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Three-Dimensional Visualization Solution to Building-Energy Diagnosis for Energy Feedback

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Abstract: Owing to the large ratio of consumption in the building sector, energy-saving strategies are required. Energy feedback is an energy-saving strategy that prompts consumers to change their energy-consumption behaviors. The strategy has been principally focused on providing energy-consumption information. However, the realization of energy savings using only consumption information remains limited. In this paper, a building-energy, three-dimensional (3D) visualization solution is thus proposed. The aim is to determine if the building manager will replace the facility after our recommendation to improve the building-energy efficiency derived from the energy information is given. This solution includes the process of diagnosing a building and providing a prediction of energy requirements if a building improvement effort is undertaken. Accurate diagnostic information is provided by real-time measurement data from sensors and building models using a close-range photogrammetry method, without depending on blueprints. The information is provided by employing visualization effects to increase the energy-feedback efficiency. The proposed strategy is implemented on two testbeds, and building diagnostics are performed accordingly. For the first testbed, the predicted energy improvement amount resulting from the facility upgrade is provided. The second testbed is provided with a 3D visualization of the energy information. The predicted value of energy improvement was derived from the improvement plan through energy diagnosis in each testbed as about 30% and as about 28%, respectively. Unlike existing systems, which provide only ambiguous data that lack quantitative information, this study is meaningful because it provides energy information with the aid of visualization effects before and after building improvements.

Keywords: energy diagnosis; close-range photogrammetry; energy efficiency; visualization of information; energy feedback

1. Introduction

In recent years, the expansion of power access and the industrialization and urbanization of China and India have led to a 30% increase in the energy demand forecast by 2040 [1]. Energy-intensive countries such as those that are members of the Organization for Economic Cooperation and Development (OECD) are striving to reduce their dependence on fossil energy, shift to renewable energies, and improve energy efficiency. However, the primary energy share of fossil fuels is more than 70% and is expected to increase steadily [1,2]. As a result, the global increase in greenhouse gas emissions has led to abnormal weather phenomena in each region of the world, causing difficulties in coping with disasters and increasing the frequency and magnitude of natural disasters related to the climate [3–5].

Much of the energy produced is consumed in buildings, typically in the United States (US) and European Union (EU), with buildings accounting for more than 40% of the energy consumption [6,7]. This finding indicates that energy consumption in buildings has a direct effect on greenhouse gas emissions. As a result, focus on its management is required and various method have been suggested to solve the problem [8–10]. In addition, since the proportion of obsolete buildings around the world is increasing and because older buildings require up to eight times the amount of energy needed per square meter per year as that required by new buildings, the overall consumption is increasing [11]. Moreover, the energy consumption of older buildings is expected to rise even further. Energy efficiency retrofit (EER) is a process that can reduce energy consumption and greenhouse gas emissions through the making of improvements to existing buildings. Various studies using EER have performed energy efficiency diagnoses for the purpose of increasing energy savings in buildings. This phenomenon indicates that building-energy diagnosis has become an important issue [12,13].

Furthermore, so-called energy feedback or eco-feedback is an energy strategy that focuses on solving the fundamental problem of how to save energy and provides information to residents and property owners to foster energy-consumption behavioral changes. The American Council for an Energy-Efficient Economy reported that savings of more than 10% are achieved when energy feedback is provided. Research is underway to realize these savings by applying an energy feedback strategy [14–16]. Since monthly utility bills are the main source of energy consumption information for users, the central idea of previous studies was to improve the visual effect of these bills to enable user awareness and change [17,18].

In the goal of effectively realizing energy savings, the main issue has remained to be the determination of the most effective means of communicating energy use [19]. Psychological literature suggests that visualizing information results in increased attention to the information [20] and thereby motivates people in accordance with the goal of the visual material [21]. Nevertheless, most energy feedback currently provided is in the form of monthly bills that lack data visualization [17]. Therefore, the present research was conducted with the consideration of visualizing information for a building depending on the user initiative to improve the building-energy efficiency.

So far, most relevant research has focused on building-energy performance diagnosis to identify poor energy performance of the building and to implement timely repairs and maintenance [22]. Through diagnosis, the performance can be evaluated. However, identifying the root cause of low performance of a building can be challenging. For this reason, the use of simulation is accepted by many studies as a tool for identifying building-energy saving factors [23]. The advantage of building-energy diagnostics based on a simulation is that it can evaluate the building-energy performance by comparing the energy consumption from the energy simulation results [24]. Pisello et al. [25] developed a method that evaluates building-energy efficiency using simulation and experimental approaches. Additionally, O'Neill et al. [26] proposed a real-time building monitoring and energy diagnostic system and demonstrated with it that, in a real building, 30% energy savings were identified during the first six months of use. Other recent studies have also been carried out supporting the decision-making process to suggest optimal building improvement methods through energy simulation. Jardi et al. [27] compared each building improvement measure using the energy simulation engine of EnergyPlus applied to Aarhus daycare centers in Denmark. When improving existing buildings to boost energy efficiency, it is important to use energy simulations to provide accurate savings information.

This study focused on the energy enhancement of existing buildings. An energy solution is applied to show how much building-energy performance can be improved after making certain building improvements, such as upgrading the building envelope or changing the equipment of the building. Furthermore, the simulation data were provided by visualization through developing a building-energy diagnosis solution for drawing the attention of the landlord and occupants to the information. It is meaningful to substantiate the building-energy diagnosis system for a real site and to apply the proposed technology for energy feedback.

The detailed process for achieving the objective of the visualization solution is outlined as follows:

(1) Perform building-energy diagnosis for existing buildings that are expected to have low efficiency.
(2) Input diagnostic data into an energy simulation program for showing the amount of energy that can be saved if specific elements are improved.
(3) Develop a building-energy, three-dimensional (3D) visualization solution to efficiently provide the given information (Figure 1).

