Determining sustainable design management using passive design elements for a zero emission house during the schematic design

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Abstract

There is an increasing trend toward building energy-saving and zero-carbon-emission house worldwide. Even if diverse sustainable technologies have been developed and adopted, existing design strategies are decided intuitively by an expert's qualitative evaluation and not by objective, quantitative design guidelines. The present study analyzes passive design elements (PDEs) from existing sustainable housing projects as a method for quantitative evaluation. PDEs could be suitable methods to house owner who does not have professional knowledge in construction of zero emission house (ZEH).

Extracted PDEs are analyzed by an analytic hierarchy process (AHP) to determine which PDEs are applicable for limited budgets. Through the AHP, PDEs are re-sorted based on the order of importance weight and predominant 7 PDEs are determined. Due to characteristic of passive house which envelops the house from outside environment, PDEs would be applied before design of house structure. Therefore predominant PDEs could be considered first when the zero emission house (ZEH) is developed. The proposed sustainable design management (SDM) based on PDEs would be profitable for decision-making during the schematic design phase, which is an important stage in selecting suitable design elements in ZEH construction, because environmental engineer or consultant could not be involved from early stage. With the utilization of SDM consisting of PDEs, potential ZEH clients could easily launch their ZEH project without early involvement of sustainable expert. Taking account of energy consumption in residential sector, application of SDM has a significant contribution for substantial carbon reduction.

Author keywords: Analytic Hierarchy Process, Design Management, Passive Design, Zero Emission House.

Introduction

Humankind is currently facing an unprecedented challenge, global warming. The building environment is one of the main sources of carbon emissions related to global warming [1]. Since Gunter Pauli's advocacy of the zero-emission concept in 1994, various industries have followed the zero-emission theory. The theory's principles also have been adopted in the construction industry as a concept for a ZEH. According to Mohamed and Alistair [2], reducing the carbon emissions in the housing sector would be an effective way to mitigate global warming. Lee and Burnett [3] also argue that the building sector accounts for 31% of the total energy consumption worldwide, and the residential sector accounts for over half of the energy consumption in the building sector. In detail, according to European Environmental Agency [4], 12% of greenhouse gas emissions are generated only in residential sector.

Numerous studies on reducing the carbon emissions have been conducted in the ZEH field. There is mounting literature on the use of hybrid heating, ventilation, and air conditioning (HVAC) systems as one of the main parts of a ZEH [5-6]. Because of advances in technology hybrid HVAC systems are now widely applied in the housing industry, from a single house to a large apartment complex. Material has also been main field of study for ZEH [7]. Maria and Justo [8] stressed that approximately 30% of total carbon emissions can be reduced through the selection of low environmental impact materials. According to the study of Harn and Chee [9], the maintenance phase accounts for over 80% of total carbon emissions during the building life cycle compared to the other phases, such as the construction or design phase. Therefore, energy saving designs that can directly reduce carbon emissions throughout the building maintenance phase has been studied. Because PDEs do not generally incur additional operating costs once they are installed, they are the design factors that have the greatest long-term effect on the maintenance phase [10-11].

PDE could be a practical and efficient solution for energy efficiency. Because passive design uses environment such as solar, wind, or geothermal energy, they need small amount of extra energy from energy grid. Moreover, because, passive design focusses on keeping energy with passive method including insulation, air-tight envelope, or thermal material, they also do not need complicated operation. Therefore, in considering above characteristic, PDE is suitable way for ZEH.

Substantial research on ZEH using PDEs has been conducted by Wang et al. [12]. They argue that the most critical factors are PDEs for reducing carbon emissions, although studies of integrated design technology combined with active and renewable design have been increasing. Suresh et al. [13] also assert the crucial role of PDEs in zero-emission or energy-saving housing by demonstrating the practical efficiency for each PDE. They strive to conduct exhaustive research on the building envelope components through technical reviews of the recent developments in various building envelopes and their energy efficiencies. Aksoy and Inalli [14] also studied the building orientation and shape as practical passive parameters. They demonstrated the importance of building orientation and shape to extract solar energy effectively.

Many studies have tended to demonstrate the practical efficiency of only one or two PDEs. The efficiency of such PDEs, however, cannot be studied individually. Jordan et al. [15] focused on realizing an integrative engineering system for energy efficient houses. Through quantitative tests, they demonstrated several factors that have practical effects on saving energy during the building maintenance phase. Lee [16] addressed the hybrid system as an integrative system between passive and active design factors. They argue that a combined design based on the relationship between fluctuating outdoor conditions and the HVAC system is a crucial factor for effective energy performance. Antvorskov [17] also examined the integrative system that is most suitable for energy performance of a building, and he demonstrated his argument practically with experimental research on hybrid ventilation systems.

