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Development of a dynamic operational rating system in energy performance certificates for existing buildings: Geostatistical approach and data-mining technique

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HIGHLIGHTS

- Problem analysis of the conventional EPCs was conducted in terms of three issues.
- Three issues consist of the building category, region category and space unit size.
- Dynamic operational rating (DOR) system in EPCs for existing building was developed.
- The DOR can be used as a tool for building energy performance diagnostics.
- The DOR can allow policymakers to establish a reasonable operational rating in EPCs.

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ABSTRACT

The operational rating system in building energy performance certificates (EPCs) has been used for systematically monitoring and diagnosing the energy performance in the operation and maintenance phases of existing buildings. However, there are several limitations of the conventional operational rating system, which can be subdivided into three aspects: (i) building category; (ii) region category; and (iii) space unit size. To overcome these challenges, this study conducted the problem analysis of the conventional operational rating system for existing buildings by using the statistical and geostatistical approaches. Based on the problem analysis, this study developed the dynamic operational rating (DOR) system for existing buildings by using the data-mining technique and the probability approach. The developed DOR system can be used as a tool for building energy performance diagnostics. To validate the applicability of the developed DOR system, educational facilities were selected as the representative type of existing buildings in South Korea. As a result, it was determined that the developed DOR system can solve the irrationality of the conventional operational rating system (i.e., the negative correlation between the space unit size and the CO_2 emission density). Namely, the operational ratings of small buildings were adjusted upward while those of large buildings were adjusted downward. The developed DOR system can allow policymakers to establish the reasonable operational rating system for existing buildings, which can motivate the public to actively participate in energy-saving campaigns.

1. Introduction

As global greenhouse gas emissions due to the use of fossil fuel have increased, the consequent climate change is threatening the human race [1,2]. It is reported that in developed regions like the United States (USA) and the European Union (EU), about 40% of greenhouse gas emissions come from the building sector. In South Korea, the building sector accounts for about 24.5% of greenhouse gas emission. Thus, the energy consumption from the building sector is a key factor in global greenhouse gas emissions [3–7].

In order to reduce the greenhouse gas emissions from the building sector, various efforts have been conducted, including political actions (e.g., regulatory and supportive policies) and technical measures (e.g., passive design, active design, and new and renewable energy techniques) [8–11]. For these efforts to be effective, it is necessary to clearly evaluate the actual greenhouse gas emissions from the building sector. That is to say, it is required to establish the reasonable assessment process for evaluating the building

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energy performance, referred to as *building energy performance diagnostics* in this study [12,13].

The EU established the *Energy Performance of Buildings Directive* (EPBD) in 2002 to improve the building energy performance and to reduce the greenhouse gas emissions from the building sector. The EPBD initiated the energy performance certificates (EPCs) for new and existing buildings; accordingly, the building's EPCs should be provided to the building purchasers and renters [14–17]. With this policy in place, all the public can not only recognize the importance of improving the building energy performance, but also how the improvement of the building energy performance can contribute to the climate change problem. Based on the EPBD policy, one of the most representative green-building policies, EU countries including the UK, Germany, and France have established their own building EPCs [18–21]. The building EPCs can be largely subdivided into two types: (i) asset rating that is the energy-demand-based estimation method (or calculation method) (i.e., grading mainly for new buildings), which is mainly affected from the physical properties of a building, such as the building envelope, window-to-wall ratio, thermal insulation, and heating system efficiency; and (ii) operational rating that is the energy-consumption-based measurement method (i.e., grading mainly for existing buildings), which is mainly affected from the occupant behaviors in the operation and maintenance phase of a building [12,13,22].

Several previous studies have reported the difference between the asset rating and the operational rating [22–26]. Kelly et al. [22] analyzed the difference between the asset rating (which was established using the SAP and RdSAP) and the operational rating (which was established using the actual energy consumption). In the UK, the asset rating was established for new or existing buildings using the government's standard assessment procedure (SAP) or the government's reduced-data SAP (RdSAP), and the operational rating was established for existing buildings using the actual energy consumptions. Majcen et al. [23] compared the theoretical energy performance of Dutch dwellings and their actual energy performance. Branco et al. [24] analyzed the difference between the theoretical energy performance of multifamily complex in Switzerland and their actual energy performance, focusing on the complete technical system which combined the optimized envelope and electrical equipment with the several renewable energy systems. Hass and Biermayr [25] investigated the rebound effect of the energy consumption for residential space heating in Austria, resulting in the rebound effect between 20% and 30%.

Meanwhile, the other studies analyzed the effect of building EPCs on the rental and capital values [27–29]. Amecke [27] analyzed the effect of building EPCs on purchasers of owner-occupied dwellings in German, resulting that the effectiveness of EPCs was limited. Fuerst and McAllister [28] analyzed the impact of building EPCs on the rental and capital values of UK commercial property assets, resulting that there is no evidence of a significant relationship between the building energy performance and the rental and capital values.

As mentioned above, most of the previous studies have mainly focused on the analysis of the difference between the estimated energy performance (i.e., asset rating) and the actual energy performance (i.e., operational rating) and some studies analyzed the effect of building EPCs on the rental and capital values. Although most of the previous studies have emphasized the importance of the operational rating in the building EPCs as a tool for building energy performance diagnostics, they have not sufficiently considered the limitations of the conventional operational rating system and have not clearly suggest the way to improve the conventional operational rating system. Therefore, this study was designed to fill the knowledge gap. That is to say, this study aimed to highlight what the potential problems of the conventional operational rating system would be, why the potential problems may arise, and how the potential problems can be solved. Towards this end, this study was conducted as follows.

- This study analyzed the potential problems of the conventional operational rating system for existing buildings by using the statistical and geostatistical approaches, which was conducted as a preliminary investigation. The potential problems can be subdivided into three aspects: (i) building category; (ii) region category; and (iii) space unit size.
- Based on the problem analysis, this study developed the dynamic operational rating (DOR) system for existing buildings by using the data-mining technique and the probability approach, which was designed as a solution to the possible problems. The developed DOR system can be used as a tool for building energy performance diagnostics. In general, *dynamic* means energetic or capable of change, while *static* means stationary or fixed.

2. Materials and methods

As a part of such green-building policies, South Korea enacted the building EPCs under the *Act on the Promotion of Green Buildings* in February 2013 [30]. Building EPCs in South Korea were established based on the display energy certificate (DEC) in the UK [31]. However, EPCs in South Korea should be differentiated from the UK's DEC, because they differ from the UK's DEC in terms of several aspects such as the building types, building sizes, building's energy usage patterns, and regional distribution [32,33]. Based on this background, the following criteria were considered in establishing the scope of this study.

- *Public buildings:* This study aimed to analyze the potential problems that may arise in implementing the UK's DEC to existing buildings in South Korea. Accordingly, this study should select the same type of building to which the UK's DEC is applied. Since the UK's DEC is used for public buildings [31], this study focused on public buildings in South Korea.
- *Building category:* When the UK's DEC establishes the operational ratings for existing buildings, they use the subcategories of the building category [31]. Thus, this study selected the educational facilities among the various public buildings because the educational facilities can be categorized further into various subtypes.
- *Region category:* In order to consider the difference in regional weather [31], the UK's DEC adjusts the category benchmark using the heating degree days over a 12-month period. This study focused on the educational facilities located in all the regions of South Korea to consider the region category.

To achieve the research objective, this study was conducted in three steps (refer to Fig. 1): (i) step 1: data collection and analysis; (ii) step 2: problem analysis of the conventional operational rating system for existing buildings by using the statistical and geostatistical approaches; and (iii) step 3: development of the DOR system for existing buildings by using the data-mining technique and the probability approach.

2.1. Step 1: Data collection and analysis

In order to conduct the problem analysis of the conventional operational rating system for existing buildings and to develop the DOR system for existing buildings as a tool for building energy performance diagnostics, data collection and analysis were conducted in three steps: (i) variable definition and data collection; (ii) data unification; and (iii) data filtering.

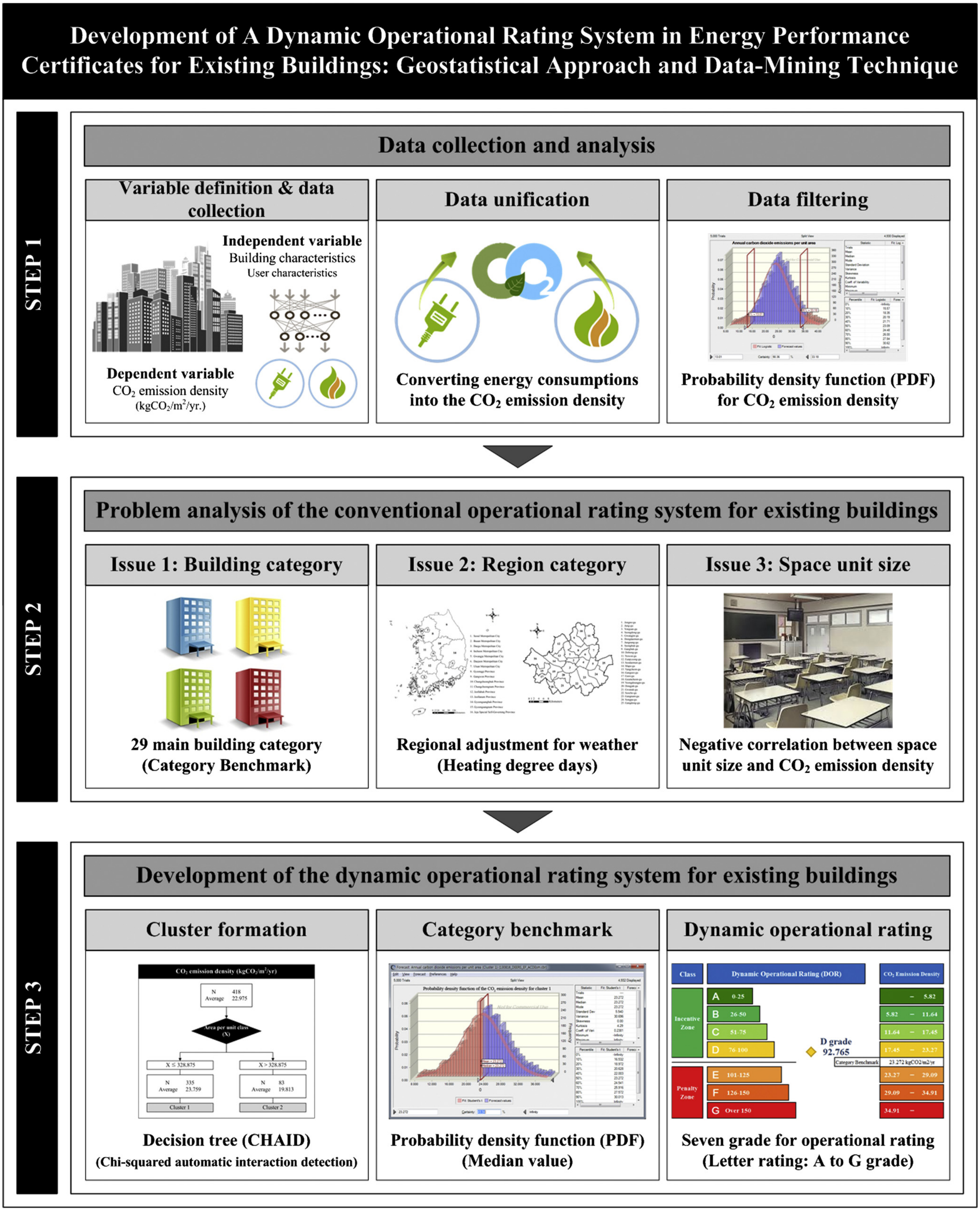

Fig. 1. Research framework.