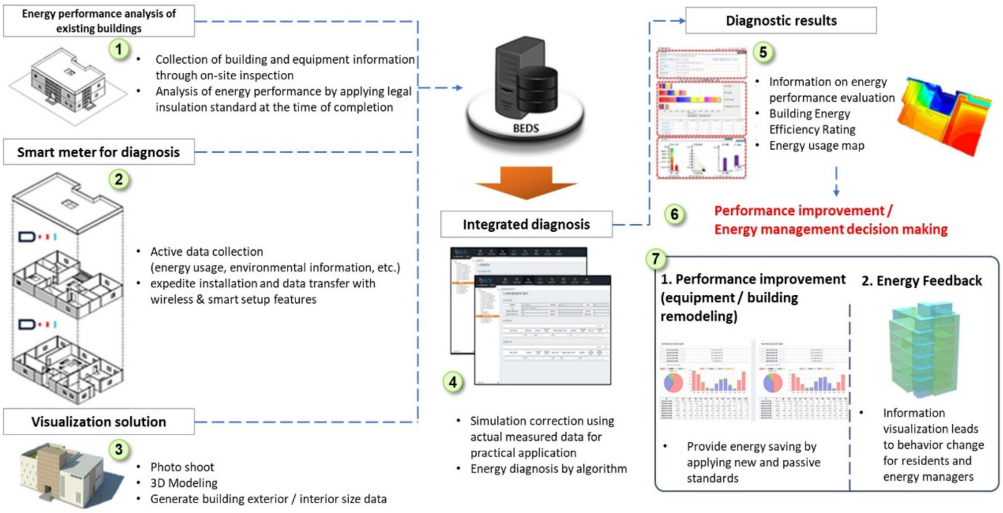


Figure 1. Integrated diagnosis algorithm process of building-energy conservation.

2. Research Method

The whole process is divided into: (1) a process for providing diagnosis results and (2) a building-energy visualization process. In the process of the building-energy diagnosis, the energy performance is analyzed by energy simulation with input diagnosis data from the existing building. The results of the analyses (e.g., energy demand, final energy, and primary energy) are provided in graph format on a website. Additionally, energy usage information and environmental information (e.g., electric energy consumption, temperature, carbon dioxide concentration, and humidity) was acquired from smart meters installed in each room and on each floor. Then, energy performance improvement is predicted with the assistance of an energy simulation program. The next task is a building-energy feedback provision. First, the building shape model is constructed using close-range photogrammetry (CRP). Second, the acquired energy information from the smart meter is linked with each zone of the building. Finally, the information is provided to the user after information grouping and coloring according to the energy consumption status of each zone is determined.

2.1. Energy Efficiency Diagnosis

To improve building-energy efficiency, various systems have been implemented worldwide to evaluate building-energy consumption. In Europe, buildings have been managed since 2002 by the Energy Performance of Building Directives (EPBD), which serves to improve building-energy systems. In the US, Standard 90.1 of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) is used for building-energy evaluations. Moreover, various systems have been developed by the society [28]. Although differences exist among building-energy evaluation methods or regulations depending on the environment of each country and region, generally, they are focused on reducing energy usage and emissions. Meanwhile, the Republic of Korea finances and manages the Energy Efficiency Grade

Certification System, which can quantitatively evaluate the energy performances of buildings. According to the system, the energy efficiency grade is calculated by multiplying the energy required for heating, cooling, and hot water supply per square meter of the building by their corresponding primary energy conversion factors. In Table 1, 10 energy-efficiency classes (ranging from 1+++ to 7) are presented, which are classified according to annual primary energy per unit area [29,30].

Table 1. Energy efficiency grading system.

Rating	Residential Building	Nonresidential Building
	Annual Primary Energy Per Unit Area (kWh/m^2 Year)	Annual Primary Energy Per Unit Area (kWh/m^2 Year)
1+++	Less than 60	Less than 80
1++	More than 60 less than 90	More than 80 less than 140
1+	More than 90 less than 120	More than 140 less than 200
1	More than 120 less than 150	More than 200 less than 260
2	More than 150 less than 190	More than 260 less than 320
3	More than 190 less than 230	More than 320 less than 380
4	More than 230 less than 270	More than 380 less than 450
5	More than 270 less than 320	More than 450 less than 520
6	More than 320 less than 370	More than 520 less than 610
7	More than 370 less than 420	More than 610 less than 700

The present research was conducted on buildings located in the Republic of Korea and the efficiency level was determined according to the Republic of Korea management grade system. Diagnoses of buildings were made according to the following process:

(1) Diagnose buildings with on-site inspection to gain architecture and facility information.
(2) Calculate the energy demand and final energy of an existing building from energy simulation as input for its structural data (Table 2).
(3) Calibrate them with consideration paid to the actual energy usage, which is measured by the diagnostic smart meter (Figure 2).
(4) Obtain the building's final energy data after applying the conversion factor to the primary energy and then assign a building-energy efficiency rating according to grading system.
(5) Recalculate energy demand, final energy, and primary energy of the building after enacting the building-energy efficiency improvement scenarios to secure an improved rating.

Table 2. Data used for diagnosis algorithm.

Field	Division	Item
Architecture	Architectural basic information	Building name, Location, Area, Bearing, Address, Floor
	Architectural details	Wall Insulation type, Wall heat storage capacity, Night operation type, Weekend operation type, Heating method, Cooling method, Air leakage rate, Presence or absence of out-air control (OAC), Presence or absence of heat recovery ventilators, Light power density
	Wall/window information	Bearing, Wall area, Wall color, Window and door area
Facility (heat source equipment)	Basic information	Use of heat source equipment, Heat source equipment type, Hot water supply temperature, Return water temperature
	Boiler	Boiler type, Boiler operation method, Fuel used, Boiler rated output, Boiler efficiency, District heating type, Heat exchanger output, Heat exchanger efficiency, Rated output of electric boiler, Electric boiler efficiency
	Heating circulation pump	Pump power, Pump control type, Weekend operation type
	Hot water piping network/circulation pump	Pump power, Pump control type
	Heating supply	Room temperature control method, Control power, Pump power, Pump quantity, Fan power, Fan quantity

Table 2. *Cont.*

Field	Division	Item
Facility (cooling) air conditioning equipment information	Basic information	Refrigerator type, capacity, Coefficient of performance
	Compressor freezer setting	Compression system, Scroll compressor control system, Cooling tower type, Coolant inlet temperature, Evaporative cooling tower type
	Air conditioning distribution setting	Heat transfer medium, Outlet temperature, Inlet temperature, Temperature difference
	Distribution network information	Pump control, Pump power, Piping pressure loss, Individual resistance
	Pressure loss type	Refrigerator pressure loss, Equipment pressure loss, Valve pressure loss
	Air conditioning distribution piping setup	Number of floors, Width, Length, Height

