TECHNOLOGICAL AND ECONOMIC DEVELOPMENT OF ECONOMY
ISSN 2029-4913 / eISSN 2029-4921

2018 Volume 24(2): 295–317
doi:10.3846/20294913.2016.1212741

DEVELOPMENT OF A DYNAMIC INCENTIVE AND PENALTY PROGRAM FOR IMPROVING THE ENERGY PERFORMANCE OF EXISTING BUILDINGS

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Received 26 November 2014; accepted 30 August 2015

Abstract. The positive effectiveness of energy policy instruments such as national carbon emissions reduction target (CERT) and energy performance certificates can be achieved by encouraging the voluntary participation of the public in the energy-saving campaign. Towards this end, this study aimed to develop a dynamic incentive and penalty program for improving the energy performance of existing buildings. Four types of incentive programs and four types of penalty programs were established based on three comparison criteria. As a building-level, the first comparison criterion is the averaging approach based on similar cases that can be retrieved using a simplified case-based reasoning model. As a community-level, the second comparison criterion is one-step higher operational and letter rating than the grade of a given building. As a national-level, the third comparison criterion is the operational and letter rating as the minimum criteria for achieving the national CERT. In this study, an elementary school facility located in Seoul, South Korea was selected to validate the applicability of the developed program. As a result, besides the category benchmark, the various comparison criteria should be provided to the public to encourage the voluntary participation of the public in the energy-saving campaign.

Keywords: policy on sustainable development, building energy performance certificate, incentive and penalty program, operational rating, voluntary participation, case-based reasoning.

JEL classification: C38, C45, C61, D78, L74, L78, Q01, Q48, R28.

Online supplementary material: Supporting information for this paper is available as online supplementary material at https://doi.org/10.3846/20294913.2016.1212741

Introduction

Various efforts have been made to reduce greenhouse gas (GHG) emissions. In particular, the Kyoto Protocol was agreed by developed countries (i.e., Annex I parties) in December 1997, and then, it has been in effect since February 2005. Accordingly, the developed coun-

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tries established a national carbon emission reduction target (CERT) as an energy policy instrument from a macroscopic view and are making various efforts to achieve their goals (e.g., Low-Carbon-Scenario 2020) (CCC 2010; IEA 2012; IPCC 2007; UNFCCC 1998).

It is reported that in the developed regions like the United States and the European Union (EU), GHG emissions from the building sector account for about 40% (DECC 2012; EIA 2012). To reduce these GHG emissions and improve the energy performance of buildings, EU adopted the Energy Performance of Building Directive (EPBD) in 2002. First, the EPBD initiated the energy performance certificates (EPCs) of buildings as an energy policy instrument from a microscopic view (CA EPBD 2011a, 2011b, 2011c; IEEP 2011; Sunikka 2005; ZCH 2011). Generally, the building's EPCs can be categorized into two types: (i) asset rating, an energy-demand-based rating system that is mainly used for new buildings and (ii) operational rating, an energy-consumption-based rating system that is mainly used for existing buildings (Kelly *et al.* 2012; Koo *et al.* 2014a; Majcen *et al.* 2013; Marchio, Rabl 1991). Since existing building stock has continued to increase, which led to a decrease in the demand for new buildings (RICS 2009), it is required to focus on improving the energy performance of existing buildings and to further study the associated operational rating system and its applications. Second, the EPBD established the various incentive programs, which can be divided into four categories: (i) fiscal instruments such as tax relief; (ii) financial measures such as loans and subsidy; (iii) market-based instruments such as emissions trading schemes; and (iv) direct incentives such as investment in public facilities and infrastructures (Murphy *et al.* 2012; Weiss *et al.* 2012). These kinds of incentive programs are related to energy retrofit strategies that can be established using energy-saving techniques and new and renewable energy systems. Besides these efforts, however, it is necessary to promote positive behaviour in occupants (e.g., the voluntary participation of the public in the energy-saving campaign), which can make the energy policy instruments (i.e., the national CERT from a macroscopic view and the building's EPCs from a microscopic view) more effective (Koo 2014; Koo, Hong 2015).

Based on the aforementioned background, this study aimed to develop a dynamic incentive and penalty programs for improving the energy performance of existing buildings. This study considered three types of comparison criteria in the building's EPCs (i.e., building-level, community-level, and national-level). These efforts can allow the public to easily understand the current status of the existing building's energy performance and to intuitionally establish their energy saving targets by considering the comparison criteria. Towards this end, the following considerations should be reflected. First, from a building-level perspective, the physical properties of existing buildings included in the same region category should be compared to each other, and then, similar buildings can be able to selected. Based on the selected similar buildings, the detailed energy saving targets can be established to improve the energy performance of existing buildings. Second, from a community-level perspective, the reasonable operational rating in the building EPC should be presented to evaluate the current status of the existing building's energy performance. Third, from a national-level perspective, it is necessary to determine whether or not action plan for improving the energy performance of existing buildings at this point can contribute to achieve the national CERT from a macroscopic view. This study assumed that, besides the category benchmark (i.e., the average value of the CO_2 emission density for existing buildings included in both the same building category and the same region category), the various comparison criteria should be presented to encourage the voluntary participation of the public in the energy-saving campaign.

This study established the research scope as follows. South Korea enacted the building's EPCs under the Act on the Promotion of Green Buildings in February 2013 (MLTM 2012), which was established based on the similar concept of the display energy certificate (DEC) for public buildings in UK (DCLG 2008). Accordingly, this study targeted public buildings, and then, this study collected the energy consumption data from 1999 to 2010 for the elementary school facility (i.e., building's subcategory) located in Seoul, the capital of South Korea (i.e., region's subcategory) (Koo, Hong 2015). Meanwhile, the UK's DEC is used for reasonably evaluating the energy performance of existing public buildings and the consequent greenhouse gas emissions. The detailed characteristics of the UK's DEC can be summarized as follows. First, the UK's DEC categorizes into 29 types of buildings with the general description and category benchmark. Second, the category benchmark stands for the typical CO_2 emission density ($kgCO_2/m^2$/yr.), which can be established using the energy consumption by energy source. Third, various preconditions are establish to determine the category benchmark, including the monthly heating degree days, the yearly occupancy period, and the proportion of the non-electric energy. Thus, the adjustment methods should be used for appropriately modifying the category benchmark. Based on these characteristics, it is determined that the category benchmark is the most important factor in implementing the operational rating system (DCLG 2008, 2013; DECC 2013).