2.1.1. Variable definition and data collection

The educational facility was selected as the representative type of public buildings in South Korea. Two kinds of energy sources are mainly used in educational facilities: (i) electricity that is used for lighting, the electric heat pump system, and electrical appliances; and (ii) gas energy that is used for the gas heat pump system and water heating [34–37]. Generally, the CO_2 emission density is used as a category benchmark in the building EPCs, which can be calculated from the aforementioned energy sources [31]. Thus, CO_2 emission density was defined as the dependent variable, and the associated project characteristics were established as the independent variables. The independent variables can be categorized into three types: location (e.g., administrative division), building (e.g., structure type, elapsed years, and total floor area), and user (e.g., persons per unit area and classes per unit area) [10,37]. Among these variables, the absolute variables (e.g., total floor area, the number of persons, and the number of classes) were used to calculate the relative values (e.g., the number of persons per unit area, the area per unit class, and the CO_2 emission density). These relative variables were used to conduct the problem analysis of the conventional operational rating system for existing buildings and to develop the DOR system for existing buildings. Table 1 shows the descriptive information on the independent and dependent variables. For example, the administrative division was defined under the nominal scale, the total floor area (m^2) was defined under the ratio scale, and CO_2 emission density ($kgCO_2/m^2/yr$) was defined under the ratio scale. Finally, based on the aforementioned criteria (i.e., public buildings, building category, and region category), this study collected the facility characteristics and energy consumption data from a total of 6137 elementary schools, 2968 middle schools, and 1528 high schools located in the 16 administrative divisions in South Korea.

2.1.2. Data unification

The two energy sources (i.e., electricity and gas energy consumption) should be converted into a common unit (i.e., primary energy consumption or CO_2 emissions) to calculate the operational rating in the building EPCs. In this study, the CO_2 emission density was established as the dependent variable (refer to Table 1). Based on the emissions factor database provided by Intergovernmental Panel on Climate Change (IPCC), the total CO_2 emissions from the two energy sources were calculated using Eq. (1), while the CO_2 emissions by energy source were calculated using Eqs. (2) and (3) [38–41].

$$CT(tCO_2) = CE(tCO_2) + CG(tCO_2) \tag{1}$$

$$\begin{aligned} CE(tCO_2) = {} & (\text{The yearly amount of electricity consumption}(\text{kW h})) \\ & \times \left(\text{Carbon dioxide emission factor for electricity}\left(\frac{tCO_2}{\text{MW h}}\right)\right. \\ & \left.\times \left(\frac{1}{10}\right)^3\right) \end{aligned} \tag{2}$$

$$\begin{aligned} CG(tCO_2) = {} & (\text{The yearly amount of gas energy consumption}(m^3)) \\ & \times \left(\text{Sensible caloric value for gas energy}\left(\frac{\text{kcal}}{m^3}\right)\right. \\ & \left.\times \left(\frac{1}{10}\right)^7\right) \\ & \times \left(\text{Carbon emission factor for gas energy}\left(\frac{tC}{\text{TOE}}\right)\right) \\ & \times (\text{The ratio of the molecular weight of } CO_2 \text{ to carbon} \\ & \left.\times \left(\frac{tCO_2}{tC}\right)\right) \end{aligned} \tag{3}$$

where CT stands for the CO_2 emissions for the total energy consumption; CE stands for the CO_2 emissions for electricity; CG stands for the CO_2 emissions for gas energy; the CO_2 emission factor for electricity is 0.4705 tCO_2/MW h; the sensible caloric value for gas energy is 9420 kcal/m^3; the CO_2 emission factor for gas energy is 0.637 tC/TOE; and the ratio of the molecular weight of CO_2 to carbon is 44 tCO_2/12 tC.

2.1.3. Data filtering

To ensure the applicability of the analysis and the associated results in this study, data filtering was conducted as follows.

- If there was a missing value in the collected data, the data was excluded from the database. Based on this standard, this study established the database for 6137 elementary schools, 2968 middle schools, and 1528 high schools (refer to Supplementary Data, SD Table S1).
- The outliers were excluded from the database. This study established the probability density function (PDF) of the CO_2 emission density for educational facilities included in both the same building category and the same region category. The PDF was determined using the *distribution fitting* function of the Crystal Ball software program. If the CO_2 emission density of a given educational facility was included in the top or bottom 5% (5% significance level), the educational facility was considered an outlier, and thus it can be excluded from the database. For example, SD Fig. S1 shows the PDF of the CO_2 emission density for elementary school facilities in Seoul. The top and bottom 5% of the CO_2 emission density were determined at 13.01 $kgCO_2/m^2$/yr. and 33.18 $kgCO_2/m^2$/yr., respectively. Based on this process, this study finally established the database for a total of 5418 elementary schools located in 16 administrative divisions in South Korea.

Table 1
Descriptive information on the independent variables and dependent variable.

Variables	Attributes		Detailed classification	Scale
Independent variable	Location	Administrative division	16 administrative division in South Korea	Nominal
	Building	Founder type	Public school, Private school	Nominal
		Structure type	Reinforced concrete, Steel, Steel reinforced concrete	Nominal
		Safety rating	Grade A, B, C, D	Nominal
		Elapsed years	() years	Ratio
		Building area	() m^2	Ratio
		Number of stories	() stories	Ratio
		Total floor area	() m^2	Ratio
	User	Number of persons	() persons	Ratio
		Number of classes	() classes	Ratio
		Persons per unit area	() persons/m^2	Ratio
		Classes per unit area	() classes/m^2	Ratio
		Area per unit class	() m^2/class	Ratio
		Persons per unit class	() persons/class	Ratio
Dependent variable	GWP[a]	CO_2 emission density	() $kgCO_2/m^2$/yr.	Ratio

[a] GWP stands for the global warming potential.

2.2. Step 2: Problem analysis of the conventional operational rating system for existing buildings

Based on the detailed analysis of the operational guideline of the UK's DEC, this study analyzed the potential problems that may arise in implementing the UK's DEC to existing buildings in South Korea. In addition, this study suggested the possible solutions to the potential problems. Towards this end, this study used the statistical and geostatistical approaches.

The UK's DEC is used for reasonably evaluating the energy performance of existing public buildings and the consequent greenhouse gas emissions. Below are the detailed characteristics of the UK's DEC [31,42–46].

- The UK's DEC establishes 29 building categories and presents their general category description with the category benchmark by building category.
- The category benchmark is the typical CO_2 emission density ($kgCO_2/m^2/yr$), which is established using the energy consumption by energy source of buildings included in the same building category.
- Various preconditions are determined to establish the category benchmark, including the monthly heating degree days, the yearly occupancy period, and the proportion of the non-electric energy. Accordingly, if the characteristics of a given building differ from such preconditions, the adjustment methods should be used for appropriately modify the category benchmark.
- The UK's DEC converts the actual energy consumption of existing buildings for a 12-month period into greenhouse gas emissions. Next, greenhouse gas emissions from a given building are converted into a standardized value using the category benchmark. It is referred to as the operational rating of the given building, and then a letter rating (seven grades, from A to G) is assigned to the given building according to the operational rating (refer to Fig. 2).

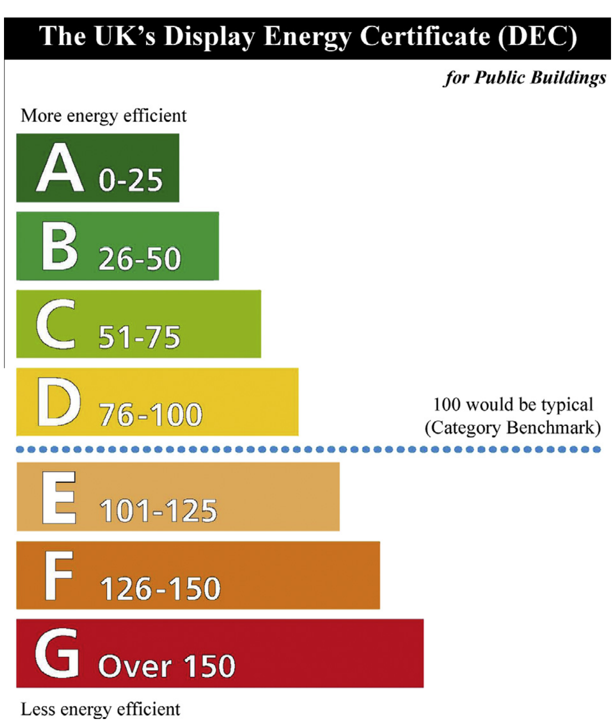

Fig. 2. Operational rating of UK's display energy certificate.

Based on the aforementioned analysis, it is found that the category benchmark is the most important factor in establishing the operational ratings of existing buildings. In the UK's DEC, however, the category benchmark would be established for the limited building categories under the predetermined conditions. Furthermore, the UK's DEC adjusts the category benchmark using the heating degree days over a 12-month period. In this adjustment, the regional weather would be merely considered to modify the category benchmark. Meanwhile, Koo et al. [13] recommended that the space unit size be considered for establishing the reasonable operational ratings of existing buildings. The reasons for this recommendation are outlined below.

- In an educational facility, the similar electrical appliances for teaching per unit class are installed regardless of the space unit size of the educational facility (i.e., area per unit class). Thus, the space unit size of the educational facility (i.e., area per unit class) is not directly proportional to the electricity consumption of the educational facility, which is affected by the electrical appliances for teaching per unit class.
- The space unit size of an educational facility (i.e., area per unit class) is closely related to the number of persons in a class or the number of persons per unit area. The closer an educational facility is located to the downtown area, the smaller the space unit size of the educational facility is. Thus, the space unit size of the educational facility (i.e., area per unit class) is not directly proportional to the heating and cooling energy consumption of the educational facility (i.e., electricity consumption in an electric heat pump system and gas energy consumption in a gas heat pump system), which is affected by the number of persons in a class or the number of persons per unit area.