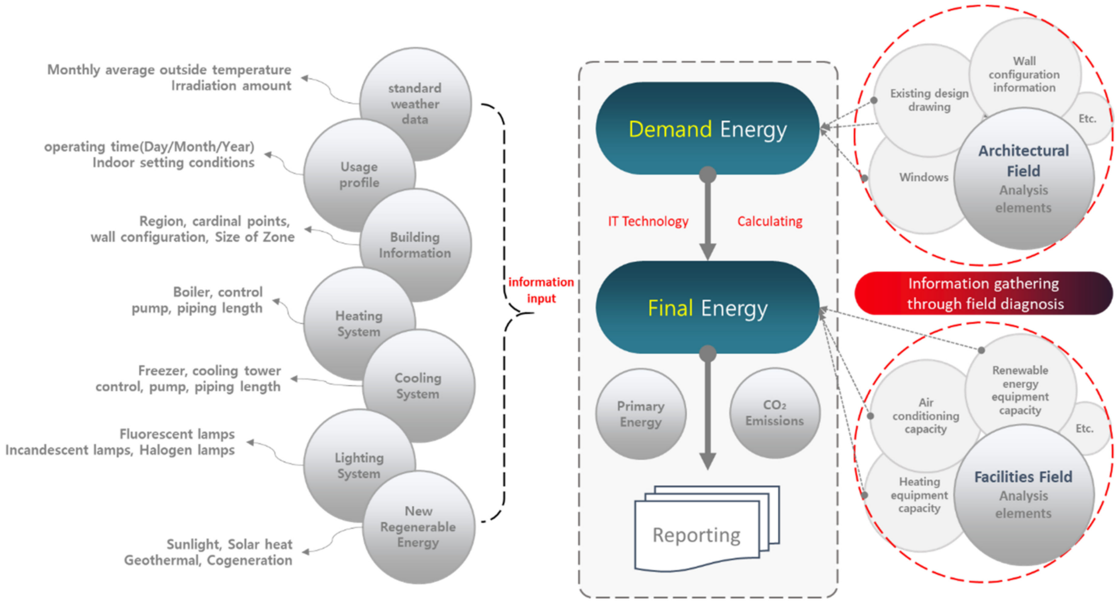


Figure 2. Principle of calculation of energy demand and final energy.

2.2. Energy Simulation

Building-energy simulation refers to the activity of creating energy models using computer-based analysis programs. These serve to evaluate the performance of all or some of the building's systems [31]. If the simulation is not applied, then no quantitative information can be provided regarding an energy efficiency increase when improvements are made. There are many building-energy simulation programs that have been developed and which can provide users with the key energy performance indicators (e.g., energy demand and environmental data) on the building, such as EnergyPlus, TRNSYS, and Passive House Planning Package [32]. EnergyPlus is a tool developed by integrating the advantages of existing analysis tools DOE-2, BLAST, and COMIS. It can evaluate realistic system controls, radiant heating, and cooling systems, but a lot of information is required for high-accuracy calculations and it is not easy for nonprofessionals to handle [33,34]. Table 3 shows the contrast of building-energy simulation tools pursuant to Crawley et al., which is the primary method used [32,35].

Table 3. Comparison and contrast of the building-energy simulation tools.

Category		EnergyPlus [32,34]	TRANSYS [32,35]	DOE-2 [32,35]	eQUEST [32,35]
Zone loads	Temperature	○	○		
	Air flow	P	E		
	Surface heat coefficient from Computational fluid dynamics	E			
	Internal thermal mass calculation	○	○	○	○
	Dry bulb temperature	○		○	○
	Dew point temperature or humidity	○	○	○	○
Building envelope and daylighting	Outside surface convention algorithm	○	○	○	
	Inside radiation view factors	○	○		
	Radiation-to-air component from convection (exterior)	○	○		○
	Solar gain and daylighting calculations	○	○		
Infiltration	Single-zone infiltration	○	○	○	○
○: available and in common use		P: partially implemented		E: requires domain expertise	

There are also many energy simulation programs mainly used in Republic of Korea such as BESS (BESS ver. 4.0, Seoul, Republic of Korea), ECO2 (ECO2 OD_v20170620_1, Republic of Korea), and ECO-CE3(Construction Energy Efficiency Evaluation) (Korea Institute of Building Energy Technology, Republic of Korea). ECO2 is based on ISO 13790 (EN 13790:2008, International Organization for Standardization) and DIN V 18599 (Fraunhofer IRB, Deutschland) and used as a simulation tool for assessing the energy efficiency rating of buildings. Users can estimate the monthly energy demand of the building and final energy amount according to the system performance as well as calculate the rating based on primary energy requirement per unit area per year (kWh/m^2·year) [36]. However, ECO-CE3 used as an energy diagnosis efficiency improvement program can compare the states before and after the improvement of energy efficiency among the three programs. Therefore, ECO-CE3 was adopted as the program to be used for this study. ECO-CE3 was a building-energy performance evaluation solution based on the EPBD international ISO 13790 standard and Germany's building-energy performance evaluation DIN V 18599 standard. It simulates the problems of the energy performance from the design stage. In addition, it can predict the annual cost of energy and the amount of carbon dioxide emitted [37].

Energy demand is the energy required by the building to maintain its interior livability (i.e., the building thermal environment). It is primarily affected by architectural design aspects such as building type, material characteristics, and window ratio [38,39]. The energy demand is supplemented by the energy needs of heating, cooling, lighting, and hot water supply. Each demand is calculated from the DIN V 18599 standard. In this study, the energy demand of heating and cooling was calculated using the heat sources and heat sink for the building zone by means of Equations (1) and (2) [40,41].

$$Q_{h,b} = Q_{sink} - \eta \times Q_{source} - \Delta Q_{C,b} \tag{1}$$

$$Q_{c,b} = (1 - \eta) \times Q_{source} \tag{2}$$

where:

- $Q_{h,b}$ is the heating energy demand for building zone (kWh)
- $Q_{c,b}$ is the cooling energy demand for building zone (kWh)
- Q_{sink} is the sum total of all heat sinks in the building zone (kWh)
- Q_{source} is the sum total of all heat sinks in the building zone (kWh)
- η is the utilization factor of the heat sources

- $\Delta Q_{C,b}$ is the heat transferred from the building elements into the building zone during periods of reduced operation on weekends and during holiday periods (kWh)

The final energy or delivered energy is the calculated quantity of energy delivered to the technical building installation (e.g., heating system, conditioning system, domestic hot water system, and lighting system) that is required for the plant to meet the energy demand. The capacity, efficiency, and insulation of the facility system are linked to the energy demand. To the energy required to meet fulfill the building demand plus the energy lost through the building facility on account of the low-quality equipment installed in the building. The final energy of heating was calculated using Equations (3) and (4). This is considered as an energy loss due to control and emission, distribution, and storage according to the facility of the building [41–43].