Before developing the dynamic incentive and penalty program, this study conducted a preliminary analysis of the conventional EPCs for existing buildings in terms of the comparison criteria. Based on the analysis results, this study established four types of incentive programs and four types of penalty programs by considering three comparison criteria (i.e., building-level, community-level, and national-level). Finally, using the collected data, this study developed the dynamic incentive and penalty program for improving the energy performance of existing buildings (refer to Supplementary Information (SI), SI Fig. S1).

1. Literature review

There are several previous studies on the energy performance of existing buildings from various viewpoints such as building-level, community-level, and national-level perspectives.

First, several studies were conducted from a building-level perspective, which can be categorized into two types: (i) studies on the selection of the optimal energy retrofit strategy in a given building (Hong *et al.* 2012a, 2012b, 2013a, 2014; Kim *et al.* 2012; Zurigat *et al.* 2003) and (ii) studies on the estimation of energy-saving potentials in a given building (Butala, Novak 1999; Hong *et al.* 2012c, 2012d, 2012e, 2013b). These previous studies used a case-based reasoning approach as a methodology with which to select similar buildings by comparing the physical properties of existing buildings. Based on the retrieved cases, these previous studies aimed to establish the detailed energy saving targets for improving the energy performance of existing buildings. Some of these previous studies also attempted to propose carbon-point-based incentive and penalty programs (CPS 2015; GCCS 2015; GT 2015). However, these efforts were limited in that they were unable to show a link to the operational rating in the building's EPCs. In addition, these previous studies used an advanced case-based reasoning (A-CBR) approach to improve the prediction accuracy of the developed models, but it is difficult to implement the A-CBR model due to its complicated algorithm.

Second, several studies were conducted from a community-level perspective, which can be categorized into two types: (i) studies on the problems of the building's EPCs (e.g., the difference between the predicted value (i.e., assess rating) and the observed value (i.e., operational rating)) (Kelly *et al.* 2012; Majcen *et al.* 2013; Marchio, Rabl 1991) and (ii) studies on the impact of the building's EPCs on the rental or sales cost (Amecke 2012; Fuerst, McAllister 2011; Koo, Hong 2015; Koo *et al.* 2014a). In particular, Koo and Hong (2015) analyzed the problems of the building's EPCs from three perspectives (i.e., building category, region category, and space unit size). Based on the analysis, they developed a dynamic operational rating system with which to conduct the reasonable assessment on the current status of the existing building's energy performance. However, besides the category benchmark, these previous studies could not provide any other comparison criteria. In addition, they could not present a link to the incentive and penalty program.

Third, several studies on the low-carbon scenario were conducted from a national-level perspective (Alderson *et al.* 2012; Ashina *et al.* 2012; Bautista 2012; Gomi *et al.* 2010; Koo *et al.* 2014b, 2015; Thollander *et al.* 2012; Wang *et al.* 2011; Winyuchakrit *et al.* 2011). Koo *et al.* (2014b, 2015) assessed the improvement of the energy performance of existing buildings by implementing various energy retrofit strategies, which were established by combining energy-saving techniques and new and renewable energy systems. Furthermore, they aimed to determine whether or not these energy retrofit strategies would ultimately achieve the national CERT from a macroscopic view. However, these previous studies could not link to the operational rating system in the building's EPCs in assessing the energy performance of existing buildings. Furthermore, they could not present a link to the incentive and penalty program.

2. Preliminary analysis of the conventional EPCs for existing buildings

2.1. Problem analysis on the conventional EPCs for existing buildings

The EPCs for existing buildings in South Korea were established based on the similar structure with the UK's DEC (DCLG 2008; MLTM 2012). Thus, before the development of the dynamic incentive and penalty program, the potential problems that can occur in the process of implementing the UK's DEC to South Korea should be analyzed in advance. Especially, from the perspective of the comparison criteria, as the UK's DEC only provides the category benchmark (i.e., the typical CO_2 emission density) in establishing the operational and letter rating of existing buildings (DCLG 2013; DECC 2013), the following problem may occur. Solution for such problem is suggested herein.

2.1.1. Problem analysis on the comparison criteria

If the category benchmark (i.e., the average value of CO_2 emission density for existing buildings included in both the same building category and the same region category) is only provided to the public as the comparison criteria in the building's EPCs, it is difficult to encourage the voluntary participation of the public in the energy-saving campaign.

It can be explained by the following three reasons. First, if the operational and letter rating of a given building are relatively less than those of the other buildings included in both the same building category and the same region category, the public is likely to believe that the category benchmark is not a reasonable and appropriate standard as the comparison criteria. Second, as the letter rating of a given building (from "A" to "G" label) is expressed as a range of the operational rating, the public may not be aware of the actual CO_2 emission density of the given building. Thus, it is difficult for the public to get motivated by the letter rating expressed as a range of the operational rating (refer to SI Table S1) (DCLG 2008). Third, as the category benchmark is established based on the only current value of the CO_2 emission density, it is difficult for the public to understand how their efforts can contribute to the national-level energy policy instrument. Therefore, the building's EPCs should provide various types of comparison criteria to encourage the voluntary participation of the public in the energy-saving campaign. Otherwise, the applicability issues of the building's EPCs may be raised in terms of the comparison criteria.

2.1.2. Solution for the comparison criteria

Various types of the comparison criteria should be provided to the public to encourage the voluntary participation of the public in the energy-saving campaign. Namely, besides the category benchmark (i.e., the typical CO_2 emission density), the following three comparison criteria should be established. As a building-level, the first comparison criterion is the averaging approach based on similar cases that can be retrieved using a simplified case-based reasoning (S-CBR) model. As a community-level, the second comparison criterion is one-step higher operational and letter rating than the grade of a given building. As a national-level, the third comparison criterion is the operational and letter rating as the minimum criteria for achieving the national CERT.

Meanwhile, the following considerations were reflected in developing the dynamic incentive and penalty program in this study. First, various types of the comparison criteria should be connected with the incentive and penalty program to encourage the voluntary participation of the public in the energy-saving campaign. Second, the operational and letter rating in the building's EPCs should be provided with a visualized chart so that the public can intuitively make a decision of whether or not to improve the energy performance of their buildings. Third, the operational and letter rating in the building's EPCs should be provided with the actual value of the CO_2 emission density so that the public can easily understand the operational and letter rating for their buildings. As a result, the potential problems in terms of the comparison criteria (which may arise in implementing the UK's DEC to existing buildings in South Korea) can be resolved, and then the reasonable incentive and penalty program can be established.