In short, this study defined the potential problems that may arise in implementing the UK's DEC to existing buildings in South Korea, which can be subdivided into three issues: (i) building category; (ii) region category; and (iii) space unit size.

2.3. Step 3: Development of the dynamic operational rating system for existing buildings

To overcome the potential problems defined in the Section 2.2, this study developed the DOR system for existing buildings as a tool for building energy performance diagnostics. The DOR system was developed in three processes: (i) cluster formation by using the decision tree (DT) method; (ii) establishment of the category benchmark by using the PDF; and (iii) calculation of the DOR by using the category benchmark. Towards this end, this study used the data-mining technique and the probability approach.

2.3.1. Cluster formation by using the decision tree method

According to the study of Koo et al. [13], there is a negative correlation between the space unit size and the CO_2 emission density, which cause the irrational operational rating in the building EPCs. To overcome this problem, the cluster formation was conducted using the DT as one of the data-mining techniques, which was based on the space unit size (i.e., area per unit class). Since the CO_2 emission density as a dependent variable is in continuous scale, CHAID (chi-squared automatic interaction detection) was used among the various DT methods [47].

As shown in Table 2 and SD Fig. S2, two clusters were established based on the space unit size of an educational facility (i.e., area per unit class), using the IBM SPSS Statistics 21.0 software program [48]. As the data accumulate, more clusters will be formed, which can allow multilateral analyses.

Table 2
Definition of the splitting criteria for the CO_2 emission density.

Cluster	Number of cases	CO_2 emission density ($kgCO_2/m^2/yr.$)	Area per unit class ($m^2/class$) (X)
1	335	23.759	$X \leqslant 328.875$
2	83	19.813	$X > 328.875$

2.3.2. Establishment of the category benchmark by using the probability density function

This study estimated the PDF of the CO_2 emission density for each of the two clusters. Fig. 3 shows the PDF of the CO_2 emission density for cluster 1, which was used to establish the category benchmark as the dynamic standard. Because the median value is usually adopted to minimize the effects of the outliers in the database, this study established the median value of the PDF (i.e., 23.272) as the category benchmark (i.e., typical CO_2 emission density) for the elementary school facilities included in cluster 1. SD Fig. S3 shows the PDF of the CO_2 emission density for cluster 2. The category benchmark for cluster 2 was determined to be the median value (i.e., 19.878) of the PDF.

2.3.3. Calculation of the dynamic operational rating by using the category benchmark

Using Eq. (4), the DOR of a given building can be calculated. For example, if the energy performance of a given building is the same as the category benchmark, the operational rating would be set to 100. If a given building is defined as a zero-energy building, the operational rating would be set to 0. If the CO_2 emission density of a given building is twice as much as the category benchmark, the operational rating would be set to 200. According to the UK's DEC and South Korea's EPCs, the letter rating can be determined as one of the seven grades shown in Fig. 2.

$$f_{DOR(GB)}(x) = \frac{f_{ACDE(GB)}(x)}{f_{TFA(GB)}(x)} \times \frac{1}{\textit{Category Benchmark}} \times 100 \qquad (4)$$

where $f_{DOR(GB)}(x)$ stands for the function for calculating the dynamic operational rating (DOR) of a given building in year x; $f_{ACDE(GB)}(x)$ stands for the function of the annual CO_2 emissions of a given building in year x; $f_{TFA(GB)}(x)$ stands for the function of the total floor area of a given building in year x; and *Category Benchmark* stands for the median value of the PDF for the cluster in which a given building is included.

In this study, the cluster formation was conducted to consider the negative correlation between the space unit size of an educational facility (i.e., area per unit class) and the CO_2 emission density. It was determined that the category benchmarks of clusters 1 and 2 were 23.272 and 19.878, respectively. Fig. 4 shows an example of the DOR for a case of cluster 1, which presents the DOR (92.765), the letter rating (D grade), and the category benchmark (23.272 $kgCO_2/m^2/yr.$). This chart can allow all the public to be aware of the energy performance of a given building.

3. Results and discussion

In order to highlight both the limitation of the conventional operational rating system and the improvement of the developed DOR system, this study conducted (i) the problem analysis of the conventional operational rating system for existing buildings in terms of three issues (i.e., building category, region category, and space unit size) and (ii) the comparative analysis between the developed DOR system and the conventional operational rating system.

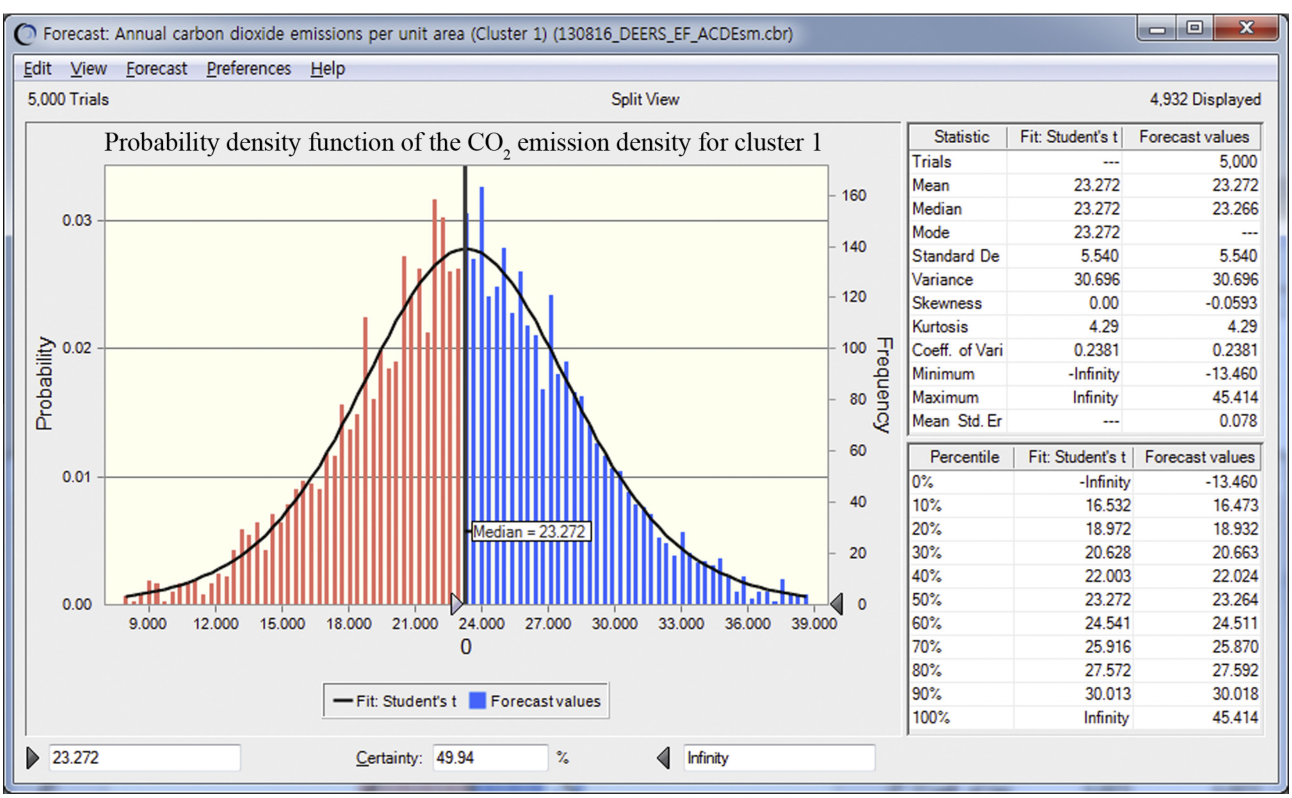

Fig. 3. Probability density function of the CO_2 emission density for cluster 1.

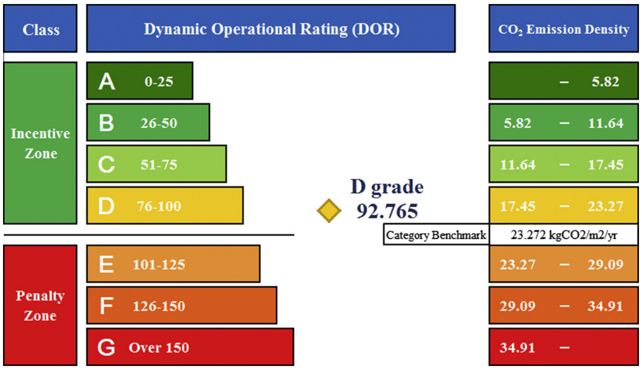

Fig. 4. Example of the dynamic operational rating for a case of cluster 1.

3.1. Problem analysis of the conventional operational rating system for existing buildings

3.1.1. Issue 1: Building category

The UK's DEC establishes 29 main building categories and proposes the category benchmark for each of building category (i.e., typical CO_2 emission density, $kgCO_2/m^2/yr.$). The category benchmark is used as the standard index for assessing the energy performance of existing buildings, and then, one of the letter ratings from A to G can be determined [31,42–46]. The problems outlined below may occur in implementing the UK's DEC to existing buildings in South Korea. Solutions for such problems are also suggested herein.

3.1.1.1. Problem analysis on the building category. The building category is generally established based on the building's physical properties. Thus, it is recommended that the energy performance of the educational facility be differentiated from that of a hospital or residential facility. Also, it is believed that the energy performance included in the same building category exists within a certain scope. This is the characteristic of the asset rating as discussed in Section 1. However, although two buildings are included in the same building category, the energy performance of one building may differ from the energy performance of the other building due to the usage pattern's characteristics such as the occupants' behavior.

South Korea has categorized educational facilities into three types: elementary, middle, and high school facilities. Table 3 shows the results of the analysis of variance (ANOVA) for the CO_2 emission density by educational facility in South Korea. One-way ANOVA was used to determine the differences among at least three groups as the two-group case can be covered by a *t*-test. When the probability (*p*-value) is less than the significance level (α), it indicates a statistically significant difference among the groups [48]. Accordingly, as the significance level (α) was set at 0.05, the mean differences among the groups (i.e., elementary, middle, and high school facility) can be said to be valid. Also, Fig. 5 shows the distribution of the CO_2 emission density by educational facility in South Korea. It was determined that building subcategories should be established through the statistical approach. Otherwise, the applicability issues of the building EPCs may be raised in terms of the building category.

Table 3
ANOVA for the CO_2 emission density by educational facility in South Korea.