Even with diverse research on ZEH and passive design, studies that systemically examine design management for ZEH are very rare. In most cases, just like the aforementioned studies, PDEs tend to be studied unsystematically [18]. Few studies have focused on systemic design management or integration of design parameters. Among these few studies, the research by Mazouz and Zerouala [19] is notable. They insist that integration of design elements can have a substantial effect on the efficiency of individual PDEs.

Moreover, in a number of ZEH projects, PDEs are selected intuitively; the choice for a specific component is mostly based on the intuition and experience of the designer. However, intuition and experience are neither absolute nor objective. A recent study of design-based projects revealed that 80%-90% of design components are selected without methodical consideration of an alternative [20]. The establishment of energy-saving strategies has been decided based on the vocational background and experiences of experts in the housing construction industry [21]. Therefore, appropriate and methodical design strategies should be required not only systemically but also syntagmatically. Moreover, because of the lack of expertise on PDEs, appropriate design strategy have not been established from early stage. In This research, importance of each PDE is analyzed by AHP for establishment of pertinent design strategy, AHP supports decision-maker in determining the priority of the decision through a quantification the importance of survey that target experts [22]. By adoption of AHP, surveyed PDEs would be objective and consistent.

Research Methodology

This research adopts a compositely methodological approach, consisting of the analysis of previous studies, a questionnaire survey, and follow-up computational analysis. From the analysis of previous studies, a total of 31 projects are considered as sample projects focusing on energy-saving engineering. Only housing projects that have an environmental purpose, utilize passive ways, or are built by eco-friendly construction methods, are considered. Among the 31 sample projects, 5 projects are developed as eco-friendly housing supported by the government, while 4 sustainable housing projects are conducted by housing provider as an experimental exhibition house to lead the passive housing market (Table 1).

Sample projects are selected from different countries which consist of leading countries including Europe and Japan and promising countries such as USA and Korea. They have also different environment and building codes. However, because, most sites are located in temperate climate regions, environmental differences following climate are not severe. Therefore, even if there is slightly design practices among countries, required sustainable elements are similar each other between USA (LEED) and UK (BREEAM).

Insert < Table 1. Sampling of sustainable housing projects > here

The questionnaires are designed based on findings of the analysis of previous studies to validate dominant PDEs and the order of importance of PDEs recognized by experts working in the housing industry. The questionnaire contains three main sections: energy saving, bio-climate, and energy acquisition. The questionnaire is designed to investigate the validity of practical evidence and preference surrounding the energy saving and carbon emission themes during the schematic design phase.

The survey participants are divided into three main sections in accordance with their working experience and professional knowledge: building designer, general contractor, and environmental consultant including engineer and sustainable engineer. They have accumulated various data and practical performances from real cases. In addition, they could predict suitable PDEs even before full drawings through their vocational experiences and knowledge.

In this research, a total of 30 experts validate appropriate factors with respect to selected PDEs. These experts are involved in 22 architectural firms, contractors, engineering firms, or environmental consultant companies and have been involved in building projects, including sustainable housing, for an average of 11.3 years. All of companies are ranked within top 25 respectively in their own business fields. All participants consist of senior directors (3), directors (2), senior managers (7), managers (12), and assistant managers (6).

A computationally intensive statistical method is utilized to analyze the quantitative questionnaire data. AHP analysis based on questionnaire is used as a main methodology in this research. And then result of AHP is repeatedly dealt with by computational analysis program, Expert Choice to increase the accuracy and consistency. This is means of determining importance values to assign weighting based on the knowledge of human experts. Through the repeated comparisons, the participants can use an actual case for the factors, or can use their judgments about the elements' relative meaning and importance [23]. In order to test the reliability of the results, the data are re-checked against major inconsistencies from the original data.

Factors affecting project success

Accurate identification of project factors could be useful to judge the reason for project success or failure. An abundance of theoretical and empirical research has been conducted since the 1960s on factors that affect a project's success. Hayfield [24] established two critical factor categories to determine if a project will be successful: macro and micro factors. The macro factors include a thorough definition of the project, an efficient method for project implementation, and comprehension of the project environment. On the other hand, the micro factors include formulation of project policies, clear and simple project organization, efficient management control, and reliable management system. In addition, according to Belassi and Tukel [25], critical factors affecting project success can be classified into four main groups: the project, project manager, organization, and external environment.