2.2. Framework for the dynamic incentive and penalty program of existing building's energy performance

As explained in Section 2.1, the dynamic incentive and penalty program needs to be developed by considering three comparison criteria. Based on these criteria, a total of four assumptions were established to determine the type of incentive and penalty program:

- Assumption 1: Based on the category benchmark (of which operational rating is 100), the incentive and penalty program can be determined as follows: (i) incentive program: if the operational rating of a given building is below 100 (i.e., letter rating A, B, C, or D), the given building should be included in the incentive program. This is because the energy performance of the given building is superior to the category benchmark. Accordingly, this study defined the range within the operational rating of 0 to 100 (i.e., the letter ratings from "A" to "D" label) as the incentive zone; and (ii) penalty program: if the operational rating of a given building is over 100 (i.e., letter rating E, F, or G), the given building should be included in the penalty program. This is because the energy performance of the given building is inferior to the category benchmark. Accordingly, this study defined the range within the operational rating of more than 100 (i.e., the letter ratings from "E" to "G" label) as the penalty zone.
- Assumption 2: Based on the comparison criteria 1 (building-level), the incentive and penalty program can be determined as follows: (i) incentive program: although a given building is included in the incentive zone (i.e., the operational rating of the given building is below 100), the incentive could not be always provided for the given building. Namely, the incentive can be available for the given building only if the operational rating of the given building is less than the average value of the operational ratings of similar cases that are retrieved using the S-CBR model; otherwise, it cannot be available; and (ii) penalty program: although a given building is included in the penalty zone (i.e., the operational rating of the given building is over 100), the penalty could not be always imposed on the given building. Namely, the penalty can be imposed on the given building only if the operational rating of the given building is more than the average value of the operational ratings of similar cases that are retrieved using the S-CBR model; otherwise, it cannot be imposed.
- Assumption 3: Based on the comparison criteria 2 (community-level), the premium in the building sale or rental process (i.e., contract premium) can be provided for the public as the incentive program. Namely, as mentioned in the section of "Introduction", in 2007, the EPBD adopted a compulsory clause that attaches the building's EPCs to the contract documents in the building sale or rental process (CA EPBD 2011a, 2011b, 2011c; IEEP 2011; Sunikka 2005; ZCH 2011). Also, the South Korean government introduced a similar energy policy instrument by enacting the Act on the Promotion of Green Buildings in February 2013 (MLTM 2012). If this energy policy instrument can be successfully applied, the contract premium for one-step higher operational and letter rating than the grade of a given building, as the incentive program, will occur in the building sale or rental process; otherwise, it will not occur. Accordingly, the contract premium can encourage the voluntary participation of the public in the energy-saving campaign. Therefore, this study defined the

contract premium as the incentive program that can be used for the comparison criteria.

- Assumption 4: Based on the comparison criteria 3 (national-level), the taxation premium such as carbon tax or progressive tax can be imposed on the public. Namely, South Korea established 30% of GHG emissions reduction target to business-as-usual by 2020 as the national CERT; and 26.9% for the building sector (KG 2011; KME 2011). The national CERT from a macroscopic view can be achieved by effectively managing the building's EPCs from a microscopic view. If the EPC of a given building can contribute to the achievement of the national CERT, the taxation premium cannot be imposed on the public; otherwise, it can be imposed. Accordingly, the taxation premium can encourage the voluntary participation of the public in the energy-saving campaign. Therefore, this study defined the taxation premium as the penalty program that can be used for the comparison criteria.

According to the aforementioned four assumptions, four types of incentive programs (refer to SI Table S2 and SI Figures S2 to S5) and four types of penalty programs (refer to SI Table S3 and SI Figures S6 to S9) were established as follows.

2.2.1. Four types of incentive programs

If the operational rating of a given building is below 100 (i.e., letter rating A, B, C, or D), the given building can be applied to the incentive program. Accordingly, this study defined the range within the operational rating of 0 to 100 (i.e., the letter ratings from "A" to "D" label) as the incentive zone (refer to assumption 1, *operational rating*). However, although a given building is included in the incentive zone, the incentive can be available for the given building only if the operational rating of the given building is less than the average value of the operational ratings of similar cases that are retrieved using the S-CBR model (refer to assumption 2, *building-level*). Meanwhile, if the energy policy instrument (which attaches the building's EPCs to the contract documents in the building sale or rental process) can be successfully applied, the contract premium for one-step higher operational and letter rating than the grade of a given building, as the incentive program, will occur in the building sale or rental process (refer to assumption 3, *community-level*). In addition, if the EPC of a given building can successfully contribute to the achievement of the national CERT, the taxation premium such as carbon tax or progressive tax, as the penalty program, cannot be imposed on the public (refer to assumption 4, *national-level*). As a result, this study established four types of incentive programs by considering the aforementioned four assumptions. Detailed descriptions of four types of incentive programs are presented in SI Table S2, and the associated visualized charts are presented in SI Figures S2 to S5, respectively.

2.2.2. Four types of penalty programs

If the operational rating of a given building is over 100 (i.e., letter rating E, F, or G), the given building can be applied to the penalty program. Accordingly, this study defined the range within the operational rating of more than 100 (i.e., the letter ratings from "E" to "G" label) as the penalty zone (refer to assumption 1, *operational rating*). However, although a given building is included in the penalty zone, the penalty can be imposed on the given building only if the operational rating of the given building is more than the average value of the operational ratings of similar cases that are retrieved using the S-CBR model (refer to assumption 2, *building-level*). Meanwhile, if the energy policy instrument (which attaches the building's EPCs to the contract documents in the building sale or rental process) cannot be successfully applied, the contract premium will not occur in the building sale or rental process (refer to assumption 3, *community-level*). In addition, if the EPC of a given building fails to contribute to the achievement of the national CERT, the taxation premium as the penalty program can be imposed on the public (refer to assumption 4, *national-level*). As a result, this study established four types of penalty programs by considering the aforementioned four assumptions. Detailed descriptions of four types of penalty programs are presented in SI Table S3, and the associated visualized charts are presented in SI Figures S6 to S9, respectively.

3. Development of the dynamic incentive and penalty program for improving the energy performance of existing buildings

In Section 2.1, this study analyzed the limitations on the conventional EPCs for existing buildings in terms of the comparison criteria. To address these limitations, as explained in Section 2.2, four types of incentive programs and four types of penalty programs were established based on three comparison criteria. As a building-level, the first comparison criterion is the averaging approach based on similar cases that can be retrieved using the S-CBR model. As a community-level, the second comparison criterion is one-step higher operational and letter rating than the grade of a given building. As a national-level, the third comparison criterion is the operational and letter rating as the minimum criteria for achieving the national CERT. Three comparison criteria can be developed based on the following processes and the associated equations.