$$Q_{h,outg} = Q_{h,b} + Q_{h,ce} + Q_{h,d} + Q_{h,s} \tag{3}$$

$$Q_{h,f} = Q_{h,outg} + Q_{h,g} - Q_{h,reg} \tag{4}$$

where:

- $Q_{h,outg}$ is the generator heat output to the heating system in the building (kWh)
- $Q_{h,ce}$ is the control and emission loss of the heating system (kWh)
- $Q_{h,d}$ is the distribution loss of the heating system (kWh)
- $Q_{h,s}$ is the storage loss of the heating system (kWh)
- $Q_{h,f}$ is the delivered energy for the heat generator (kWh)
- $Q_{h,g}$ is the generation loss of the heating system to the installation space (kWh)
- $Q_{h,reg}$ is the quantity of regenerative energy used (kWh)

Each subfactor is derived from the diagnostic information. Then, energy demand and the primary energy of each building service (e.g., heating, cooling, lighting, and domestic hot water supply) are derived from the methods of the DIN V 18599 standard. Total energy demand and primary energy are determined separately for each building service. However, primary energy, which has the greatest impact on climate change among all three types (i.e., energy demand, final energy, and primary energy), is the fossil energy needed to meet final energy. It is calculated as the quantity of energy considering the energy required outside of the building by the preceding process chains for obtaining, converting, and distributing the respective fuels used. The total primary energy of the building is calculated using the following equation, which involves multiplying the primary energy factor by the total final energy (5) [40,44,45].

$$Q_p = \sum_j Q_{f,j} \times f_{p,j} \tag{1}$$

where:

- Q_p is the heating primary energy for building zone (kWh)
- $Q_{f,j}$ is the delivered energy for each energy service (kWh)
- f_p is the primary energy factor

In addition, diagnostic information also serves to help calibrate the model to be a representation that is similar to a real building. For example, in the energy model, the area information is applied from an architectural drawing, but the drawing area and the actual area are not the same. So, a diagnosis method such as photogrammetry, which will be described on next paragraph, is used in the calibration for the energy simulation model.

2.3. Close-Range Photogrammetry-Based 3D Models

To provide diagnosis information and gather feedback on a building, current spatial information is required because the as-built passive and active data of the target building may have been altered through years of service, or the data may not be available at all. CRP is a noncontact technology that is used to determine the 3D geometry (i.e., location, size, and shape) of an actual object by measuring and analyzing the two-dimensional (2D) ground photographs [46]. The collinearity condition is an essential equation of photogrammetry, which is based on the theory that the perspectival center, the image point, and the corresponding object point all lie on one line [47]. A 3D model is constructed by geometrically establishing the relationship between the 3D object coordinates and the object coordinates of a 2D image through the underlying perspectival system [48].

The advantages of CRP are that it can acquire 3D information of structures in a relatively short time and that it can easily construct a model for a building without requiring an as-built drawing. In addition, its accuracy is high. Many studies have thus used CRP to measure structural deformations [46,49]. Owing to its accuracy and capacity to work without restrictions, CRP is a useful tool for providing intuitive building shape information. In addition, it can also help to match the simulation model with the actual model by improving the reliability of the building's shape and area information, which is input into the building-energy simulation program.

A 3D model can be constructed using a photomodeler developed in Canada's Eos system. To construct such a model, junction lines that can be recognized by the photomodeler are required to represent the same part of the structure, because the positions of these lines in different photographs obtained at different locations are different.

2.4. Information Visualization

Information visualization refers to visualizing data using graphical elements to clearly and effectively convey the information. There are seven visualization elements: brightness, color, texture, shape, location, direction, and size [50]. Humans can easily distinguish differences in length, shape, orientation, and color without much effort. This ability is referred to as "pre-attentive processing." time and effort are required to distinguish the information differences [51]. To provide intuitive and efficient energy information, this study focused on grouping data and linking them to the model, thereby distinguishing them according to their characteristics. The visualization was conducted using color.

3. Implementation

3.1. Testbeds

The testbeds for the present study were chosen to reflect a real building-energy management scenario in the Republic of Korea. Of all buildings in Korea, 99.97% are small and medium-sized, with 91% of the total building-energy consumption nationwide completed by these buildings [52]. In addition, for buildings measuring greater than 3000 square meters, energy use regulations have been implemented through various national and local government policies. In Korea, also, energy use has been regulated for buildings larger than 3000 square meters from the government-led "building-energy efficiency rating certification system" and the region-led "energy consumption certification system". However, energy management is not usually implemented in buildings because there are no regulations for buildings with an area of less than 3000 square meters. Also, generally speaking, obsolete or low-energy-efficiency buildings require a large amount of primary energy in Europe. For instance, 35% of the buildings are older than 50 years of age, and therefore need to improve their energy efficiency through diagnoses [16]. Therefore, in this study, these classes of buildings requiring energy management were selected as testbeds. Both of these kinds of buildings do not have energy management protocols in place and their energy consumption and costs were high.

Table 4 illustrates the two testbeds used for energy diagnosis and energy information purposes. Testbed 1 is a business and factory facility located in Ansan City, Gyeonggi Province. It has a high base energy consumption, owing to the ongoing production occurring in the factory. Testbed 2 is a business and residential building in Seoul. The building-energy efficiency levels were evaluated through pre-energy diagnostics for the two testbeds. For testbed 1, the energy efficiency was re-evaluated after providing a building-energy efficiency improvement plan. For testbed 2, real-time energy consumption data were provided to help users realize energy savings.

Table 4. Testbed descriptions.

	Testbed 1		**Testbed 2**	
Building purpose	Business Facilities/Neighborhood facilities		Business facilities	
Location	Yeongmal-ro, Eunpyeong-gu, Seoul, Republic of Korea		Danwon-gu, Ansan-si, Gyeonggi-do, Seoul, Republic of Korea	
Building area	Total floor area	1889 m^2	Total floor area	2517 m^2
	Number of floors	5th floor	Number of floors	2nd floor
	View of the building	Panel board	View of the building	Panel board
				

3.2. Build Cloud-Based Database

To perform building-energy diagnosis and build a visualization solution, it is necessary to construct a database for data input to compute the energy demand and final energy. The database comprises the energy consumption amount, environmental data, building spatial information, and equipment data. The database also considers the requirement of login keys to access the energy information webpage so that only the appropriate user can view it. This is because the database is intended to provide information by visualizing it on a webpage instead of in paper format, such as the format of existing monthly bills.

