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The post-occupancy dilemma in green-rated buildings: A performance gap analysis

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Abstract

The traditional construction industry has a significant and far-reaching impact on the environment, economy, and society. Green-certified buildings, with LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), DGNB (Deutsches Gütesiegel Nachhaltiges Bauen), or other certifications during the design stage, have great potential for increasing the effective use of resources and energy, reducing pollution, etc., and so their number has increased greatly in recent years. The post-occupancy evaluation (POE) of green buildings involves assessing whether they meet expected performance during the in-use phase and comprises four steps: (i) carrying out the research purpose/goal; (ii) determining the research objectives; (iii) conducting data collection, analysis, and visualization; and (iv) obtaining the results and drawing conclusions. However, there is a lack of reviews of POE research and analysis of reasons for actual performance gaps. In response and through a comprehensive literature review/analysis, this article summarizes the actual performance gaps of various green-certified projects, analyzes the reasons for failures, and proposes potential solutions. It is found that 74%, 12%, and 14% of the projects perform better, similar, and worse, respectively, than their non-green counterparts. Future POE green building projects can be optimized from the perspective of the building, user, and POE system. To optimize green building actual performance, it is important to ensure the sufficient education of installation and maintenance personnel and occupants’ green behavior, while interior design and decoration, the impact of user demographics, and POE performance indicators are key factors to be considered in green building design strategies and lifecycle evaluation systems.
Keywords

Post-occupancy evaluation; green building; performance gap

Nomenclature

POE Post-occupancy Evaluation
GB Green Building
GB POE Post-occupancy Evaluation of Green Building
HVAC Heating, Ventilation, and Air-Conditioning
LEED Leadership in Energy and Environmental Design
BREEAM Building Research Establishment Environmental Assessment Method
DGNB Deutsches Gütesiegel Nachhaltiges Bauen
IEQ Indoor Environmental Quality
SLEPT Social, Legal, Economic, Political, Technology

1. Introduction

In recent decades, the construction industry has been shown to have great environmental, social, and economic impacts on society. The energy consumed in the buildings sector, which consists of residential and commercial end-users, accounts for almost 20.1% of the world’s total consumed delivered energy [1]. As part of a global response to human impacts causing pollution, resource shortages, and global climate change, green buildings (GB) are expected to have an
outstanding performance in energy efficiency, resource-saving, and other aspects during the construction, occupancy, renovation, repurposing, and demolition process. In a broad sense, green building refers to being environmentally responsible and resource-efficient throughout a building’s life cycle. But at the company level, green buildings need to align with the organization’s core values and sustainability objectives.

Therefore, lacking a definite definition to date, buildings awarded LEED, BREEAM, DGNB, or other GB certifications during the design stage, are broadly recognized as green buildings. The green building certification system promotes sustainable design and construction practices through a suite of rating processes that identify projects that implement strategies for better environmental, economic, and social performance. Since the 1990s, a series of green building rating and certification systems have been developed that are adapted to regional conditions, and share compliance and correlation with each other [2]. Of these, LEED (Leadership in Energy and Environmental Design) – introduced in the U.S. in 1993 as one of the most complete and internationally recognized green building evaluation standards – was used as a reference worldwide. Other widely used certification systems include BREAM in the UK, DGNB in Germany, Green Mark in Singapore, and Green Star in Australia. The number of LEED registrations has steadily increased since its implementation, reaching 69,066 in 2019 in the U.S. [3]. However, there is no clear evidence that certified sustainable buildings reach their expected performance and benefits during the operational stage.

The post-occupancy evaluation of green buildings (GB POE) involves a general process of evaluating the performance of buildings after they have been occupied for several years. Various POE systems, such as LEED for Building Operations and Maintenance (LEED O+M), focus
on every aspect of a building’s footprint to provide for the green improvement of existing buildings. Other GB POE relevant studies are also conducted worldwide, aiming to recognize the performance of specific features of existing GB. Despite some studies indicating that green-rated buildings do not perform as well as expected in their actual operation [4, 5], with their indoor environmental quality (IEQ) being even worse than their non-green counterparts [6], green buildings now seem to be in a state of post-occupancy dilemma, enjoying undeserved fame after actually put into use. There have been a series of studies of the purpose, indicators, and data processing methods of GB POE [7, 8], but the reasons why green buildings fail to perform in the operation stage have yet to be systematically summarized and responded to.