3.1. Comparison criteria 1 (Building-level: averaging approach using the S-CBR model)

As one of the comparison criteria in the building's EPCs to establish the incentive and penalty programs, this study proposed the building-level comparison criterion (i.e., the averaging approach based on similar cases that are retrieved using the S-CBR model). The S-CBR model can be developed by combining the basic CBR approach with the optimization process using genetic algorithm (GA). Similarly, in the previous studies (Hong *et al.* 2012c, 2012d, 2012e, 2013b; Koo *et al.* 2011, 2013, 2014a; Lee *et al.* 2014), an advanced CBR (A-CBR) model was developed to predict the unknown value by combining the basic CBR approach with a filtering mechanism using artificial neural network (ANN) model and multiple regression analysis (MRA) model as well as the optimization process using GA. Although the A-CBR model was developed to solve the weakness of the basic CBR approach (i.e., its lower prediction accuracy compared to those of ANN and MRA models), the development process of the A-CBR model was very complicated. This is because the A-CBR model was developed for prediction. However, as it is required to develop the model for comparison, this study developed the S-CBR model to simplify the complicated process of the A-CBR model as well as to improve the prediction accuracy of the A-CBR model. SI

Figure S10 shows the detailed process for developing the S-CBR model and the associated equations. The S-CBR model can be used for establishing the building-level comparison criterion as the averaging approach, which can encourage the voluntary participation of the public in the energy-saving campaign. The comparison criteria 1 (building-level) can be established in the following three steps: (i) data collection; (ii) cluster formation using the decision tree (DT) method; and (iii) retrieval of similar cases using the S-CBR model.

3.1.1. Data collection

According to the guideline for the operational rating in UK (DCLG 2008, 2013; DECC 2013), this study defined the CO_2 emission density ($kgCO_2/m^2/yr$) as the dependent variable, which was used as the category benchmark in the building's EPCs. The CO_2 emission density can be established using two energy sources (i.e., electricity and gas energy consumption) which are mainly used in educational facilities in South Korea. Meanwhile, this study defined the project characteristics affecting the CO_2 emission density as the independent variables, which can be largely categorized into three types (i.e., location factor, building factor, and user factor) (Koo, Hong 2015). Table 1 shows the descriptive information on the independent variables and dependent variable. For example, the structure type was defined under the nominal scale, the elapsed years and the area per unit class were defined under the continuous scale, and the CO_2 emission density was defined under the continuous scale. Finally, this study collected the facility characteristics and energy consumption data from a total of 418 elementary schools located in Seoul, South Korea. Based on the collected data, this study developed the dynamic incentive and penalty programs for improving the energy performance of existing buildings.

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

Variables		Attributes	Detailed classification	Scale
Independent variable	Location factor	Administrative division	16 administrative division in South Korea	Nominal
	Building factor	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	Continuous
		Building area	( ) m^2	Continuous
		Number of stories	( ) stories	Continuous
		Total floor area	( ) m^2	Continuous
	User factor	Number of persons	( ) persons	Continuous
		Number of classes	( ) classes	Continuous
		Persons per unit area	( ) $persons/m^2$	Continuous
		Classes per unit area	( ) $classes/m^2$	Continuous
		Area per unit class	( ) $m^2/class$	Continuous
		Persons per class	( ) persons/class	Continuous
Dependent variable		CO_2 emission density	( ) $kgCO_2/m^2/yr.$	Continuous

3.1.2. Cluster formation using the DT method

Koo and Hong (2015) conducted the correlation analysis between the space unit size (i.e., area per unit class) and the CO_2 emission density, resulting in the negative correlation. This result indicated the irrationality of the operational rating in the conventional EPCs. To address this challenge, cluster formation was conducted using DT based on the space unit size (i.e., area per unit class). Since the dependent variable (i.e., the CO_2 emission density) was defined under the continuous scale, this study selected the CHAID (chi-squared automatic interaction detection) among various DT methods (Dahan *et al.* 2014). As a result, two clusters were established based on the space unit size (i.e., area per unit class) as the independent variable (refer to Table 2).

Table 2. Definition of the splitting criteria for the cluster formation

Classification	Number of cases	Independent variable (X) (the area per unit class)	Dependent variable (Y) (the CO_2 emission density)
Cluster 1	335	$X \leq 328.875$	23.759
Cluster 2	83	$X > 328.875$	19.813

3.1.3. Retrieval of similar cases using the S-CBR model

The S-CBR was developed in the following three processes: (i) Selection of similar cases using the basic CBR approach; (ii) establishment of the optimization process using GA; and (iii) establishment of the filtering engine.

(i) Selection of similar cases using the basic CBR approach

As expressed in Equation (1), the basic CBR approach can retrieve similar cases by considering the case similarity that can be calculated by the attribute similarity and the attribute weight. For the attribute similarity, if a given attribute is defined under the continuous scale, the attribute similarity can be calculated using Equation (2). The calculated attribute similarity should be more than the minimum criterion for scoring the attribute similarity (MCAS); otherwise, it is determined at 0. If a given attribute is defined under the nominal scale, when the attribute value of the given case is equal to that of the retrieved case, the attribute similarity can be considered 100; otherwise, it is determined at 0. Meanwhile, this study defined the attribute weights with a range of 0 to 100 in the optimization process using GA (refer to square (1) of SI Figure S10).

$$f_{CS}(m) = \frac{\sum_{i=1}^{n}\left(f_{AW_i} \times f_{AS_i}\right)}{\sum_{i=1}^{n}\left(f_{AW_i}\right)}; \tag{1}$$

$$f_{AS}(n) = \begin{cases} 100 - \left(\dfrac{\left|AV_{Test\_Case} - AV_{\mathrm{Retrieved}\_Case}\right|}{AV_{Test\_Case}} \times 100\right) & \text{if } f_{AS}(n) \geq f_{MCAS}(n) \\ 0 & \text{if } f_{AS}(n) < f_{MCAS}(n) \end{cases}, \tag{2}$$

where: f_{CS} stands for the function for calculating the case similarity; f_{AW} stands for the function for calculating the attribute weight; f_{AS} stands for the function for calculating the attribute similarity; n stands for the number of attributes; m stands for the number of cases; AV_{Test_Case} stands for attribute value of test case; $AV_{Retrieved\_Case}$ stands for attribute value of retrieved case; and f_{MCAS} stands for the function for calculating the *MCAS*.