Based on the above review, it is clear there are diverse factors that critically impact a project. Furthermore, thorough recognition of respective project factors is more important to the success of a project. The present study examines PDEs in greater detail, the role of carbon reduction and practical preference.

Selection procedure and initial PDEs

Factor selection

There are criteria for the practical review of energy-saving housing projects. Firstly, recent projects built from early 1990 to 2011 are reviewed to collect effective elements, which can be applicable in the near future. Secondly, even if housing projects are developed for an environmental purpose or by sustainable methods, excessively large projects having over 200 units are excluded from the review. This is because many design factors installed in large-sized housing projects have basic differences in their application.

According to the Kimberly et al. [26], classification standard, most energy-saving elements can be divided into three main categories: passive design elements (PDEs), active design element, and renewable energy elements. Among these three categories, PDEs have the strongest effect on energy performance throughout the maintenance phase [13,27-28]. Although a passive concept is dominant, all of the hybrid and integrated concept-based design elements are excluded from PDEs, because it is too difficult to judge which of the elements relates most significantly to efficiency if they each have a distinct effect on reducing carbon emissions. Hence, only definite PDEs are considered.

Finally, 36 PDEs are classified from 31 sample projects. Even if absolutely enormous PDEs are utilized in 31 sample projects, selected PDEs are adopted at least 3 different projects. This means that selected 36 PDEs could be adopted extensively even diverse regions. In addition, lots of PDEs belonging to 36 PDEs have been researched in academic fields as mention in Introduction.

Although other effective design elements which are not dealt with in this research are included in renewable energy and active design, only 36 elements are considered as PDEs in this study. These elements are re-classified into 20 PDEs through the filtering process such as Material analysis, Design process analysis shown in Fig. 1.

Most of all, among 36 PDEs, some PDEs that are less related to energy saving or reducing carbon emissions are excluded. Although, for example, biotope is one of the important elements in sustainable housing, it was excluded because biotope does not have a direct relationship with energy-saving or reducing carbon emissions [29].

Insert < Fig 1. Factor selection process > here

Secondly, through the Material analysis, factors which use similar material are merged into a single design element. For example, a green roof, roof plant, sedum roof, and moss roof have very similar material as well as construction costs [30]. Lastly, through the Design process analysis, factors having similar design processes are also combined as one design element. High-efficient window factor, vacuumed glazing window factor, and triple glazing window factor can be combined as one PDE, because they have very similar insulating performance as well as detail design.

PDE data description

As a result of the data filtering, 20 PDEs are selected to calculate their own importance. All of the factors can be mainly divided into three categories; energy saving, bio-climate, and energy acquisition although they have their own individual characteristics.

Insert < Table 2. 20 Selected PDEs description > here

Currently sustainable PDEs focus more on the energy saving element than responding to bio-climate or energy acquisition elements, as shown by the analysis results in Table 2. From the economic perspective of the house owner, a more attractive way for protecting the environment is energy saving. Through energy saving, not only the energy cost of a house, but also carbon emissions could be reduced [31].

Therefore, if PDEs are recognized as applicable and considerable for ZEH at low application cost, PDEs could be quite positive proposal to potential clients who are intending to construct ZEH. Even if some PDEs, such as solar panels, solar mirror lights or double skin, require special installation, PDEs are generally applied within the building itself, which means that they do not need complex installation equipment after the building has been erected. Moreover, many parts of PDEs are closely related with the building design, such as a sunroom, window and building orientations, and zoning plan, which are decided during the schematic design phase. Thermal and building insulation techniques in particular are the dominant part of many PDEs. From the perspective of cost-effectiveness and work feasibility, the 20 selected PDEs are evaluated and then, all of the PDEs are enumerated in order of importance alongside the relevant function.