Classification	Sum of squares	df	Mean square	F	Sig.
Between groups	127,238.025	2	63,619.013	180.051	0.000
Within groups	3,756,000.878	10,630	353.340	–	–
Total	3,883,238.903	10,632	–	–	–

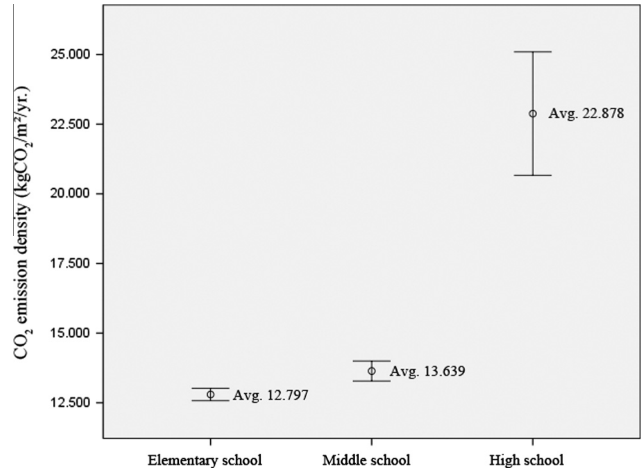

Fig. 5. Distribution of the CO_2 emission density by educational facility in South Korea.

3.1.1.2. Solutions for the building category. To calculate the reasonable operational ratings of existing buildings, it is necessary to establish a subcategory system in the building category using the statistical approach. The subcategories of educational facilities should be established by considering the different CO_2 emission density by educational facility (i.e., elementary, middle, and high school facilities). The category benchmark for the subcategories of educational facilities should also be established. As a result, the potential problems in terms of the building category (which may arise in implementing the UK's DEC to existing buildings in South Korea) can be resolved, and then, the reasonable operational ratings of existing buildings can be established.

In the analysis of the other issues (i.e., issue 2 for region category and issue 3 for space unit size), the analysis target was limited to the elementary school facility to remove the potential problems in advance.

3.1.2. Issue 2: Region category

In order to consider the difference in temperature that may arise from the regional distribution of buildings, the UK's DEC uses the heating degree days over a 12-month period and adjusts the category benchmark of the 29 main building categories. It considers only the regional weather in adjusting the category benchmark [31,42–46]. Such an approach, however, can cause problems in implementing the UK's DEC to existing buildings in South Korea. Solutions for such problems are also suggested herein.

3.1.2.1. Problem analysis on the region category. Compared to the surrounding regions, metropolitan cities generally have a dense population, which leads to an increase in the number of residents per unit area in buildings. This ultimately brings about an increase in the energy consumption per unit area. Therefore, even with the buildings included in the same region category, their energy performances may differ due to the social and economic characteristics of the corresponding area. Accordingly, if the regional weather is only considered in the category benchmark adjustment process, it may cause the differences between the category benchmark of a given building category and the actual energy performance. Ultimately, the reasonable operational ratings of existing building cannot be established.

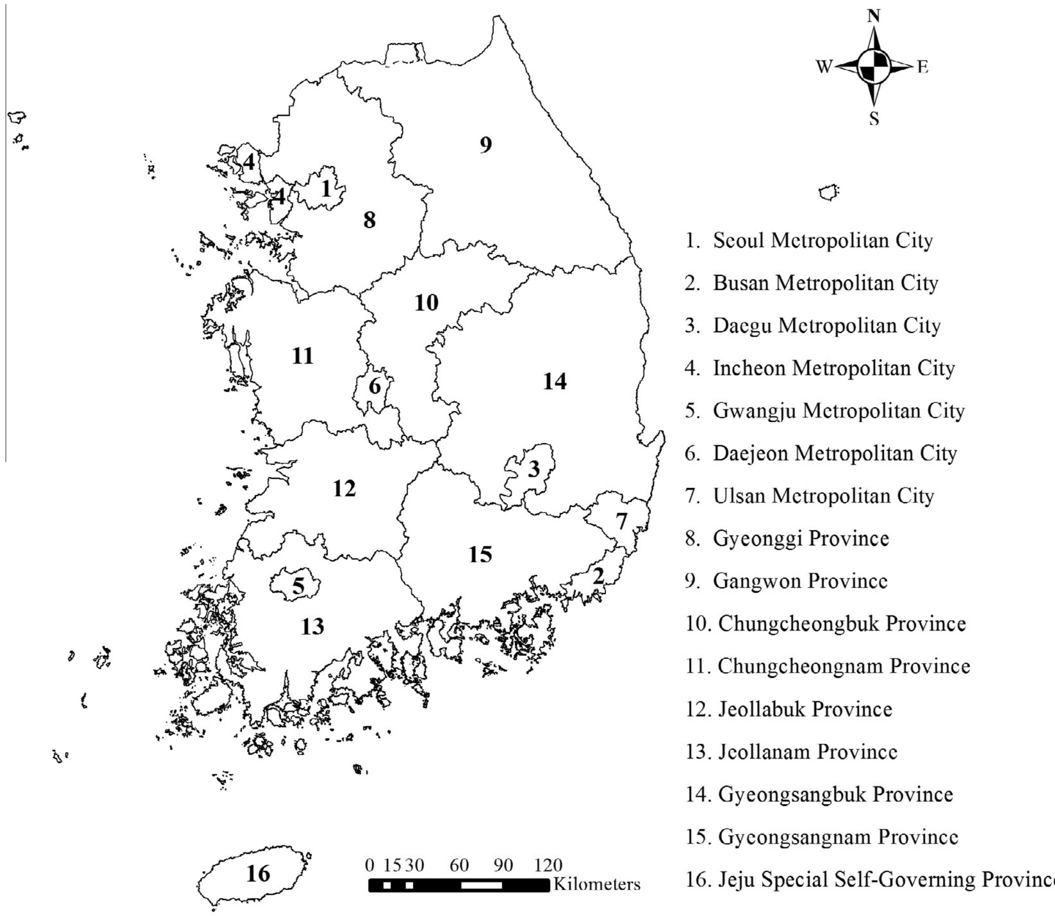

Fig. 6. Geographical locations of the administrative divisions in South Korea.

Fig. 6 shows the geographical locations and region names of 16 administrative divisions in South Korea, which consist of seven metropolitan cities (Nos. 1–7 in Fig. 6) and nine provinces (Nos. 8–16 in Fig. 6). Fig. 7 shows the map of the CO_2 emission density for the elementary school facilities in South Korea. In this study, the ArcMap 10.1 software program of ArcGIS 10.1 was used to show the regional distribution of the CO_2 emission density for the elementary school facilities in South Korea. Among the various methods, Kriging, a type of geographic information system interpolation, was applied [49–54]. Although the regional weathers of the metropolitan cities (Nos. 1–7 in Fig. 7) are similar to the regional weathers of the surrounding cities, the CO_2 emission density of the metropolitan cities is relatively higher than the CO_2 emission density of the surrounding cities. Based on this, it could be determined that the category benchmark cannot be sufficiently adjusted by considering only the heating degree days. Thus, the applicability issues of the building EPCs may be raised in terms of the region category.

ANOVA was conducted by considering both the building category (issue 1) and the region category (issue 2). SD Table S2 shows the results of the ANOVA for the CO_2 emission density of the educational facilities by region category. As the significance level (α) was set at 0.05, the mean differences among the groups (i.e., elementary school, middle school, and high school) by region category (i.e., 16 administrative divisions in South Korea) can be said to be valid [48]. It was determined that the category benchmark should be established by considering both the building and region categories.

3.1.2.2. Solutions for the region category. To calculate the reasonable operational ratings of existing buildings, it is necessary to establish a subcategory system of the region category using the geostatistical approach. It is necessary to subcategorize the region into 16 administrative divisions in South Korea as shown in Fig. 6. Based on the subcategory system of the region category, the energy consumption data should be separately managed, and then the category benchmark should be established. As a result, the potential problems in terms of the region category (which may arise in implementing the UK's DEC to existing buildings in South Korea) can be resolved, and then the reasonable operational ratings of existing buildings can be established.

In the analysis of issue 3 (i.e., space unit size), the analysis target was limited to Seoul (the capital of South Korea) to remove in advance the potential problems in terms of the region category (issue 2).

3.1.3. Issue 3: Space unit size

The UK's DEC does not consider the negative correlation between the CO_2 emission density and the space unit size of buildings in establishing the category benchmark for the 29 main building categories [31,42–46]. Such an approach, however, can cause problems in implementing the UK's DEC to existing buildings in South Korea. Solutions for such problems are suggested herein.

3.1.3.1. Problem analysis on the space unit size. Generally, an increase in the population density of a city causes an increase in the number of residents per unit area in buildings. Thus, as the

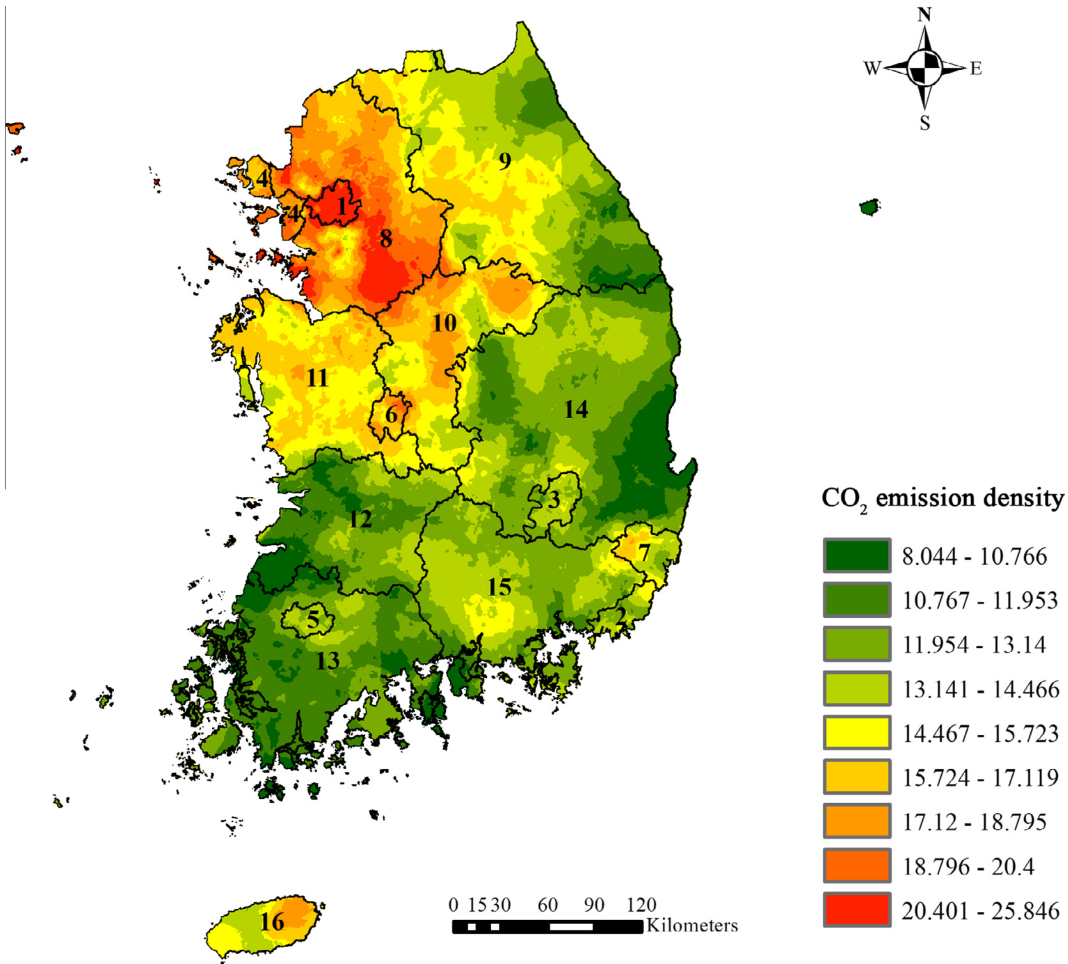

Fig. 7. Map of the CO_2 emission density by educational facility in South Korea.