As expressed in Equations (3) and (4), the average prediction accuracy (APA) and the mean absolute percentage error (MAPE) can be calculated using the actual value and the predicted value of the dependent variable:

$$f_{APA} = 100 - f_{MAPE}; \tag{3}$$

$$f_{MAPE} = \left(\frac{1}{m} \times \sum_{i=1}^{m} \left| \frac{AV_i - PV_i}{AV_i} \right| \right) \times 100, \tag{4}$$

where: f_{MAPE} stands for the function for calculating the *MAPE*; *AV* stands for the actual value of the dependent variable; *PV* stands for the predicted value of the dependent variable; m stands for the number of cases; and f_{APA} stands for the function for calculating the average the prediction accuracy:

(ii) Establishment of the optimization process using GA

Generally, GA can be used to find the optimal solution for the optimization objective (i.e., maximization of the prediction accuracy in this study). As shown in SI Figure S11, the following two types of optimization parameters were defined as the adjustable parameter of the optimization algorithm in the development process of the S-CBR model: (i) MCAS and (ii) RAW (the range of the attribute weight). As mentioned in Equations (1) and (2), the adjustable parameters (i.e., MCAS and RAW) were applied to calculate the case similarity. Meanwhile, in the CBR approach, the prediction result (i.e., the CO_2 emission density in this study) can be provided with the project characteristics of the retrieved cases as a reference. Thus, it is very important to determine the number of the retrieved cases. In this study, the final decision-maker can determine the selection rate (i.e., the number of the retrieved cases) in optimization process. The software program "Evolver" was used to conduct the optimization process using GA (refer to square (2) of SI Fig. S10).

- Adjustable parameter 1 (MCAS): This study defines the MCAS with a range of 0% to 100% as the adjustable parameter in the optimization process using GA, which is applied to calculate the attribute similarity.
- Adjustable parameter 2 (RAW): This study defines the RAW with a range of 0 to 100 as the adjustable parameter in the optimization process using GA, which is applied to determine the attribute weight.

(iii) Establishment of the filtering engine

According to the study of Koo *et al.* (2011), it was found that, in the CBR method, the relationship between the case similarity and the prediction accuracy is not always proportional. That is, although the case similarity of a given case is very high, the prediction accuracy of the given case can be extremely low (refer to the red line circle (A) of SI Fig. S12) or vice versa (refer to the blue line circle (B) of SI Fig. S12). Thus, a filtering engine should be established to sort out the similar cases with the high prediction accuracy among all the retrieved cases. As expressed in Equations (5) and (6), the filtering engine can be established using both the CO_2 emission density of a given building (*CDED(GB)*) and the *MAPE* of the *S-CBR* model (f_{MAPE}) (refer to square (3) of SI Figure S10). If the CO_2 emission density of a retrieved case exists between the minimum limit (*Min.Limit*) and maximum limit (*Max.Limit*) of the filtering engine, the retrieved case can be finally resorted out to establish the building-level comparison criterion.

$$Min.Limit = CDED(GB) \times \left(1 - \frac{f_{MAPE}}{100}\right); \tag{5}$$

$$Max.Limit = CDED(GB) \times \left(1 + \frac{f_{MAPE}}{100}\right), \tag{6}$$

where: *Min.Limit* stands for the minimum limit of the filtering engine for sorting out the similar cases with the high prediction accuracy among all the retrieved cases; *CDED(GB)* stands for the CO_2 emission density of a given building ($kgCO_2/m^2/yr$); f_{MAPE} stands for the function for calculating the *MAPE* of the *S-CBR* model; and *Max.Limit* stands for the maximum limit of the filtering engine for sorting out the similar cases with the high prediction accuracy among all the retrieved cases.

3.2. Comparison criteria 2 (Community-level: one-step higher operational and letter rating)

As one of the comparison criteria in the building's EPCs to establish the incentive and penalty programs, this study proposed the community-level comparison criterion (i.e., one-step higher operational and letter rating than the grade of a given building). If the energy policy instrument (which attaches the building's EPCs to the contract documents in the building sale or rental process) can be successfully applied, the contract premium for one-step higher operational and letter rating than the grade of a given building will occur in the building sale or rental process. This approach can encourage the voluntary participation of the public in the energy-saving campaign. The comparison criteria 2 (community-level) can be established in the following four steps: (i) data collection (refer to Section 3.1.1); (ii) cluster formation using the DT method (refer to Section 3.1.2); (iii) establishment of the category benchmark using the probability density function (PDF); and (iv) calculation of the dynamic operational rating using the category benchmark. The first two steps were explained in Sections 3.1.1 and 3.1.2.

3.2.1. Establishment of the category benchmark using the PDF

Koo and Hong (2015) established the category benchmark as the dynamic standard by applying the PDF of the CO_2 emission density, which can be developed using the software program "Crystal Ball". It was determined that the median values of the PDFs for clusters 1 and 2 were determined at 23.272 and 19.878 ($kgCO_2/m^2/yr$), respectively. These values can be used as the category benchmark (i.e., typical CO_2 emission density) (please refer to Koo, Hong (2015) if further understanding is required).

3.2.2. Calculation of the dynamic operational rating using the category benchmark

Koo and Hong (2015) calculated the dynamic operational rating of a given building by using the category benchmark established in Section 3.2.1 (refer to Equation (7)). For example, if the CO_2 emission density of a given building is equal to the category benchmark, the operational rating of the given building can be determined at 100. If the CO_2 emission density of a given building is twice as much as the category benchmark, the operational rating of the given building can be determined at 200. As explained in SI Table S1, the letter rating can be determined as one of seven grades (please refer to Koo, Hong (2015) if further understanding is required).

$$f_{DOR(GB)} = \frac{f_{CDED(GB)}}{Category\ \ Benchmark} \times 100, \tag{7}$$

where: $f_{DOR(GB)}$ stands for the function for calculating the dynamic operational rating of a given building; $f_{CDED(GB)}$ stands for the function of the CO_2 emission density of a given building ($kgCO_2/m^2/yr$); and *Category Benchmark* stands for the median value of the PDF in a cluster where a given building is included ($kgCO_2/m^2/yr$).

SI Figure S13 shows the dynamic operational rating of a given building included in cluster 1. This figure presents the dynamic operational rating (92.765), the letter rating (D grade), and the category benchmark (23.272 $kgCO_2/m^2/yr$). In this case, one-step higher operational and letter rating than the grade of a given building can be determined at the dynamic operational rating (75.0), the letter rating (C grade), and the CO_2 emission density (17.450 $kgCO_2/m^2/yr$).