Analytic hierarchy process (AHP)

AHP method as a one of the decision elements is performed using a scale of weight, to generate the input data. Several scale of comparison simulates most closely human decision making when comparing objects [32]. Since the first introduction by Saaty [23], AHP have dealt with complex problems as a new approach, which often involves a great deal of uncertainty. AHP provides a simple process for weighting portions of the hierarchy that cannot be enumerated directly. This model extracts expert knowledge that can guide effective cognition of useful weights. AHP uses a hierarchy to represent a decision problem and then develops priorities for the alternatives based on the participant's judgments throughout the model [23,33]. Once the hierarchy is built, the participants systematically evaluate its various elements by comparing them such as pairwise comparison. Since the main advantage of this approach is a possibility to compare the criteria in pairs rather than all at a time. This method also allows the conversion of qualitative estimates elicited from experts to quantitative estimates, implying that the values of the criteria weights can be calculated [34]. However, AHP do not apply to problems that have resource feasibility, and optimization requirement. In spite of this limitation, the advantages of AHP are that it is relatively easy to use, very simple, allows for rapid re-planning, can incorporate qualitative and subjective factors, and provides a methodology to measure the consistency of these judgements [35].

Factor weight calculation

The important weights of the 20 selected PDEs are calculated. A pairwise comparison method used for the importance weight of PDEs is based on the statistical data on the criteria describing the compared alternatives or expert estimates [36]. Estimation of the exact efficiency of each PDE is very difficult, even though there is a distinct positive influence on energy consumption with integrated PDEs. The first step of the analytic hierarchy process (AHP) is to classify a hierarchy by organizing the problem. The next step is to evaluate the relative importance of the factors with respect to the overall objective using a set of pairwise comparison matrices.

A total of 570 question sections are designed to be closed-ended questions using a scale from '0' (lowest level) to '17' (highest level). The experts select one element that seems to be more important corresponding to the factors being compared, giving a subjective judgment by their vocational experience and knowledge. According to the degree of importance of the chosen element, the scale of importance of each PDE is estimated.

The last step is that the AHP measures the overall consistency of judgments by means of a consistency ratio (CR). The CR provides a way of measuring how many errors were created when providing the expert judgments. If the CR is below '0.1', the errors are fairly small and thus, the final estimate can be accepted [37]. If it is more than '0.1', the judgments may be somewhat random and should perhaps be revised. This was proposed by Saaty [23] to measure the inconsistency in the pairwise comparison using Eq 1. The CR equals is given by division of CI by random consistency index (RI). The RI value depends on number of compared factors. RI values for different numbers of factors are presented in Table 3.

C= $\frac{\mathrm{CI}}{\mathrm{RI}}$…………………….(Eq. 1)

where CR is consistency ration, CI is consistency index, and RI is random consistency index.

Insert < Table 3. Random consistency index (RI) [33] > here

The value of the CI is calculated using Eq 2. [37]

CI= $\frac{(\lambda_{\max} - n)}{n - 1}$ ……………...(Eq 2)

Where n is the number of compared factors, and λ_{max} is the maximum eigenvalue of a judgment matrix which corresponds to the group of compared factors.

An appropriate CR value justifies extracting expert knowledge that can guide effective cognition of useful weights. Therefore, after CR checking, if the figures present inconsistent results, judgment should be repeated. This is because the selected alternatives have their own importance weight following the results of the data calculation based on the expert's choice. The priority of the PDEs, which would be considered and applied to the practical ZEH construction, is presented as a concrete figure according to each weighted result.

Among the 20 PDEs, the top seven elements are southern window+northern facade insulation, natural ventilation, air-tight structure, triple-pane glazing/ vacuum glazing window, external insulation system, zoning Plan, and double skin element, as seen in Table 4. These top elements are also top ranked in the priority results, except for the airtight structure element; this result based on multiple selections from the experts, is utilized as back-data for the final estimation of the PDEs importance weight.

Insert < Table 4. 20 Selected PDEs and Weight > here

According to the report of the Passive House Institution [38], generally four to six PDEs are applied to construct each energy-saving house. Moreover, the Building Research Establishment (BRE) examined seven PDEs to explain the characteristics of their experimental houses in BRE Innovation Park. This means that, five to seven PDEs would be considered when constructing a ZEH, owing to the cost-efficiency aspect [39]. In addition, only the top seven elements are dominant as compared to other PDEs in this research, as seen in Table 4. Therefore, this research also focuses on the top 7 PDEs.

Even if, another design element can be added or subtracted from this list owing to a limited budget or the client's preference, it is reasonable to predict that the PDEs could be considered and applied in the same order as presented in Table 4 in almost all cases of passive concept based ZEH. Moreover, some elements that conventionally have been utilized in zero-emission houses such as a roof garden, solar panels, and sun-rooms are not highly ranked as critical factors for PDEs. This result shows that in accordance with complicated equipment in housing, design preferences have been shifting from conventional elements in ZEH.