space unit size of a building (e.g., area per unit class in educational facility and household size in residential building, etc.) decreases, the CO_2 emission density of the building increases. This is because there is the negative correlation between the CO_2 emission density and the space unit size. Therefore, if this negative correlation is not considered in establishing the category benchmark, the CO_2 emission density of a given facility increases as its space unit size decreases, ultimately resulting in a lower operational rating for the facility.

3.1.3.1.1. Macroscopic view. Table 4 shows the results of the correlation analysis between the space unit size and the CO_2 emission density of the elementary school facilities in South Korea. It was determined that the correlation between the number of persons per unit area and the area per unit class is negative (−0.583) and that the correlation between the area per unit class and the CO_2 emission density is also negative (−0.348). That is to say, the lower the space unit size (i.e., area per unit class) of a given building is, the higher the CO_2 emission density of the building becomes. Consequently, the operational rating of the building also becomes lower.

Through geostatistical analysis, the aforementioned trends from the macroscopic view can be found intuitively as follows.

- It can be concluded that the correlation between the number of persons per unit area and the area per unit class is negative. As shown in Fig. 8, the number of persons per unit area in the metropolitan cities (Nos. 1–7 in Fig. 8) is relatively higher than the number of persons per unit area in the other regions. Accordingly, the metropolitan cities (Nos. 1–7 in Fig. 8) are

Table 4
Correlation analysis between the space unit size and the CO_2 emission density of elementary school facilities in South Korea.

Variables		Person per unit area (person/m^2)	Area per unit class (m^2/class)	CO_2 emission density (kgCO_2/m^2/yr.)
Person per unit area (person/m^2)	Pearson correlation	1	−.583**	.278**
	Sig. (2-tailed)	–	0.000	.000
	N	5418	5418	5418
Area per unit class (m^2/class)	Pearson correlation	−.583**	1	−.348**
	Sig. (2-tailed)	0.000	–	.000
	N	5418	5418	5418

**Correlation coefficient is significant at 0.01 level (both sides) [48].

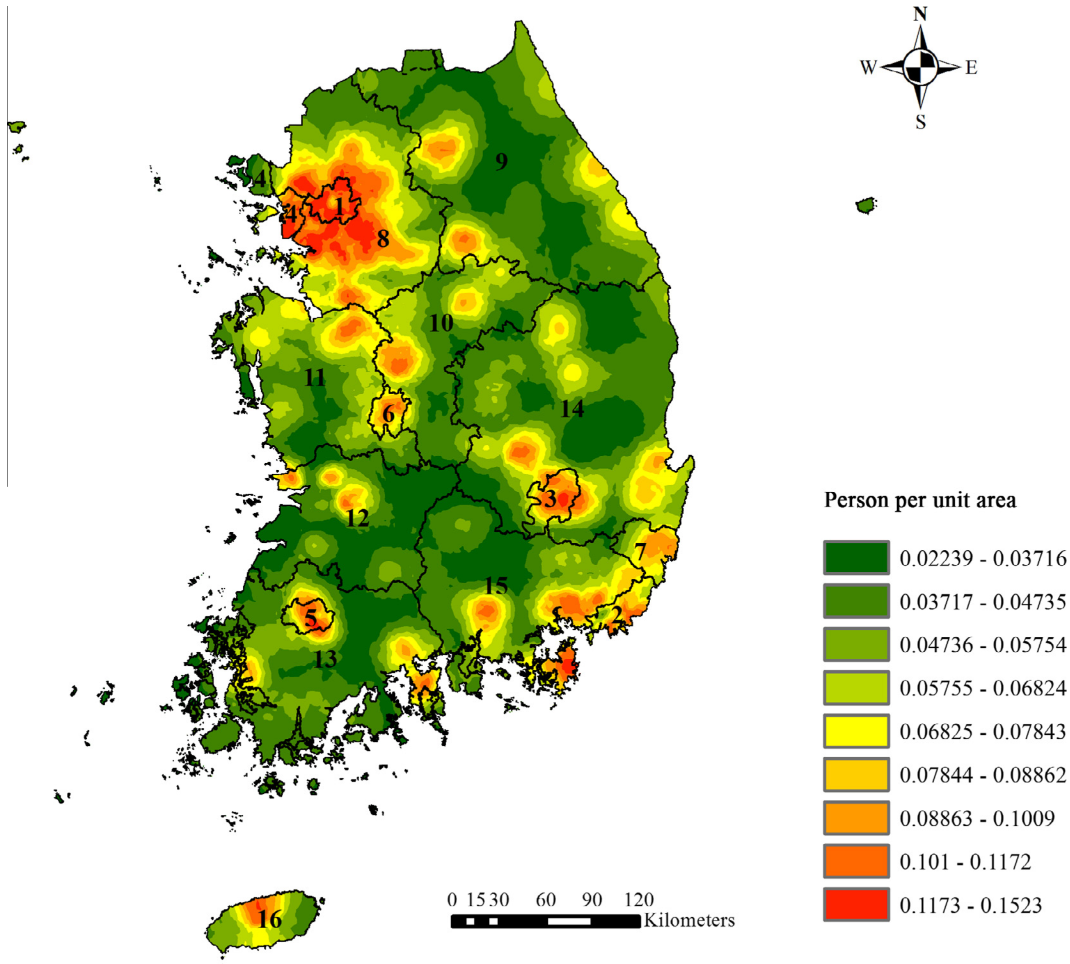

Fig. 8. Map of the number of persons per unit area by educational facility in South Korea.

colored red or yellow. Especially, Seoul Metropolitan City (the capital of South Korea; No. 1 in Fig. 8) and Gyeonggi province (a satellite city; No. 8 in Fig. 8) are colored dark red. On the other hand, as shown in Fig. 9, the area per unit class in the metropolitan cities (Nos. 1–7 in Fig. 9) is relatively lower than the area per unit class in the other regions. Accordingly, the metropolitan cities (Nos. 1–7 in Fig. 9) are colored green or yellow. Especially, Seoul Metropolitan City (No. 1 in Fig. 9) and Gyeonggi province (No. 8 in Fig. 9) are colored dark green.

- It can be concluded that the correlation between the area per unit class and the CO_2 emission density is negative. As shown in Fig. 9, the area per unit class in the metropolitan cities (i.e., colored green or yellow) is relatively lower than the area per unit class in the other regions. On the other hand, as shown in Fig. 7, the CO_2 emission density in the metropolitan cities (Nos. 1–7 in Fig. 7) is relatively higher than the CO_2 emission density in the other regions. Accordingly, the metropolitan cities (Nos. 1–7 in Fig. 7) are colored red or yellow. Especially, Seoul Metropolitan City (No. 1 in Fig. 7) and Gyeonggi province (No. 8 in Fig. 7) are colored dark red.

Based on the aforementioned results from the macroscopic view, it was determined that the space unit size (i.e., area per unit class) should be considered in establishing the category benchmark for the elementary school facility. Otherwise, the applicability issues of the building EPCs may be raised in terms of the space unit size from the macroscopic view.

3.1.3.1.2. Microscopic view. SD Table S3 shows the results of the correlation analysis between the space unit size and the CO_2 emission density of the elementary school facilities in terms of the region category. As previously mentioned in the results from the macroscopic view, it was determined that the correlation between the space unit size (i.e., area per unit class) and the CO_2 emission density was also negative from the microscopic view.

Through geostatistical analysis, the aforementioned trends from the microscopic view can be found intuitively as follows. Fig. 10 shows the geographical locations and region names of the 25 administrative divisions in Seoul.

- It can be concluded that the correlation between the number of persons per unit area and the area per unit class is negative. As shown in Fig. 11, the number of persons per unit area in the regions where the metropolitan cities' administrative duties and office buildings are concentrated (Nos. 1–3 in Fig. 11) is relatively lower than the number of persons per unit area in the other regions. Accordingly, the regions (Nos. 1–3 in Fig. 11) are colored dark green. On the other hand, as shown in Fig. 12, the area per unit class in the regions where the metropolitan cities' administrative duties and office buildings are concentrated (Nos. 1–3 in Fig. 12) is relatively higher than the area per unit class in the other regions. Accordingly, these central regions (Nos. 1–3 in Fig. 12) are colored light red or yellow.

