conditioning Systems in a Perimeter Zone for a Variable Air Volume System in Office Buildings, Journal of Asian Architecture and Building Engineering, 9(1), pp.243-250.

18) Park, C. and Kim, T. (2011) Formation and Transformation of Japanese Migrant Fishing Village Colonies in Korea, Journal of Asian Architecture and Building Engineering, 10(2), pp.289-296.

19) Ramesha, T., Ravi, P. and Shuklab, K. (2010) Life cycle energy analysis of buildings; An overview. Energy and Buildings, 42(10), pp.1592-1600.

20) Song, S., Koo, B. and Lee, S. (2010) Cost Efficiency Analysis of Design Variables for Energy-efficient Apartment Complexes, Journal of Asian Architecture and Building Engineering, 9(2), pp.515-522.

21) Song, G. (2004) Buttock temperature in a sedentary posture on plywood flooring of varying thickness over the ONDOL heating system, Journal of Wood Science, 50(6), pp.498-503.

22) Song, K. (2003) A comparison of thermo-physiological responses of human body by thickness variations of plywood covering on Ondol system, Journal of Korean Society Living Environment System, 10(3), pp.169-175.

23) Song, S., Koo, B. and Lee, S. (2010) Cost Efficiency Analysis of Design Variables for Energy-efficient Apartment Complexes, Journal of Asian Architecture and Building Engineering, 9(2), pp.515-522.

24) Statistics Korea. (2014) http://www.index.go.kr (accessed March 5. 2014)

25) Won, J., Park, B. and Sohn, J. (2001) Evaluation of thermal comfort and heat retrieving characteristics of hydronic radiant floor heating system according to floor finishing materials, The Society of Air-conditioning and Refrigerating Engineers of Korea, 12, pp.424-429.

26) Yang, I. (2010) Development of an Artificial Neural Network Model to Predict the Optimal Pre-cooling Time in Office Buildings, Journal of Asian Architecture and Building Engineering, 9(2), pp.539-546.

27) Yi, S. and Komatsu, Y. (2010) Investigation of the Maintenance Condition in Public Facilities Focus on Comparison of the Municipalities in Tokyo, Journal of Asian Architecture and Building Engineering, 9(1), pp.125-130.

28) Zheng, Q., Lee, D., Lee, S., Kim and, J. Kim and S. (2011) A health performance evaluation model of apartment building indoor air quality. Indoor and Built Environment, 20, pp.26-35.