In response, this paper conducts a systematic review of studies of GB POE to establish their actual performance, reasons for malfunction, and provide suggestions for improvement to the various stakeholders involved. There are four goals: 1) to present an overview of green building POE systems, 2) to review the literature relating to POE projects, 3) to investigate the reason for performance gaps during the operational stage, and 4) to identify the research needed to improve GB performance.

2. Methods

2.1. Data acquisition methods

Throughout this paper, GB POE refers to a combination of a great many activities aimed at evaluating and rating building performance during the in-use stage, which consists of four steps of (i) carrying out the research purpose/goal; (ii) determining the research objectives; (iii)
conducting data collection, analysis, and visualization; and (iv) obtaining the results and drawing conclusions. As depicted in Fig. 3, these are tightly bound with each other, constantly affecting each other.

FIGURE 1. POE system overview.

A total of 422 journal papers is firstly identified using the keywords of post-occupancy “evaluat*”, “POE”, “green building”, “sustainable building”, and “evaluation NEAR/5 building” in the WoS Core Collection database between 2010 and 2020. CiteSpace, a literature analysis tool that can visually present the relationship between scientific research studies, is used to build the keyword co-occurrence cluster based on the 422 papers. Of these, 49 studies involve specific POE projects and 15 are carried out from a comparative perspective. For the purpose of this study, these 15 publications are selected and a specific system and project analysis is performed for a further in-depth review of building types, climate zone, country, evaluation indicators, and results.
2.2. Publication analysis

Fig. 1 shows the trend and regional distribution of research into GB POE from 2010 to 2020, indicating that the number of studies increases yearly. They are also unequally distributed around the world, with more from China, the United States, and European countries, which shows GB POE to be applied more in economically prosperous areas – most likely because there are more GB applications there, and there is a stronger awareness of the associated benefits involved.

2.3. Keywords analysis of the collected publications

To understand the relevant research trends and hotspots of GB POE, CiteSpace is used to carry out a literature keyword frequency and cluster analysis and select 15 keywords with a
higher frequency for visualization. Fig. 2 shows their occurrence and co-occurrence clusters: the clusters representing the key aspects of the current research field, and the node tags representing the detailed topics. As is shown, five clusters with the highest concentration degree labeled by keywords are indoor environment quality (#0), general model (#1), rule-based LEED evaluation method (#2), eco-efficiency evaluation (#3), and prospective framework (#4). The different research directions are now concentrated with a high degree of correlation. Publications themed with such keywords as “evaluation method development” and “occupant environmental education” are emerging, indicating a trend towards the assessment and optimization of the actual GB operation process. Based on the cluster analysis, further research is conducted to identify how POE projects are carried out focusing on a relevant aspect, such as green building performance and indoor environment quality, as detailed in the following section.

FIGURE 3. Keyword analysis
3. Findings

3.1. The GB POE system

First originating from the field of environmental psychology in the 1960s, POE is recognized and valued as a process that can improve, and help explain, the performance of the built environment [9]. Information and operational data of existing buildings are collected and analyzed in accordance with system procedures and methods. After many years’ development, GB POE is now widely conducted, and a series of evaluation systems have evolved under different demands and backgrounds based on various standards.

Over the last five decades, several classification methods of the POE system have been developed based on different features. For example, three POE levels are listed: indicative, investigative, and diagnostic, according to the amount of time, resources, and personnel involved and the depth and breadth of investigation [10]. Here, we categorize existing POE systems into comprehensive and segmented performance evaluations in terms of the aspects analyzed. Comprehensive systems such as LEED v4 for Building Operations and Maintenance cover more aspects to evaluate comprehensive building performance in the operational phase and are generalized for a diverse set of applications. In contrast to the overall system, segmented evaluation assesses fewer aspects of the performance of green buildings for a detailed evaluation of specific features, adopted mostly by academic institutes and private consulting firms for either academic studies or marketing purposes [9]. When establishing GB POE systems, it is important to first take the purpose/goal, depth of study, GB, and evaluation aspects into consideration. Therefore, we define GB POE as “a purpose-oriented system that evaluates
a series of indicators of a specific green-certified building in the operation phase”. The results in terms of the four steps are as follows.

3.1.1. Step 1: Research purpose

Broadly speaking, the POE’s purpose is to assess the environmental impacts of existing buildings and provide guidelines for improvement and future design [7]. The POE purposes are categorized as direct or indirect according to whether the POE project aims to generalize an advanced and in-depth body of knowledge for a broader application [8]. In terms of actual POE systems, the purposes of green building POE are divided into three groups based on their research aspects: (1) evaluation of the decrease in environmental load [11, 12], (2) evaluation of improvement in environmental quality [13], and (3) evaluation of green building economic benefits [14]. Environmental load refers to the impact of the building operation on the ecosystem, resulting from the addition to the environment of heating, lighting, cooling, ventilation, etc. Environmental quality includes indoor and outdoor environmental quality, thermal comfort, etc., all playing an important role in influencing occupants’ health, performance, and productivity [15, 16]. Economic benefits are the advantages of green building. These mainly comprise financial values, containing cutbacks in resources and energy costs, other general management expenses, and socio-economic benefits [17].