3.3. Comparison criteria 3 (National-level: national CERT)

As one of the comparison criteria in the building's EPCs to establish the incentive and penalty programs, this study proposed the national-level comparison criterion (i.e., the operational and letter rating as the minimum criteria for achieving the national CERT). If the building's EPCs can successfully contribute to the achievement of the national CERT from a macroscopic view, the taxation premium such as carbon tax or progressive tax cannot be imposed on the public. This approach can encourage the voluntary participation of the public in the energy-saving campaign. The comparison criteria 3 (national-level) can be established in the following processes and the associated equations.

3.3.1. The national target of the CO_2 emission density in the future

This study collected the energy consumption data for the elementary schools from 1999 to 2010 provided by *Educational Statistical Yearbook* (KESS 2015). Based on the collected historical data, this study calculated the annual growth rate of the CO_2 emission density by using the concept of *compound annual growth rate (CAGR)*. The *CAGR* can be expressed in Equation (8), which stands for the average growth rate based on the assumption that a growth rate for several years maintains a certain growth rate every year. Next, this study analyzed the historical trends in the CO_2 emission density from 2011 to 2020 by using the value of *CAGR* (refer to Equation (9)). Finally, *the national target of the CO_2 emission* *density* (*nCDED*(t_f)) in 2020 can be estimated by applying *the national CERT (nCERT(t_f))* to *the CO_2 emission density (CDED (t_f))* in 2020 (refer to Equation (10)).

$$CAGR\ (t_0, t_p) = \left(\frac{CDED\ (t_p)}{CDED\ (t_0)} \right)^{\frac{1}{(t_p - t_0)}} - 1; \tag{8}$$

$$CDED\ (t_f) = CDED\ (t_p) \times \left(1 + CAGR\ (t_0, t_p)\right)^{(t_f - t_p)}; \tag{9}$$

$$nCDED\ (t_f) = CDED\ (t_f) \times \left(1 - nCERT\ (t_f)\right), \tag{10}$$

where: $CAGR(t_0, t_p)$ stands for compound annual growth rate (%) from year t_0 *(starting point)* to year t_p (present); $CDED(t_0)$ stands for the CO_2 emission density ($tCO_2/m^2/yr$) in year t_0 *(starting point);* $CDED(t_p)$ stands for the CO_2 emission density ($tCO_2/m^2/yr$) in year t_p (present); $CDED(t_f)$ stands for the CO_2 emission density ($tCO_2/m^2/yr$) in year t_f (future); $nCDED(t_f)$ stands for the national target of the CO_2 emission density ($tCO_2/m^2/yr$) in year t_f (future); and $nCERT(t_f)$ stands for the national CERT (%) in year t_f (future).

3.3.2. The improved national target of the CO_2 emission density in the future

The national long-term goal can be determined using Equations (8) to (10). However, the specific goal at this point should be established based on the national long-term goal to encourage the voluntary participation of the public. The specific goal at this point can be determined using the following Equations (11) to (13). First, *the CERT at this point (CERT(t_p))* should be established to calculate *the improved CO_2 emission density at this point (iCDED(t_p))* (refer to Equation (11)). Next, *the improved compound annual growth rate (iCAGR)* can be recalculated by considering the *iCDED(t_p)* (refer to Equation (12)). Finally, using the value of *iCAGR*, this study can estimate *the improved national target of the CO_2 emission density (inCDED(t_f))* (refer to Equation (13)):

$$iCDED\ (t_p) = CDED\ (t_p) \times \left(1 - CERT\ (t_p)\right); \tag{11}$$

$$iCAGR\ (t_0, t_p) = \left(\frac{iCDED\ (t_p)}{CDED\ (t_0)} \right)^{\frac{1}{(t_p - t_0)}} - 1; \tag{12}$$

$$inCDED\ (t_f) = iCDED\ (t_p) \times \left(1 + iCAGR\ (t_0, t_p)\right)^{(t_f - t_p)}, \tag{13}$$

where: $iCDED(t_p)$ stands for the improved CO_2 emission density ($tCO_2/m^2/yr$) in year t_p (present); $CDED(t_p)$ stands for the CO_2 emission density in year t_p (present); $CERT(t_p)$ stands for the CERT (%) in year t_p (present)*;* $iCAGR(t_0, t_p)$ stands for the improved compound annual growth rate (%) from year t_0 *(starting point)* to year t_p (present); $CDED(t_0)$ stands for the CO_2 emission density in year t_0 *(starting point)*; and $inCDED(t_f)$ stands for the improved national target of the CO_2 emission density in year t_f (future).

3.3.3. Establishment of the carbon emissions reduction target at this point

As shown in Equation (14), *the national target of the CO_2 emission density ($nCDED(t_f)$)* (refer to Equation (10)) should be equal to *the improved national target of the CO_2 emission density ($inCDED(t_f)$)* (refer to Equation (13)). Accordingly, using the aforementioned Equations (8) to (13), *the CERT for the CO_2 emission density ($CDED(t_p)$) at this point ($CERT(t_p)$)* can be calculated, which can be expressed in Equation (15):

$$nCDED\left(t_f\right) = inCDED\left(t_f\right); \tag{14}$$

$$CERT\left(t_p\right) = 1 - \left(1 - nCERT\left(t_f\right)\right)^{\left(\frac{t_p - t_0}{t_f - t_0}\right)}, \tag{15}$$

where: $nCDED(t_f)$ stands for the national target of the CO_2 emission density ($tCO_2/m^2/yr$) in year t_f (future); $inCDED(t_f)$ stands for the improved national target of the CO_2 emission density ($tCO_2/m^2/yr$) in year t_f (future); $CERT(t_p)$ stands for the CERT (%) in year t_p (present); and $nCERT(t_f)$ stands for the national CERT (%) in year t_f (future).

Meanwhile, South Korea established 30% of GHG emissions reduction by 2020 as the national CERT; and 26.9% for the building sector. Therefore, using Equation (15), $CERT(t_p)$ was determined at 15.14% by applying 26.9% to $nCERT(t_f)$. Namely, the specific goal at this point was determined at 15.14%, which can achieve the national-level target.

4. Results and discussion

This study developed the dynamic incentive and penalty program for improving the energy performance of existing buildings by considering the various comparison criteria. This study conducted the detailed analysis on the prediction performance of the developed S-CBR model as the averaging approach and validated the applicability of the developed incentive and penalty programs through the case study.