Design management using PDEs

Involvement during schematic design phase

Almost all PDEs investigated in this research are closely related to building structure and shape, unlike installation of sustainable equipment that should be added after construction of the basic structure. Sustainable design applied during the schematic design phase is more efficient than adaptation during the design development stage by at least 15% for energy saving in a building [40]. For example, some PDEs that are ranked within top seven elements, such as southern window+northern facade insulation, natural ventilation, zoning plan elements, should be considered and determined during the schematic design phase. As these kinds of elements strongly influence building shape and size, they are directly related to construction costs as well as energy performance [41].

As seen in Table 4 (Red bar graph), one-third of the PDEs are directly related to the basic building structure and housing shape or size. Although other PDEs also are related to the building structure, the degree of influence on building structure is negligible in terms of construction costs and period, because these PDEs could be applied without complicated installation after completion of the basic building structure. This means that because of the distinct characteristics of the passive design concept that utilize minimum equipment installation, numerous PDEs could be considered and applied during the schematic design phase [42-43]. Moreover, when considering the size of or budget for a residential building, residential building does not require quietly complicated or diverse equipment. Almost all PDEs are applied before the designer plans the basic building structure or shape or the designers determine the area or volume of housing.

Description of top seven PDEs

Among the top seven elements, three elements belong to the bio-climate category and the remaining four elements belong to the energy saving category. This result indicates that in terms of the passive design concept, the most important factors are not related to energy acquisition but those related to energy saving, such as high efficiency windows or insulation systems. These seven PDEs pertain not to how required energy can be acquired artificially, but to how they can be harmonized with the environment and building itself.

Southern window+northern façade insulation, natural ventilation, and zoning plan factor are strongly related to basic architectural design following the environmental conditions. On the other hand, other factors such as air-tight structure, triple-plane glazing/vacuum glazing window, external insulation system, and double skin are related to energy saving through creation of an effective building envelope.

- Southern window+northern façade insulation: windows are installed facing a southern direction to allow as much solar energy as possible, and northern walls are insulated against the harsh wind from the north during the winter season [44].
- Natural ventilation: Concept is similar to the southern window+northern façade insulation. Taking wind direction and speed into consideration, indoor air quality could be improved using an appropriate open plan [45-46].
- Zoning plan: This element is associated with architectural design. To achieve highly efficient heating, the housing plan is divided into three main sections: heating zone, non-heating zone, and buffer zone. The main living space, including the living room and bed room, belongs to the heating zone, and these rooms are designed adjacent to each other. Subsidiary spaces, which do not need heating, such as corridors or utility spaces are allocated together as the non-heating zone.
- Air-tight structure: This factor is related to the construction method for preventing heat conduction between the interiors and exteriors [47]. A heat-bridge and cold-bridge could be prevented through the incentive external wall construction during summer and winter seasons. Even a small part could influence the air-tightness of the entire building.
- Triple-plane glazing/vacuum glazing window: This factor is also similar to the air-tight structure. However, this factor only focuses on the window material instead of

the external wall, because most of the thermal bridges occur through windows; nevertheless, the window area generally accounts for 16% -20% of the total building envelope [48]. For this factor, indoor temperature is maintained by utilizing highly effective window materials.

- External insulation: This factor is related to the method of installing insulation. There are three main insulation installation methods: inside insulation, central insulation, and outside insulation [49]. In terms of energy saving, the most efficient measure among the three insulation methods is external insulation. Because of external insulation, the building structure is not exposed to the outside environment, which prevents contraction and expansion of the building structure, one of the main reasons for the thermal bridge [50].
- Double skin: This factor is similar to the external insulation factor. Currently, numerous housing projects are constructed as high-rise buildings, especially in Asia. Herein, the external wall shifts to curtain wall construction using material such as metal or window panels. In a building with curtain wall construction, the double skin system controls the solar radiation and indoor temperature [51-52]. During the summer season, indoor-air quality is improved by discharging warmed air within a buffer zone between the double skins. When warmed air is discharged to the outside, indoor air is also discharged simultaneously. Conversely, through the inflow of warmed air indoors from the buffer zone, energy costs could be reduced in the winter [53]. Moreover, a double skin shade could not only prevent inflow of direct solar radiation but also acquire solar heat from solar panels.

Sustainable design management (SDM)

During the schematic design phase, a designer does not ensure whether certain PDEs applied to the project have essential influence on energy performance. The prediction of practical cost-effective is very difficult for designers and clients when they set carbon emission level during the schematic design phase.