Thus, the visualization solution was implemented on the web and a cloud-type database was also built for a large number of users (e.g., residents and administrators) to provide them with access to the webpage. Users for a given building were grouped and provided with an identification number unique to that building that is used as a key to access the webpage. The building information table stored each floor and zone usage data; building environment data (e.g., humidity, temperature); and external environment data. A table log was used to store collected hourly data for each floor and zone in chronological order. In addition, data were collected by day, month, and year and used as basic data for energy diagnosis (Figure 3).

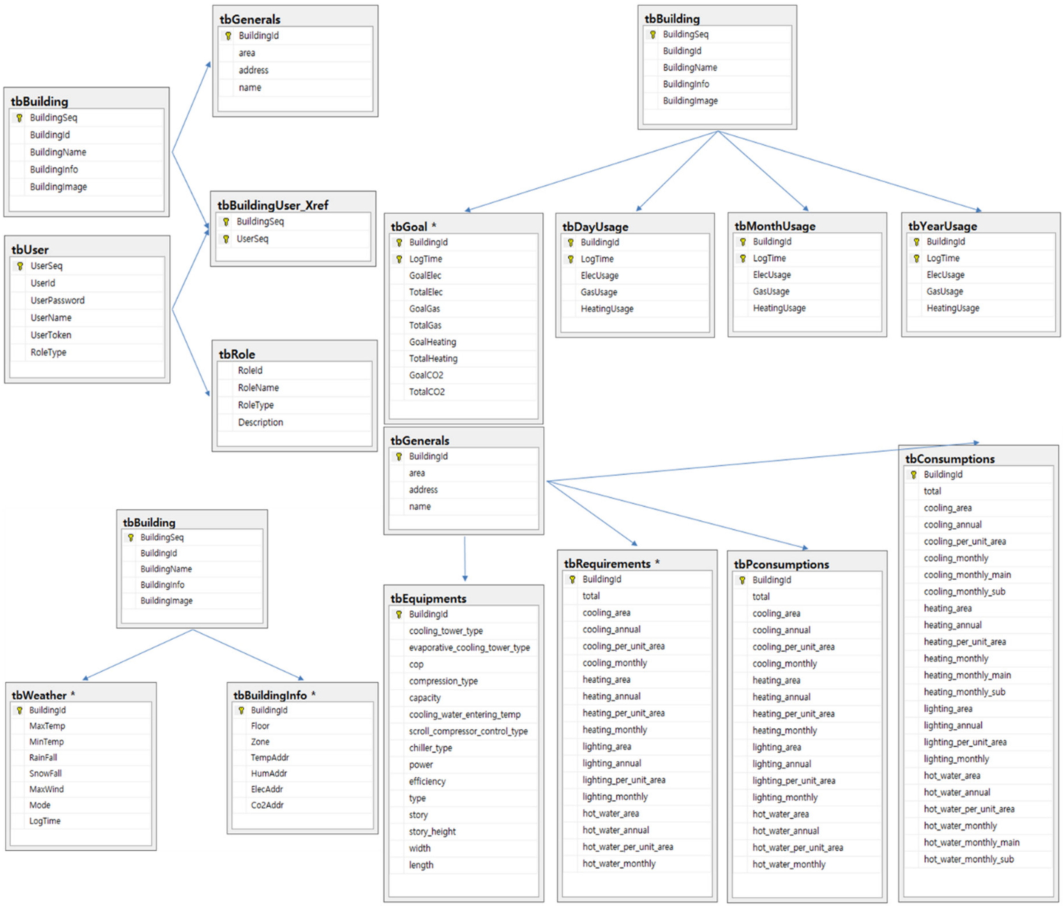


Figure 3. Composition of the database for energy visualization.

3.3. Diagnosis and Improvement of Building-Energy Performance

For testbed 2, calculation of the energy demand was performed by inputting information, such as the insulation type of the target building, operation profile, indoor heating and cooling supply method, lighting degree, walls, and window areas (Figure 4). In addition, the final energy was analyzed by using the information of the heat source device (cooling/heating), heating and cooling distribution system, heating and cooling circulation device, distribution network scale and pressure loss, and hot water system application (Figure 5).

Testbed 1 was diagnosed in the same manner, and calculations were performed to obtain the results of the diagnosis. The estimated primary energy calculated from the present state of the building, the state of the equipment, and the amount of usage information was 599 kWh/(m^2 a) and 590.1 kWh/(m^2 a) for each testbed, respectively. The energy efficiencies of nonresidential buildings were determined to be six; this implies energy efficiency improvement to be urgent, since this is a low rating.

The annual primary energy for heating of testbed 1 was the highest at 41.2% (590.1 (kWh/(m^2 a))) among heating, cooling, lighting, and hot-water supply factors. Therefore, heating improvement was necessary. The energy demand after considering the facility change was analyzed and compared with the previous one. A comparison and analysis of the energy demand for the thermal percolation of the envelope (e.g., wall, roof) were conducted. The final energy was calculated with the application of the heat flow rate according to the current energy savings design standard and was compared and analyzed. In addition, final energy changes of the facility after its redesign were analyzed and compared with the pre-redesign final energy. The amount of final energy after the redesign was calculated with consideration of the type of the equipment to be replaced and its coefficient of performance. Unlike conventional energy simulation programs, which are available to assist with management, this solution, which is constructed by use of the minimum legislation for building-energy performance evaluation, can be used by members of the public such as a landlord. Energy performance improvement scenarios can be obtained simply by modifying the architecture and facility element information in the graphic user interface (GUI).