4.1. Validation of the prediction performance of the S-CBR model

This study compared the prediction performance of the S-CBR model to those of the other models which were often used in previous studies (i.e., MRA, ANN, CBR, and A-CBR models). Table 3 shows the comparison of the prediction performance by model (i.e., the average prediction accuracy and the standard deviation of the prediction accuracy). The results showed that the average prediction accuracy of the S-CBR model was superior to those of the other models in all the two clusters: 82.678% for cluster 1 and 80.575% for cluster 2. In addition, the standard deviation of the prediction accuracy was superior to those of the other model in all the two clusters: 14.991% for cluster 1 and 16.050% for cluster 2. Compared to the MRA, ANN, CBR, and A-CBR models, it was determined that the prediction performance of the S-CBR model was improved. As a result, the S-CBR model simultaneously obtained the advantage of the MRA and ANN models (i.e., excellent prediction accuracy) as well as the advantage of the CBR model (i.e., prediction result can be provided with the project characteristics of the retrieved historical cases as a reference). Therefore, it is believed that the S-CBR model is suitable for establishing the comparison criterion as the averaging approach in developing the dynamic incentive and penalty program.

Table 3. Comparison of the prediction performance by model

Model	Cluster 1		Cluster 2	
	APA[a]	SDPA[b]	APA	SDPA
MRA[c] model	81.129	19.546	74.686	26.300
ANN[d] model	80.701	20.013	78.510	30.522
Basic CBR[e] model	72.652	34.455	63.045	39.294
A-CBR[f] model	82.364	18.318	78.584	30.077
S-CBR[g] model	82.678	14.991	80.575	16.050

Note: [a]*APA* stands for average prediction accuracy; [b]*SDPA* stands for standard deviation of prediction accuracy; [c]*MRA* stands for multiple regression analysis; [d]*ANN* stands for artificial neural network; [e]*CBR* stands for case-based reasoning; [f]*A-CBR* stands for advanced cased-based reasoning; and [g]*S-CBR* stands for simplified cased-based reasoning.

4.2. Case study for incentive programs

Using the test case included in the incentive zone (i.e., letter rating is "*D*"), the model application was conducted to validate the applicability of the developed incentive programs.

SI Table S4 shows the project characteristics of the test case and the associated five similar cases that are retrieved using the S-CBR model. The average value of the operational ratings of the retrieved cases can be calculated at 102.397. Figure 1 shows the dynamic operational rating of the test case (92.765) and three comparison criteria: (i) comparison criteria 1 (building-level): averaging approach (102.397); (ii) comparison criteria 2 (community-level): one-step higher operational and letter rating (75.0 and C grade); and (iii) comparison criteria 3 (national-level): national CERT (78.723). According to the following descriptions (refer to SI Table S2), it was determined that the test case was included in "*Type I-1*" of incentive programs.

- Based on the assumption 1, the operational rating of the test case (92.765) is "*below*" 100 (i.e., incentive zone).
- Based on the assumption 2, the operational rating of the test case (92.765) is "*less*" than the average value of the operational ratings of the similar cases retrieved using the S-CBR model (102.397) (i.e., incentive available).
- Based on the assumptions 3 and 4, one-step higher operational and letter rating than the grade of the test case (assumption 3) (75.0 and C grade) is "*less*" than the operational rating as the minimum criteria for achieving the national CERT (assumption 4) (78.723).

Since the test case is included in "*Type I-1*" of incentive programs, it can obtain the carbon point as much as the saving rate as an incentive based on the comparison criteria 1 (building-level: averaging approach). However, if the test case is applied to the conventional

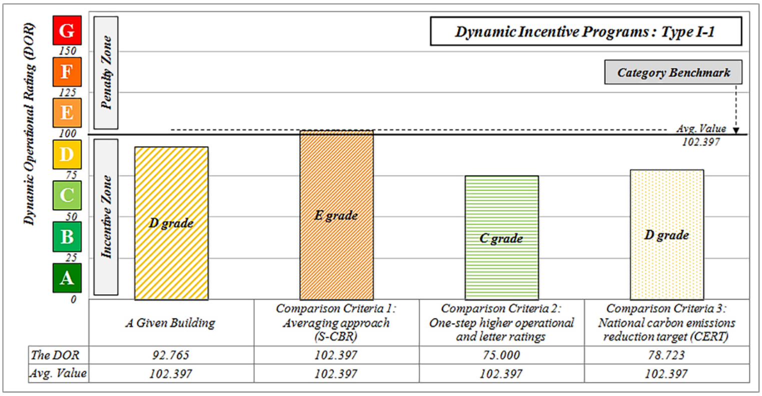

Fig. 1. Comparison chart for the incentive programs (the operational rating)

carbon point system, which uses the historical energy consumption of a given building (CPS 2015; GCCS 2015; GT 2015; Koo *et al.* 2014a), it may not obtain such carbon point because its energy saving potential is very small. This result means that there is the irrationality of the conventional carbon point system. Meanwhile, if the test case can achieve the comparison criteria 2 (community-level: one-step higher operational and letter rating) (75.0, C grade) in the following year, it will not only get the contract premium as an incentive but be also exempted from the taxation premium as a penalty. On the other hand, if the test case can merely achieve the comparison criteria 3 (national-level: national CERT) (78.723) in the following year, it will not get the contract premium as an incentive but be exempted from the taxation premium as a penalty.

SI Figure S14 shows the actual value of the CO_2 emission density of test case (21.266 $kgCO_2/m^2$/yr.) and three comparison criteria: (i) comparison criteria 1 (building-level): averaging approach (23.474 $kgCO_2/m^2$/yr.); (ii) comparison criteria 2 (community-level): one-step higher operational and letter rating (17.193 $kgCO_2/m^2$/yr. and C grade); and (iii) comparison criteria 3 (national-level): national CERT (18.047 $kgCO_2/m^2$/yr.). Since the actual values of three comparison criteria can be easily recognized, it can encourage the voluntary participation of the public in the energy-saving campaign.

4.3. Case study for penalty programs

Using the test case included in the penalty zone (i.e., letter rating is "*F*"), the model application was conducted to validate the applicability of the developed penalty programs.

SI Table S5 shows the project characteristics of the test case and the associated three similar cases that are retrieved using the S-CBR model. The average value of the operational ratings of the retrieved cases can be calculated at 137.079. Figure 2 shows the dynamic operational rating of the test case (130.391) and three comparison criteria: (i) comparison criteria 1 (building-level): averaging approach (137.079); (ii) comparison criteria 2 (community-level): one-step higher operational and letter rating (125.0 and E grade); and (iii) comparison criteria 3 (national-level): national CERT (110.653). According to the following descriptions (refer to SI Table S3), it was determined that the test case was included in "*Type P-2*" of penalty programs.