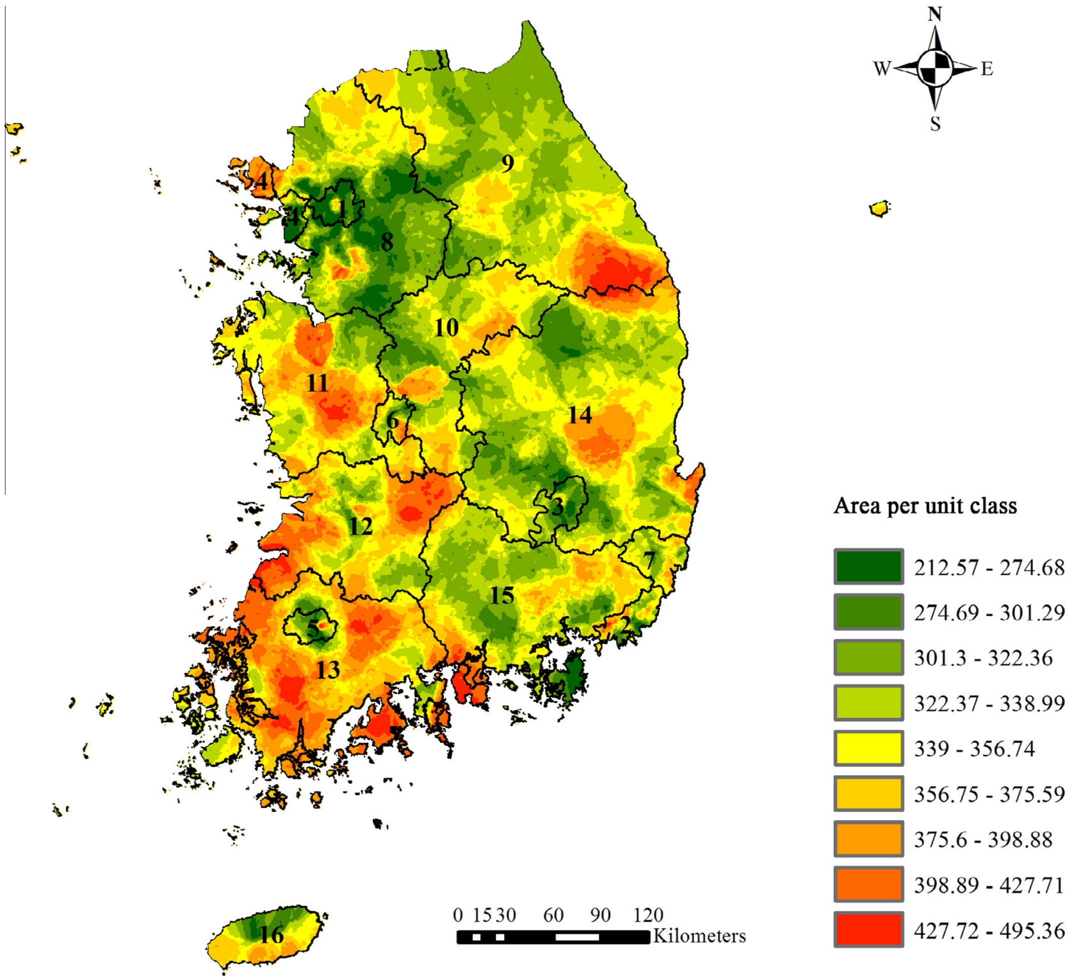

Fig. 9. Map of the area per unit class by educational facility in South Korea.

- The correlation between the area per unit class and the CO_2 emission density is shown to be negative. As shown in Fig. 12, the area per unit class in the regions where the metropolitan cities' administrative duties and office buildings are concentrated (i.e., colored light red or yellow) is relatively higher than the area per unit class in the other regions. On the other hand, as shown in Fig. 13, the CO_2 emission density in the regions where the metropolitan cities' administrative duties and office buildings are concentrated (Nos. 1–3 in Fig. 13) is relatively lower than the CO_2 emission density in the other regions. Accordingly, these central regions (Nos. 1–3 in Fig. 13) are colored light red or yellow.

Based on the aforementioned results from the microscopic view, it was determined that the space unit size (i.e., area per unit class) should be considered in establishing the category benchmark for the elementary school facility. Otherwise, the applicability issues of the building EPCs may be raised in terms of the space unit size from the microscopic view.

3.1.3.2. Solutions for the space unit size. To calculate the reasonable operational ratings of existing buildings, it is necessary to conduct the cluster formation by considering the negative correlation between the space unit size and the CO_2 emission density. The building energy consumption data should be separately managed by cluster, and then the category benchmark should be established using the separated cluster data. Accordingly, the irrationality of the building EPCs (which can be caused by the negative correlation between the space unit size and the CO_2 emission density) can be solved in advance. As a result, the operational ratings of small buildings can be adjusted upward, while the operational ratings of large buildings can be adjusted downward.

3.2. Comparative analysis between the developed dynamic operational rating system and the conventional operational rating system

Table 5 shows the results of the comparative analysis between the developed DOR system (i.e., developed system) and the conventional operational rating system (i.e., conventional system). This study analyzed both the distribution of the operational ratings by cluster from the macro perspective and the percentage change of educational facilities in the stated range by cluster from the micro perspective.

3.2.1. Distribution of the operational ratings by cluster

This study analyzed the distribution of the operational ratings by cluster (i.e., space unit size) in the developed system and the conventional system.

(i) *Cluster 1 (Space unit size: small building):* The overall operational ratings were adjusted upward (i.e., the letter ratings were changed to grade A from grade G). As shown in the third column (A) and sixth column (D) of Table 5, the average operational rating in the developed system (102.54, the dark blue line in Fig. 14) decreased by 1.88 points, compared to the average operational rating in the conventional system

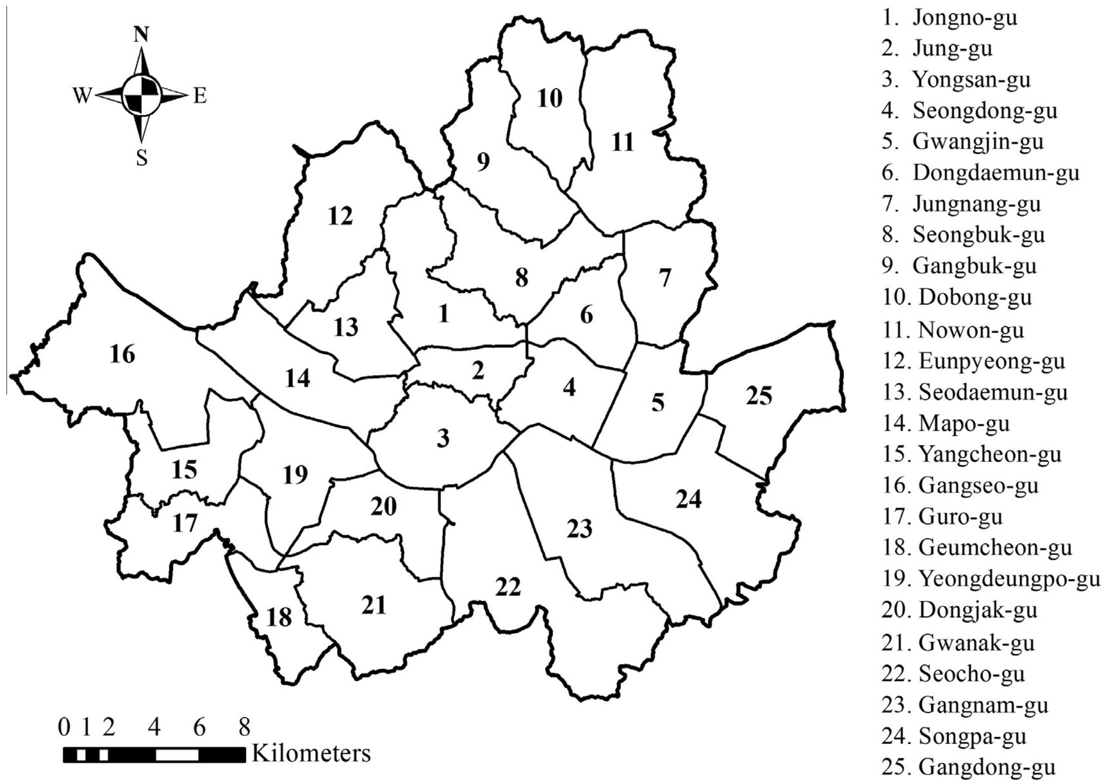

Fig. 10. Geographical locations of the administrative divisions in Seoul Metropolitan City.

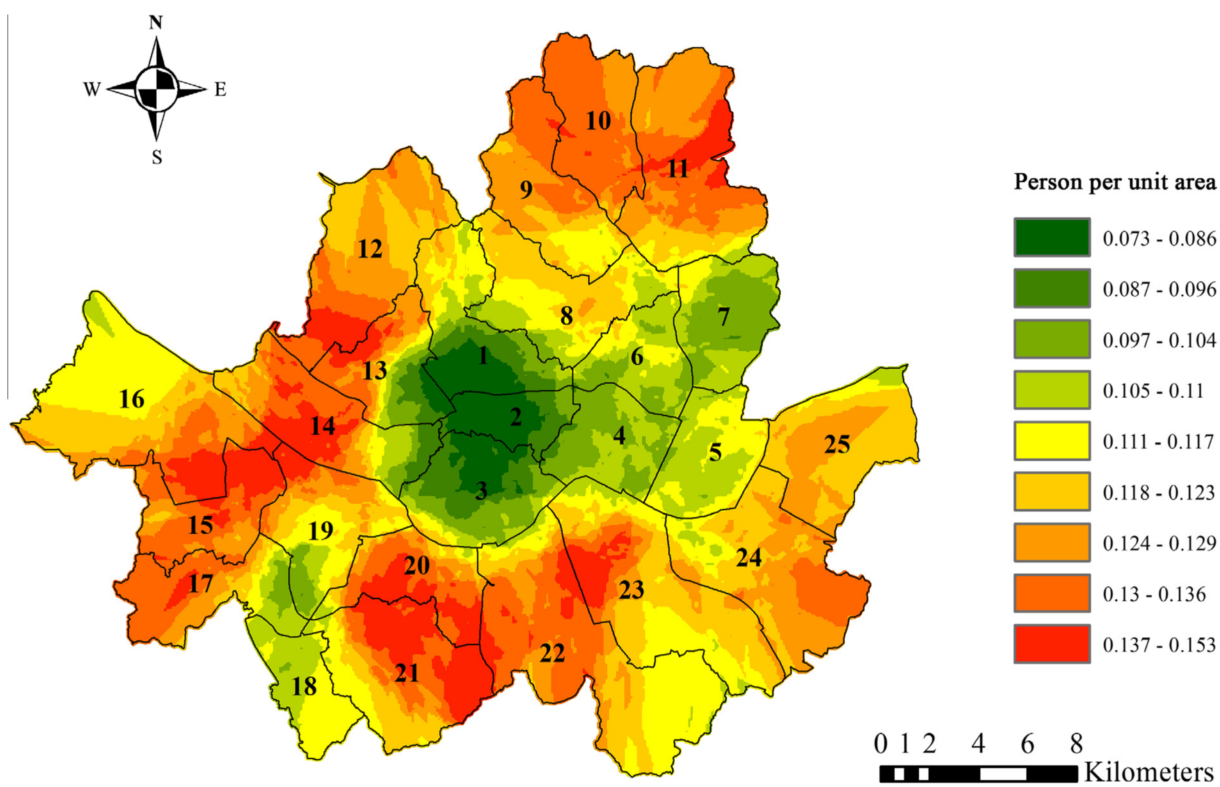

Fig. 11. Map of the number of persons per unit area by educational facility in Seoul.