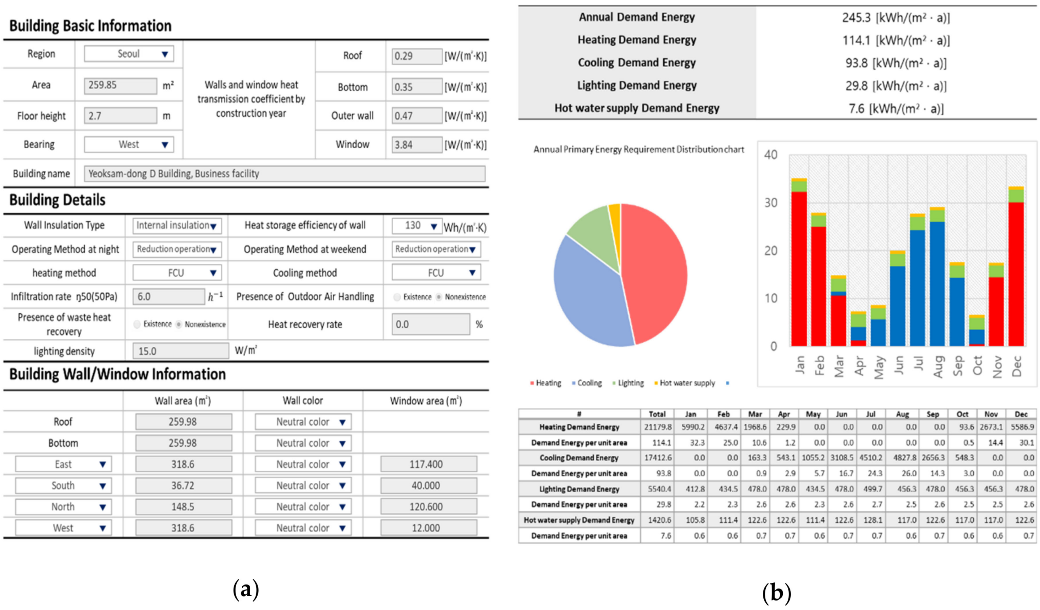


Figure 4. Building-energy performance simulator. UI: analysis of energy demand through diagnosis of the architecture part of testbed 2. (**a**) Input architecture data of testbed 2; (**b**) Energy demand.

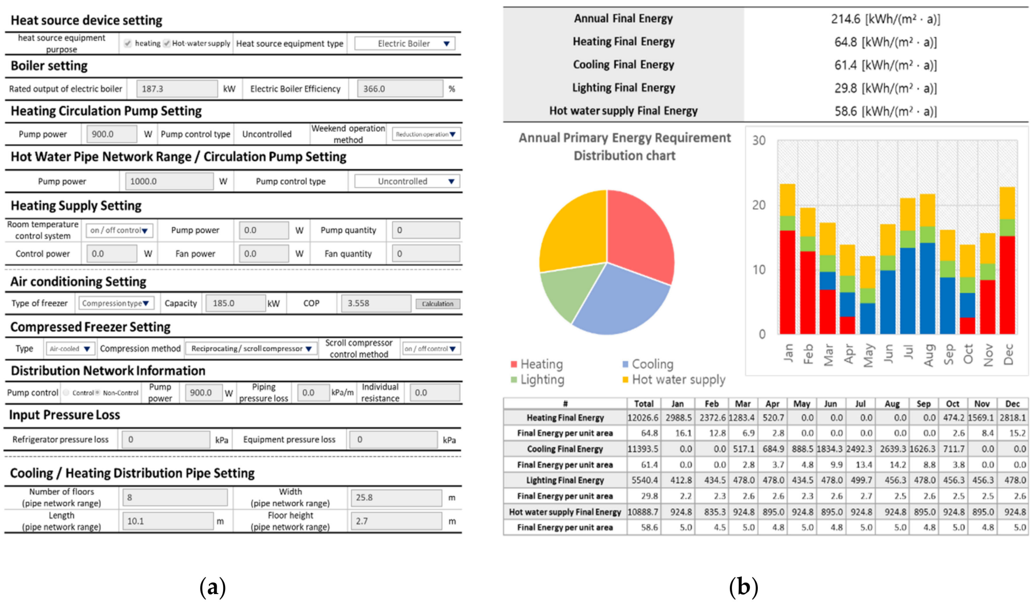
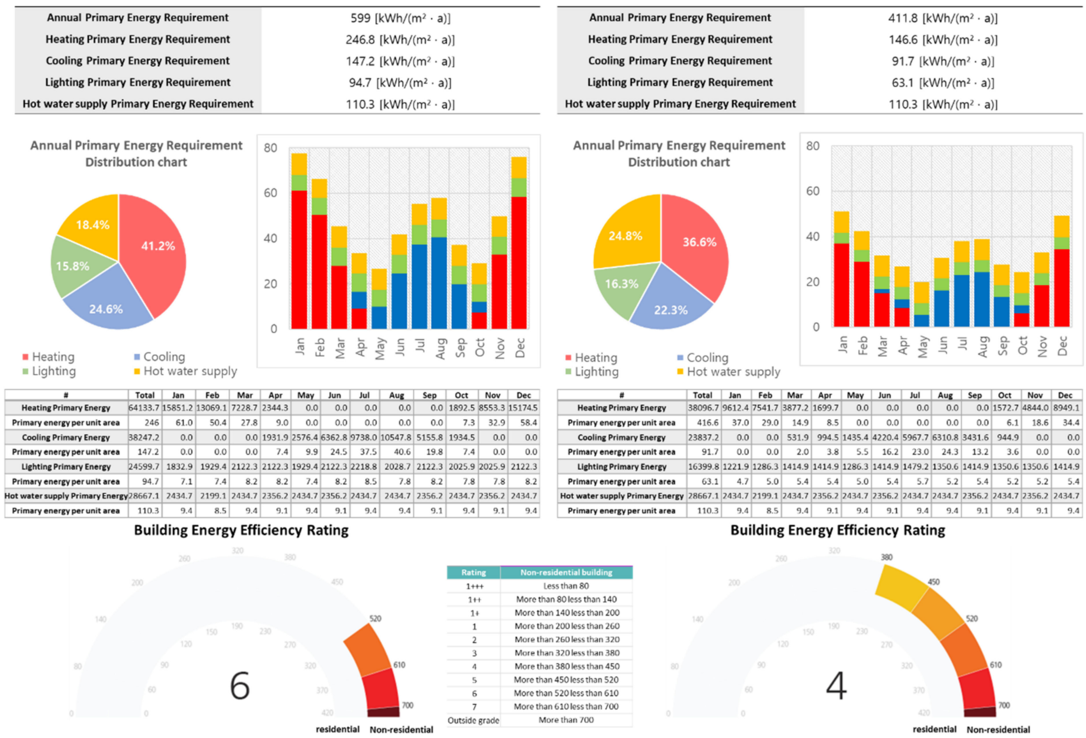


Figure 5. Building-energy performance simulator. UI: analysis of final energy through diagnosis of the facility part of testbed 2. (**a**) Input facility data of testbed 2; (**b**) Final energy.

In this diagnosis solution, as shown in Table 5, the energy performance improvement plan according to the energy diagnosis result was applied for testbed 1, and the analysis results are as follows (Figure 6): the primary energy requirement decreased from 599 kWh/(m^2 a) to

411.8 kWh/(m^2 a), resulting in a 32.3% reduction versus as seen with existing buildings. In particular, the improvement of the heating facilities, which consumes the largest portion of energy, had a higher improvement percentage as compared with the others (from 246 kWh/(m^2 a) to 146.6 kWh/(m^2 a)), demonstrating a significant reduction in the overall final energy. As a result, the building-energy efficiency rate also increased from six to four. Furthermore, the performance can be improved in various other ways by the choices of landlords or building managers. This diagnosis solution can help them to choose the improvement scenario with high cost-effectiveness by comparing the reduction rate of required energy with the cost of building facility change.