Even if equipment engineers are involved during the schematic design phase, they cannot provide concrete energy-saving strategies as there are no tangible design drawings for selecting suitable PDEs. In addition, involvement of sustainable engineer from early stage is reason of increasing initial cost. Therefore, sustainable design management guides are required to clients in many cases of ZEH. In some case, however, PDEs are excessively adopted without any organized design strategy. Even if installed equipment is the latest one, performance of equipment is not efficient.

Application of sustainable design from schematic design phase is more efficient at least 15% for energy saving [40]. Therefore, systematical sustainable design management (SDM) which could increase energy performance should be established from schematic design phase. In addition, it could also avoid unnecessary rework following design change which is caused by non-strategic application of sustainable design.

As a kind of SDM tool, PDEs selected according to an importance weight order may be used valuable as a design management tool or design guidelines for construction of ZEH. Because SDM is able to support the choice of suitable PDEs to avoid unpredictable rework, it would make positive influence on construction cost [54]. With the use of SDM, lots of potential clients who hesitate over the construction of ZEH can apply PDEs more easily.

Contribution to existing knowledge

Comparison with existing studies

Numerous studies have been conducted to resolve carbon emission problem. However, a majority of studies focus on renewable energy and active design, such as improving HVAC performance. Only a small number of studies have been focused on PDEs. Moreover, these few studies only examine the practical performance of one or two PDEs by thorough experimental measurements. Although the efficiency and feasibility of each PDE have been analyzed, it is very difficult to determine which PDE is more preferred by experts during the schematic design phase and which application order for PDEs is more available for limited budgets. The present study not only examines different kinds of PDEs based on practical projects but also focusses on the importance order by an expert's choice. Therefore, this research is useful as a design guide for decision-making instead of solely relying on intuitive judgment.

Contribution to zero carbon emission

According to a report published by PASSIVHAUS [28], 21% of potential ZEH clients are abandon their ZEH plan due to the high-cost. Construction cost of ZEH is 32% higher than the cost of normal house [55]. Even if diverse PDEs should be considered and compared for ZEH, involvement of sustainable consultant is difficult from schematic design phase because client cannot afford to contact with them for small scale of house project.

However, if there is an applicable SDM consisting of PEDs at schematic design phase, it could be a support to both clients and designers to conduct ZEH project. Result of this research is estimated by importance and preference of PDEs which are used in existing energy-saving house projects. Top 7 PDEs which are ranked objectively by expert could be considered and adopted priory for ZEH. PDEs analyzed in this research can play as a SDM without early support of environmental expert. Moreover, this easy approach for sustainable design would make ZEH to be attractive and widen. With utilization of SDM based on top 7 PDEs, client who hesitating to construct ZEH because they do not have professional knowledge in passive technology will have more opportunities to recognize what sustainable elements are applicable and what relations are between PDEs and basic building plan. More clients considering construction of ZEH will be purposed to construct ZEH in the near future. With the application of SDM, ZEH could achieve a 75% reduction in space heating requirements, compared to standard practice for UK new build [56]. The PDEs therefore gives a robust method to help the industry achieve the 80% carbon reductions. Taking account of energy consumption in residential sector which accounts for 12% of overall energy consumption, this research could be a significant contribution for substantial carbon reduction.

Conclusion

PDEs extracted from existing housing projects were examined for construction of ZEH. The importance of and preference for 20 practical PDEs were then examined by relevant experts using a questionnaire. Through the AHP, analysed PDEs were re-sorted according to importance weight order. As a result, sustainable design management (SDM) in ZEH construction was set based on the top seven high-ranked PDEs. This indicates that SDM can be applied for most types of housing, because all of the PDEs examined in this study were selected from diverse types of housing projects, from a single house to an apartment complex. The decision-maker can acquire practical and available information about dominant PDEs with the utilization of this SDM during the schematic design phase. Conclusively, this improved SDM would be useful for energy saving and reducing carbon emissions through the expansion of ZEH construction. However, further studies are required to improve several aspects of the suggested SDM. Firstly, PDEs selected by importance weight order should be re-classified into several secondary categories, in accordance with external conditions, such as housing type, size, and location. The decision maker may be able to apply appropriate design strategies during the schematic design phase with the application of re-classified sub-categories. Furthermore, supplementary studies of SDM will be required for its application to non-residential buildings. Because half of carbon emissions are from the residential sector, commercial and industrial sectors remain to be studied.

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Insert < Appendix 1. 36 PDEs description> here