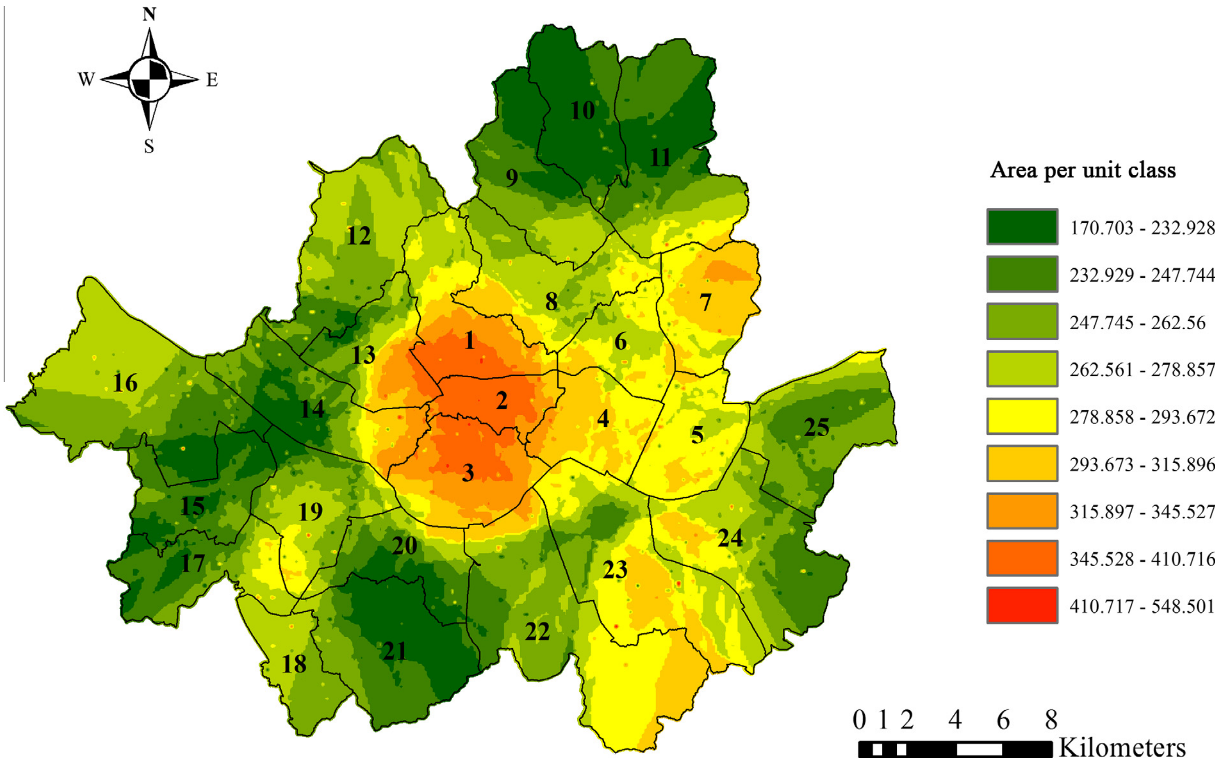

Fig. 12. Map of the area per unit class by educational facility in Seoul.

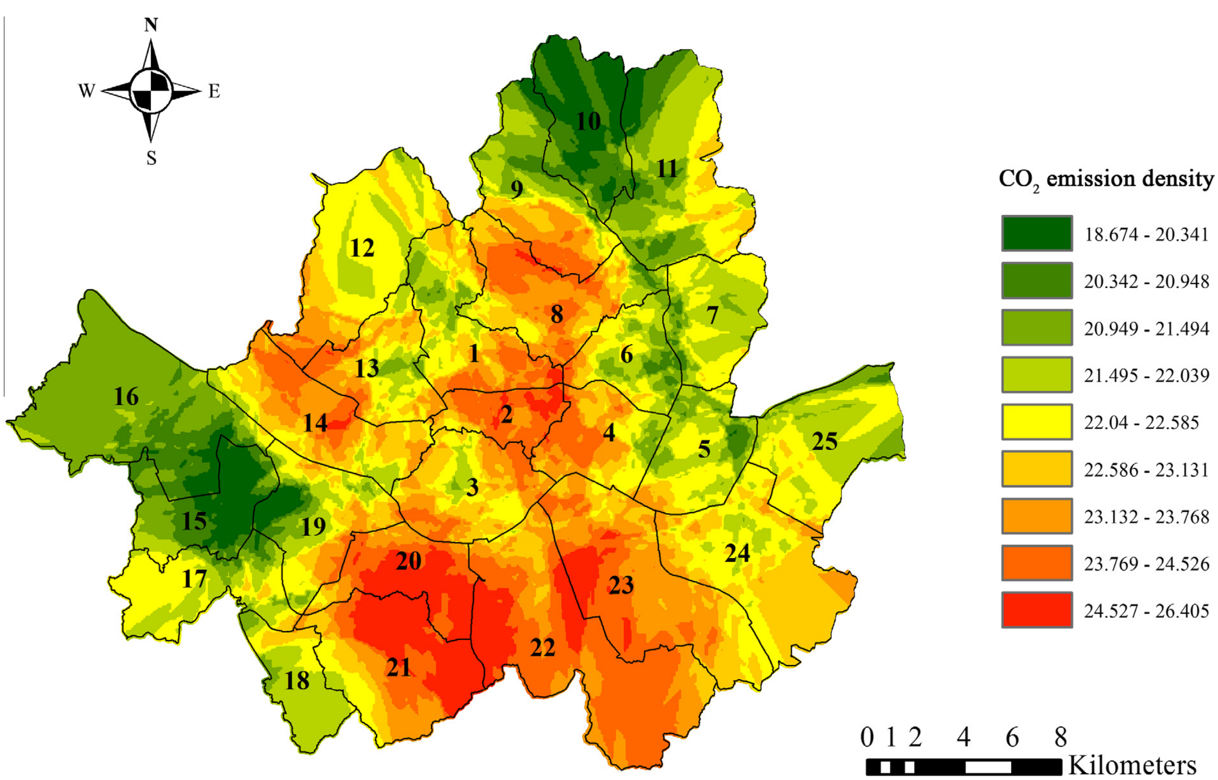

Fig. 13. Map of the CO_2 emission density by educational facility in Seoul.

(104.42, the light blue line in Figs. 14 and 15). In addition, as shown in the fifth column (C) and eighth column (F) of Table 5, the ratio of the cases included in grades A to D (the letter rating) increased from 45.7% (the conventional system) to 50.1% (the developed system) while the ratio of the cases included in grades E to G (the letter rating) decreased from 54.3% (the conventional system) to 49.9% (the developed system) (refer to Figs. 14 and 15).

Table 5
Comparative analysis between the developed DOR system and the conventional operational rating system.

Classification			Conventional system[a]			Developed system[b]		
Cluster	A–G label		Sum of OR[c]	Number of cases	Ratio (%)	Sum of OR	Number of cases	Ratio (%)
			(A)	(B)	(C)	(D)	(E)	(F)
Cluster 1 (Space unit size: Small)	A	0–25	0.00	0	45.7%	0.00	0	50.1%
	B	26–50	94.17	2		141.99	3	
	C	51–75	2035.28	31		2097.80	32	
	D	76–100	10,763.79	120		11,905.97	133	
	E	101–125	14,352.75	130	54.3%	13,350.82	121	49.9%
	F	126–150	5248.73	39		4711.40	35	
	G	More than 150	2485.49	13		2143.16	11	
	Sum		34,980.20	335	–	34,351.15	335	–
	Average		104.42	–	–	102.54	–	–
Cluster 2 (Space unit size: Large)	A	0–25	23.39	1	67.5%	0.00	0	50.6%
	B	26–50	135.98	3		122.70	3	
	C	51–75	1265.07	21		1212.38	19	
	D	76–100	2722.92	31		1790.65	20	
	E	101–125	2299.42	21	32.5%	3479.78	31	49.4%
	F	126–150	534.08	4		817.05	6	
	G	More than 150	324.06	2		666.98	4	
	Sum		7304.91	83	–	8089.54	83	–
	Average		88.01	–	–	97.46	–	9.45

[a] Conventional system stands for the conventional operational rating system.
[b] Developed system stands for the developed dynamic operational rating system.
[c] OR stands for the operational rating.

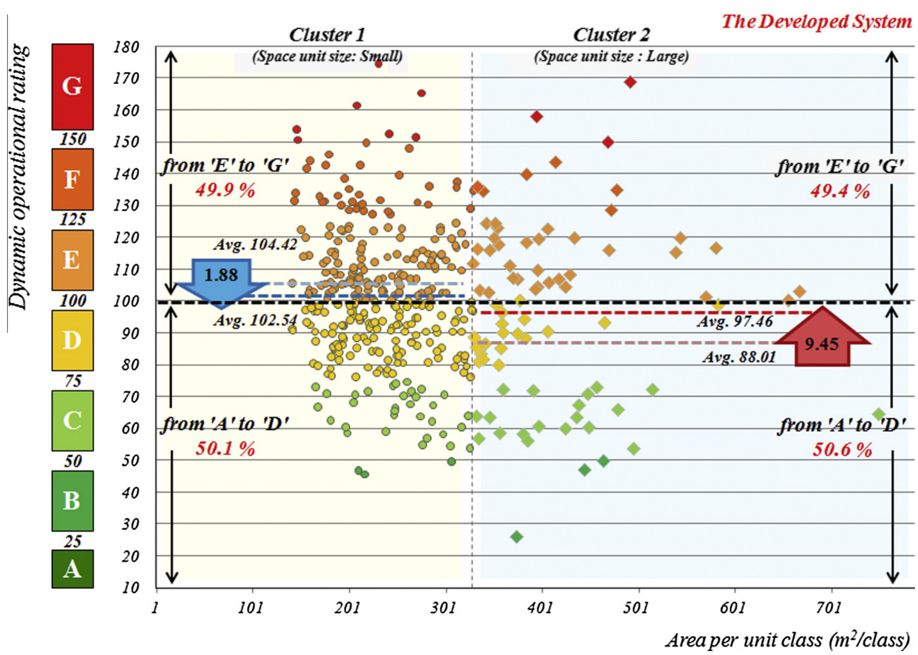

Fig. 14. Distribution of the operational rating by cluster in the developed system.

(ii) *Cluster 2 (Space unit size: large building):* The overall operational ratings were adjusted downward (i.e., the letter ratings were changed to grade G from grade A). As shown in the third column (A) and sixth column (D) of Table 5, the average operational rating in the developed system (97.46, the dark red line in Fig. 14) increased by 9.45 points, compared to the average operational rating in the conventional system (88.01, the light blue line in Figs. 14 and 15). In addition, as shown in the fifth column (C) and eighth column (F) of Table 5, the ratio of the cases included in grades A to D (the letter rating) decreased from 67.5% (the conventional system) to 50.6% (the developed system), while the ratio of the cases included in grades E to G (the letter rating) increased from 32.5% (the conventional system) to 49.4% (the developed system) (refer to Figs. 14 and 15).