(**a**) (**b**)

Figure 6. Estimated primary energy requirement and energy efficiency rate (testbed 1). (**a**) Before improvement equipment; (**b**) After improvement equipment.

Table 5. Energy performance improvement plan for test.

Field	Element	Input Field	Changes
Building	Performance type	Shell heat conduction ratio	Applying current legal standards (1 year → 17 years)
Equipment	Lighting equipment	Light density	When LED is applied (15 W/m^2 → 10 W/m^2)
	Heat source equipment	Efficiency (COP)	Energy consumption efficiency first-grade product application
	Conveying equipment	Not applicable	Individual heating and cooling
	Heat recovery	Not applicable	Individual heating and cooling

3.4. Close-Range Photogrammetric-Based 3D Models and Energy Visualization

Canon EOS 750D DSLR (Canon Inc., Japan), a nonmetric camera with a Canon EF-S 24 mm/F 2.8 STM lens (Canon Inc., Japan), was used to conduct CRP. Close-up photographs were obtained at various angles of the testbeds. In this study, photographs of the exterior of the buildings were obtained and the contiguous sections of the exterior and interior spaces were photographed. The corners of the bottom and uppermost parts of the target buildings were hence considered as the junctions, and the lines connecting them were recognized as the building edges. Accordingly, a sufficient number of images were obtained to minimize modeling errors and eliminate modeling blind spots. In this study, a 3D model was constructed using CRP technology for testbed 2 (Figure 7).

Figure 7. Building 3D modeling on testbed 2 using close-range photogrammetry (CRP).

A building-energy 3D visualization solution GUI for testbed 2, which visualized the energy consumption and environmental information of each zone of the building, was provided through the linkage between the model and the constructed database (Figure 8). To operate the 3D model effectively in the GUI, element functions were implemented, such as model objectification and an information presentation textbox. The model operation area enabled the visualization of the model with all its imbedded data at any angle or any specific zone. It was developed using Unity 3D, which is a 3D engine, and the information area was designed as a script in the engine to deliver the data of the selected zone. This solution can easily transmit the spatial information to users by implementing the building shape information as it currently exists. Moreover, it is possible to intuitively provide the energy usage characteristics of the specific zone to the user by assigning color differentiations according to energy consumption. In addition, GUIs were developed that can provide a 360° rotation function. Then, the completed solutions were uploaded to the homepage. As mentioned previously, our goal was to enhance the intuitiveness of providing information to users via information visualization techniques.

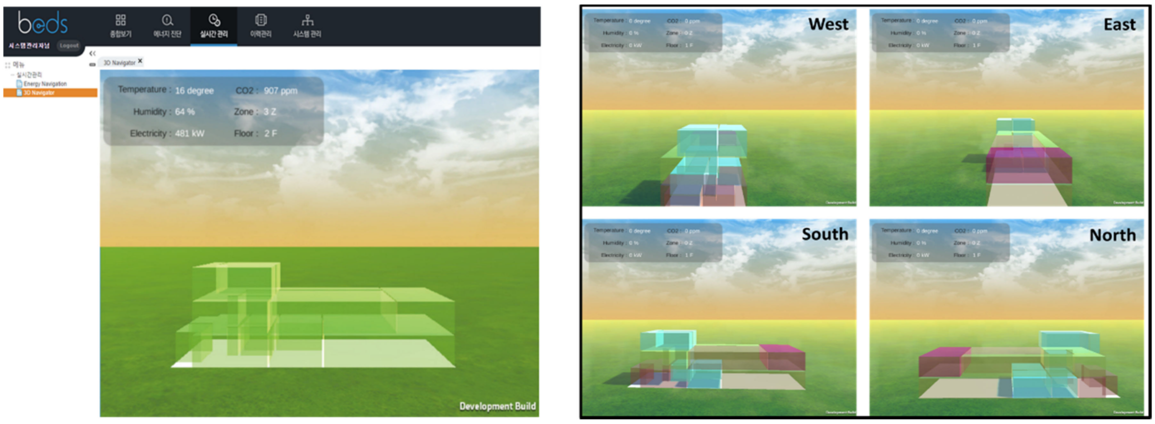
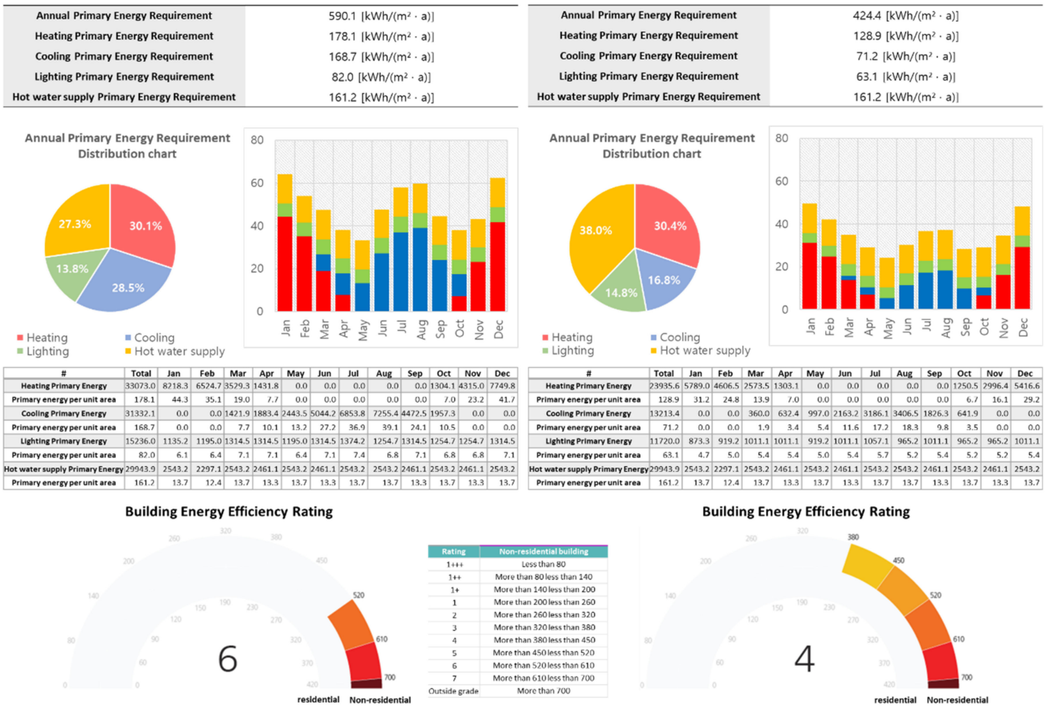


Figure 8. The developed building-energy 3D visualization solution.