- Based on the assumption 1, the operational rating of the test case (130.391) is "*over*" 100 (i.e., penalty zone).
- Based on the assumption 2, the operational rating of the test case (130.391) is "*less*" than the average value of the operational ratings of the similar cases retrieved using the S-CBR model (137.079) (i.e., penalty not available).
- Based on the assumptions 3 and 4, one-step higher operational and letter rating than the grade of the test case (assumption 3) (125.0 and E grade) is "*more*" than the operational rating as the minimum criteria for achieving the national CERT (assumption 4) (110.653).

Since the test case is included in "*Type P-2*" of penalty programs, it should turn in the carbon point as much as the increase rate as a penalty based on the comparison criteria 1 (building-level). However, if the test case is applied to the conventional carbon point system, which uses the historical energy consumption of a given building, it may not turn in such carbon point because its energy saving potential is very large. This result means that there is the irrationality of the conventional carbon point system. Meanwhile, if the test case can achieve the comparison criteria 3 (national-level: national CERT) (110.653) in the following year, it will be not only exempted from the taxation premium as a penalty but also get the contract premium as an incentive. On the other hand, if the test case can merely achieve the comparison criteria 2 (community-level: one-step higher operational and letter rating) (125.0, E grade) in the following year, it will be not exempted from the taxation premium as a penalty but get the contract premium as an incentive.

SI Figure S15 shows the actual value of the CO_2 emission density of test case (29.891 $kgCO_2/m^2/yr.$) and three comparison criteria: (i) comparison criteria 1 (building-level): averaging approach (31.425 $kgCO_2/m^2/yr.$); (ii) comparison criteria 2 (community-level): one-step higher operational and letter rating (28.656 $kgCO_2/m^2/yr.$ and E grade); and (iii) comparison criteria 3 (national-level): national CERT (25.367 $kgCO_2/m^2/yr.$). Since the actual values of three comparison criteria can be easily recognized, it can encourage the voluntary participation of the public in the energy-saving campaign.

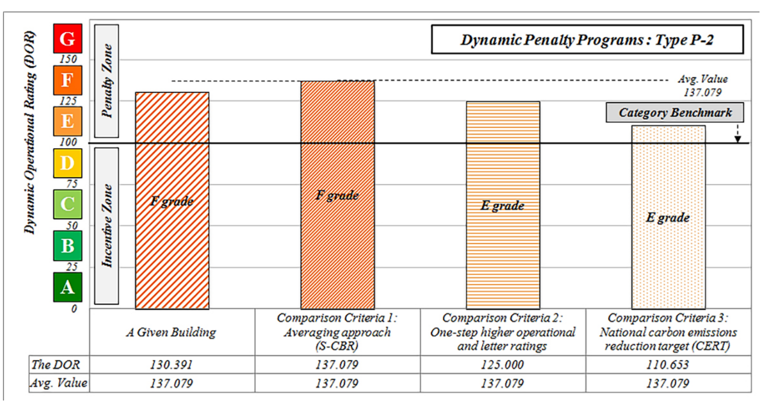

Fig. 2. Comparison chart for the penalty programs (the operational rating)

Conclusions

This study aimed to develop the dynamic incentive and penalty program for improving the energy performance of existing buildings. Four types of incentive programs and four types of penalty programs were established based on three comparison criteria (i.e., building-level, community-level, and national-level). In this study, an elementary school facility located in Seoul, South Korea, was selected to validate the applicability of the developed program. The main findings can be summarized as follows.

First, it was determined that the prediction performance of the S-CBR model as the averaging approach was improved, compared to those of the MRA, ANN, CBR, and A-CBR models. As a result, the S-CBR model simultaneously obtained the advantage of the MRA and ANN models (i.e., excellent prediction accuracy) as well as the advantage of the CBR model (i.e., the prediction result can be provided with the project characteristics of the retrieved historical cases as a reference). It can be concluded that the S-CBR model is suitable for establishing the comparison criterion as the averaging approach in the dynamic incentive and penalty program.

Second, besides the category benchmark, various comparison criteria should be provided to the public to encourage the voluntary participation of the public in the energy-saving campaign. The results of the case study can be summarized below:

- (i) Incentive programs: Since the test case is included in "*Type I-1*" of incentive programs, it was concluded that the test case can obtain the carbon point as much as the saving rate as an incentive based on the averaging approach. However, if the test case is applied to the conventional carbon point system, the test case may not obtain such carbon point because its energy saving potential is very small, which comes from the irrationality of the conventional carbon point system.
- (ii) Penalty programs: Since the test case is included in "*Type P-2*" of penalty programs, it was concluded that the test case should turn in the carbon point as much as the increase rate as a penalty based on the averaging approach. However, if the test case is applied to the conventional carbon point system, the test case may not turn in such carbon point because its energy saving potential is very large, which comes from the irrationality of the conventional carbon point system.

In conclusion, this study analyzed the irrationality of the conventional carbon point system from the perspective of the comparison criteria. Various types of comparison criteria were used to develop the dynamic incentive and penalty program for improving the energy performance of existing buildings and for encouraging the voluntary participation of the public in the energy-saving campaign. Meanwhile, it is required to collect their own data (e.g., building characteristics, user information, and actual energy consumption data by energy source) so as to implement the developed dynamic incentive and penalty program to any other country or sector in the global built environment. These data can be commonly available for the different countries, which can be collected from the facility managers, energy service providers, and government agency. For example, EU countries can collect the aforementioned data based on the European Project "*TABULA – EPISCOPE*" as an important typological collection of building energy consumption data. The EPISCOPE aims to make the energy retrofit processes in the European housing sector to be more transparent and effective. This project will contribute to ensure whether or not the climate protection targets will be achieved (IEEP 2014, 2015). In addition, based on the latest technology such as internet of things and smart sensing technology, the real-time energy consumption data can be used in establishing the dynamic incentive and penalty program, which can be connected to the energy consumption patterns of the occupants. Moreover, agent-based modeling can be used to accurately reflect how the dynamic incentive and penalty program really works and to analyze the impact of the dynamic incentive and penalty program on the behaviour patterns of occupants. Consequently, the developed program can be used as an energy policy instrument to enable policymakers to establish the reasonable incentive and penalty program for improving the energy performance of existing buildings. Also, a visualized chart for intuitive decision-making can enable the public to be clearly aware of the existing building's energy performance.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP; Ministry of Science, ICT & Future Planning) (No. NRF-2015R1A2A1A05001657).

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