3.2.2. Percentage change of educational facilities in the stated range by cluster

This study analyzed the percentage change of educational facilities in the stated range (i.e., grades A to G) by cluster (i.e., space unit size) between the developed system and the conventional system.

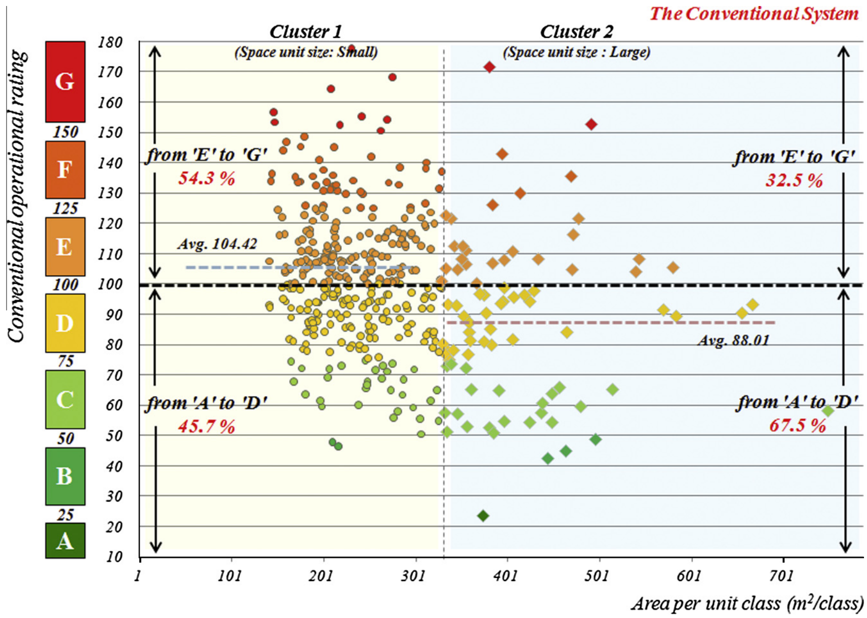

Fig. 15. Distribution of the operational rating by cluster in the conventional system.

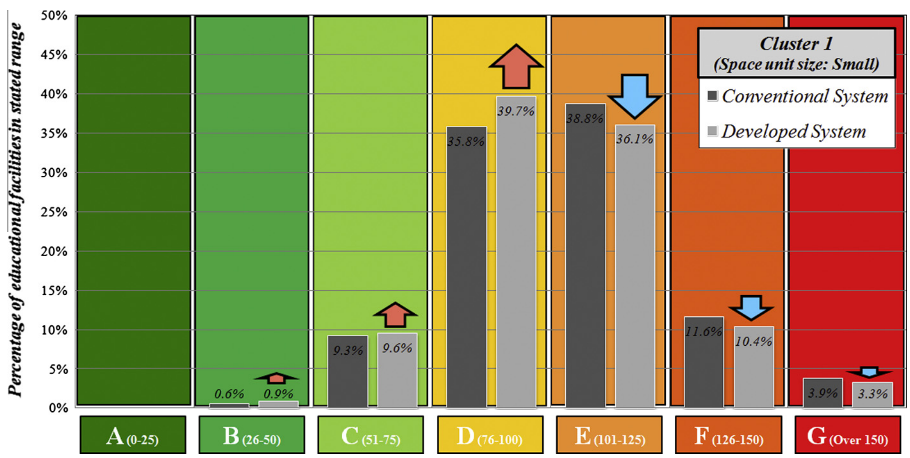

Fig. 16. Percentage change of educational facilities in the stated range for cluster 1.

(i) *Cluster 1 (Space unit size: small building):* As shown in Fig. 16, when the develop system is applied to cluster 1 (i.e., small buildings), it is determined that the percentage of educational facilities in the grades A to D increases within the range of 0.3% to 3.9%, compared to the conventional system. Meanwhile, it is determined that the percentage of educational facilities in the grades E to G decreases within the range of 0.6% to 2.7%, compared to the conventional system.

(ii) *Cluster 2 (Space unit size: large building):* As shown in Fig. 17, when the develop system is applied to cluster 2 (i.e., large buildings), it is determined that the percentage of educational facilities in the grades A to D decreases within the range of 1.2–13.2%, compared to the conventional system. Meanwhile, it is determined that the percentage of educational facilities in the grades E to G increases within the range of 2.4–12.0%, compared to the conventional system.

3.2.3. Discussion

This study has solved the irrationality of the operational rating in the building EPCs (which occurred due to the negative correlation between the space unit size and the CO_2 emission density). In the conventional system (refer to the fifth column (C) of Table 5), the small building that is included in cluster 1 has a higher CO_2 emission density due to a smaller space unit size, and thus, it has a lower operational rating in the building EPCs (refer to Fig. 16). Meanwhile, the large building that is included in cluster 2 has a lower CO_2 emission density due to a larger space unit size, and thus, it has a higher operational rating in the building EPCs (refer to Fig. 17). This is because there is the irrationality of the conventional operational rating system. To address this challenge, this study developed the DOR system by considering three-categorized problems in the conventional system (i.e., building category, region category, and space unit size). Through the application of the developed system (refer to the eighth column (F) of Table 5 and Fig. 14), the overall operational ratings of the small buildings (included in cluster 1) were adjusted upward (102.54), compared to those in the conventional system (104.42). Meanwhile, the overall operational ratings of the large buildings (included in cluster 2) were adjusted downward (97.46), compared to those in the conventional system (88.01). Therefore, it can be concluded that a reasonable operational rating system is developed.

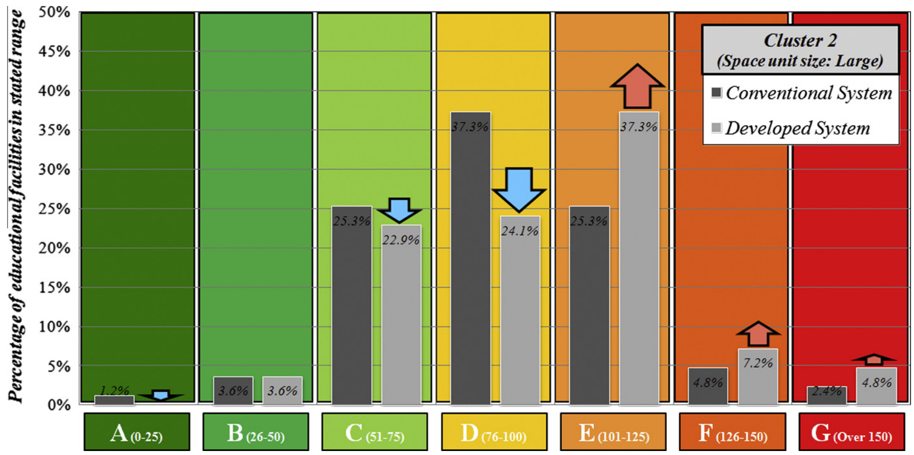

Fig. 17. Percentage change of educational facilities in the stated range for cluster 2.

4. Conclusions

This study aimed to highlight what the potential problems of the conventional operational rating system for existing buildings would be, why the potential problems may arise, and how the potential problems can be solved. This study used the statistical and geostatistical approaches to analyze the potential problems of the conventional operational rating system for existing buildings. Furthermore, this study used the data-mining technique and the probability approach to develop the DOR system for existing buildings. The results of this study can be summarized as follows.

First, this study analyzed the potential problems that may arise in implementing the UK's DEC to existing buildings in South Korea, which can be summarized as follows. This approach of the problem analysis can be applied to the other countries by considering the specific conditions of each country.

- For the building category (issue 1), it was determined that the building category should be subdivided through the statistical approach (i.e., ANOVA) using the CO_2 emission density for the buildings included in the same building category (refer to Section 3.1.1).
- For the region category (issue 2), it was determined that the region category should be subdivided through the geostatistical approach using the CO_2 emission density by region. The building energy consumption data should be separately managed by region, and then the category benchmark should be established using the separated regional data (refer to Section 3.1.2).
- For the space unit size (issue 3), it was determined that the cluster formation should be conducted by considering the negative correlation between the space unit size and the CO_2 emission density. The building energy consumption data should be separately managed by cluster, and then the category benchmark should be established using the separated cluster data (refer to Section 3.1.3).

Second, this study developed the DOR system for existing buildings to solve the aforementioned potential problems (which can occur due to the negative correlation between the space unit size and the CO_2 emission density). It was determined that the developed DOR system can solve the irrationality of the conventional operational rating system. In other words, the operational ratings of small buildings were adjusted upward (i.e., the letter ratings of the small buildings were changed to grade A from grade G) while those of large buildings were adjusted downward (i.e., the letter ratings of the large buildings were changed to grade G from grade A). In conclusion, it is expected that the reasonable operational ratings of existing buildings can be established by using the developed DOR system, which can motivate all the public to actively participate in energy-saving campaigns.

Meanwhile, the developed DOR system can be applied for various purposes such as encouraging all the public to voluntarily participate in energy-saving campaigns, evaluating the historical trend in the energy performance of existing buildings, estimating the operational ratings of new buildings in the early design phase, and analyzing the effect of the operational ratings of existing buildings on the rental and capital values. For these purposes, the research team has currently conducted the follow-up studies to extend the application of the developed DOR system from the perspective of energy policy.

- The research team aims to develop a dynamic incentive and penalty program for improving the energy performance of existing buildings based on the developed DOR system. The results of this study will be able to encourage the voluntary participation of all the public in the energy saving campaign, resulting in the achievement of the positive effectiveness of the energy policy such as national carbon emissions reduction target and energy performance certificates [55].
- The research team aims to develop a dynamic energy performance curve for evaluating the historical trends in the energy performance of existing buildings based on the developed DOR system. The results of this study will make all the public to be clearly aware of the historical trends in the energy performance of their buildings and to establish the optimal energy retrofit strategy for their buildings [56].
- The research team aims to develop an estimation methodology for the dynamic operational rating of a new residential building in the early design phase by combining the data-mining techniques (i.e., case-based reasoning, artificial neural network, and multiple regression analysis) and the stochastic approach. The results of this study will be used for the contractors in a competitive bidding process to improve the real estate asset value (i.e., the rental and capital values) by considering the building energy performance [57].

In order to implement the developed DOR system to any other country or sector, it is necessary to collect their own data such as the building characteristics, user information, and energy consumption data. It is commonly available for the different countries, which can be collected from the facility managers and energy service providers. Therefore, it is expected that the developed DOR system can be extended to any other country or sector in the global environment.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.05.003.

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