To improve the efficiency of energy feedback, we provided users with information on the webpage to reduce energy consumption and encourage the building manager to upgrade the facility in accordance with our recommendations. In the case of testbed 2, a visualization solution was provided with the energy diagnostic solution and uploaded to the webpage. This solution is expected to be effective in reducing energy consumption by changing users' behavior patterns and promoting motivation in the landlord for the improvement of building facilities. Through an analysis of the energy performance of testbed 2, an energy efficiency improvement plan, which is similar to that of testbed 1, was derived and the plan was applied. The primary energy requirement measured in the preliminary building energy diagnosis was 590.1 kWh/(m^2 a). However, based on the building energy that was re-diagnosed after the applied efficiency improvement plan was developed, the primary energy requirement became 424.4 kWh/(m^2 a) (Figure 9).



(a) (b)

Figure 9. Estimated primary energy requirement and energy efficiency rate before and after providing the energy visualization solution (testbed 2). (**a**) Before application of visualization solution; (**b**) Before application of visualization solution.

3.5. Discussion

An energy diagnostic solution was developed according to each methodology and testbeds, which are typical buildings in the blind spot of energy management due to lack of regulation, were evaluated. A minimum set of regulations were applied regarding energy simulation to enable not only for them to be used by experts but also by landlords and other individuals of the general public who can directly affect the improvement of buildings. Various scenarios for building improvement can be presented and the energy savings rate per scenario can be grasped in a manner that is directly related to the cost reduction rate. The results of the various scenarios can be judged to help support the motivation of building owners to improve the building and decision-making processes.

In addition, a 3D energy visualization solution was developed to provide intuitive and clear feedback. This was accomplished by providing energy information in a 3D visualization method instead of in existing textual and graph-oriented formats. The CRP method was used to construct 3D models and to link energy and environment information stored in real-time in the database with the corresponding 3D model according to the given floor and zone. To enhance comprehension of the information inside the given building, rotation function and elements that visualize the energy overuse points using color changes were implemented and the GUI was uploaded on the webpage for the purpose of energy feedback. It was considered that the visualization-based energy feedback led to possible changes in user behaviors and increased the energy-efficiency rating as compared with giving feedback via the current format of monthly bills.

While the CRP method was used for building modeling, it was also used for building-energy diagnostic accuracy. Existing building-energy diagnosis systems have many uncertainties regarding input data for use in simulation tools. In the case of building area, there are no architectural drawings, or the area data of architectural drawings (blueprints) did not match with the real area. Accurate area information is required to estimate energy demand, while reliable area data are required to calculate the exact energy demand; as such, diagnosis using the CRP method can obtain accurate modeling and area data as an alternative to reduce the uncertainty associated with energy simulations.

The Hohm (Microsoft Corp., Redmond, WA, USA) and PowerMeter (Google, Mountain View, CA, USA) services, which monitor real-time energy performance and provide graphical energy data to residents, have been previously employed. Their use was expected to lead to reduced energy consumption by providing specific information such as monthly electricity usage and electricity consumption rates for household appliances [53,54]. However, both services were recently terminated by their respective manufacturers. This suggests that it is not feasible to realize a high-energy saving effect by providing only information to residents. The solution in this study provides users with a visualization of the energy consumption information of the zone in the 3D model. The user can acquire energy information after the improvement of the building by inputting simple variables. So, from the standpoint of energy feedback, this is considered as a way to realize energy savings by drawing more attention to the user.

4. Conclusions

In this study, energy-saving measures were sought for buildings having a notable contributing role in climate change. Developed nations worldwide are reducing the proportion of fossil fuel use and increasing the proportion of renewable energy; however, older buildings remain less energy-efficient. In addition, there are many buildings that require energy efficiency improvements on account of insufficient energy management regulations. Presenting energy efficiency improvement scenarios of buildings using energy simulations is meaningful in the concept of energy feedback because it suggests directions for improvement for these inefficient buildings. Furthermore, it is predicted that data stored in a database in real time can provide diagnostic information so as to allow for a flexible response to changes in energy efficiency that occur due to ongoing climate changes and the deterioration of buildings.

To cope with climate change and energy problems, this paper presented a developed energy visualization solution for buildings with high-energy consumption rates. Two detailed key elements were applied in this study to the energy visualization solution: (1) the provision of diagnosis information and related recommendations for building efficiency improvements using energy simulations and (2) the realization of energy feedback based on those visualizations. The solution was developed for the purpose of saving energy by bring energy performance evaluations to the familiar field from the expert field. The main conclusions drawn from this paper regarding the energy diagnosis solution are summarized as follows:

- The developed solution provides diagnosis information from a proposed energy simulation. In the solution, energy prediction information can be calculated and presented on a webpage via input numerical data according to actual or virtual change of architectural and facility information. When replacing with high-efficiency equipment, it is possible to provide reliable energy-saving information instead of ambiguous information through the simple input of the equipment information from all users.
- The energy diagnosis was performed on two testbeds and the results were analyzed. Based on the analyzed results, building energy improvement plans were applied and the energy saving rates were measured at about 30% and 28%, respectively.

- Although the solution does not automatically derive the optimum improvement direction of the building energy, it can show the energy-saving amount according to variable building improvement scenarios depending on the users. In the sense of the energy feedback, intuitive information supporting methods enhances user motivation to more effectively manage energy consumption.
- To increase the effect of this energy feedback, we developed a 3D visualization solution that can be also applied to buildings without architectural drawing information. Considering visualization is effective in energy feedback, intuitive and real-time measured information would likely have a positive impact on energy savings.

The proposed solution, which included the concept that quantitative energy consumption-predicting information gathered through energy model was similar with the actual building energy due to calibrating though the building energy diagnosis and tools for intuitiveness, was applied in real buildings to conduct energy feedback.

However, users do not know what information they should focus on and the factors that contribute to energy savings. Identifying high-interest energy information for the user can increase the energy management efficiency. Therefore, future research should conduct an assessment on residents and energy management experts to analyze usage patterns based on the user experience research method and thereby elucidate the user degree of interest and level of concentration regarding the given information.

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