3.1.2. Step 2: Research objectives

After establishing the POE purpose, it is necessary to determine the research objectives and identify the study project’s specific features for tailoring the evaluation system to fit the actual
needs and core values of the project. As Newsham et al. point out, further work needs to be undertaken to define green building rating schemes in such a way as to ensure more consistent success at the individual building level [18]. A “one-size-fits-all” approach is not appropriate since different building characteristics may influence the evaluation outcome. Therefore, the GB POE comprises the following time, spatial, and object dimensions when establishing systems to avoid the impact of building characteristics, as shown in Fig 4.

**FIGURE 4.** The three POE project dimension

*Time Dimension:* While most current evaluation systems are designed for the short-term state of the building – 2 years or less – the ages and/or durations of time in the building affect the evaluation of environmental satisfaction [19]. For instance, it is noted that the lifecycle carbon emissions of green buildings starts to match with that of their non-green counterparts over time, which is termed the turning point [20]: hence, a sufficient duration of evaluation is needed to encompass this phenomenon. Additionally, in the time dimension, seasonal factors need to be considered, including weather conditions, measurement times, and seasonal changes [21].
Spatial Dimension: GB performance can be affected by spatial elements, such as country/region, climate zone, and site location. Since the climate is a crucial factor influencing a building’s real energy-saving performance [22], different regions need to develop adapted scoring mechanisms and items [23].

Object Dimension: When formulating a GB POE, it is also necessary to consider the nature and characteristics of each GB individually, including building types, usage, age, height, scale, and stakeholders’ core demands. As Hong et al. state, the construction year, number of floors, window-wall ratio, and building orientation are the most influencing indicators of energy consumption when conducting a POE study [24]. Additionally, the core demands of stakeholders (users, designers, and facility managers) need to be considered, since stakeholder support and satisfaction is crucial for successful GB [26]. It is helpful to examine the perspectives of different end-users from varied research angles and methodologies, including the significant human factors of building users’ experience and perceptions [25]. Of all stakeholders, the government organizations have the most influence, followed by owners and end-users with property management companies and NGOs [26]. Stakeholders’ core demands are not only influential during the in-use phase, but also at the design stage, for instance, where green building energy-saving design projects are regarded as a type of multiple attribute group decision-making problem and providing an empirical application [27] – simplifying the traditional decision-making process and involving various stakeholders’ opinions, and thus achieving higher satisfaction during the post-occupancy stage.
3.1.3. Step 3: Data collection, analysis, and visualization

In this step, multiple data collection, analysis, and visualization methods are conducted to determine the final results and suggestions for system improvement, building design, and renovation.

The data collection tools used can be commonly described as information gathering tools, including questionnaires, meters, and temperature sensors. The major information gathering tools are listed as perception tools, monitoring tools, and observation tools, with perception tools the most commonly used [7]. The data collection tools selected depend on the specific POE rating indicators involved. The current such indicators are mainly environment-centric or human-centric, with environment-centric evaluation indicators mainly focused on energy [28], IEQ [29], etc., while human-centric evaluation indicators mainly focus on surveys of household satisfaction [30].

The term ‘Analysis methods’ refers to the scoring process of qualitative and quantitative indicators of buildings using mathematical models to calculate the overall scores of the building and analyze the results. Different POE protocols determine the data analysis methods used and various GB POE evaluation index systems based on the time, spatial, and object dimensions involved. The statistical models used can be divided into either real-time data analysis [31], which analyzes buildings-in-use data, or performance prediction analysis [32, 33], to predict building performance based on existing data. In real-time data analysis, building data are collected and entered into models to evaluate the actual performance of buildings [34], while in performance prediction analysis, various statistical methods are used to predict the future performance of buildings [35] – thus conducting sustainable strategies in advance. The display
of the data analysis results is particularly important, as it can help the various stakeholders involved to better participate in the operation of green buildings through an improved understanding of the actual efficiency of the building in the operation phase. A green benefit map is analyzed based on BIM [8], while the process and data can be mapped and stored using BIM standards for use by stakeholders to take further actions [36]. Visual Basic 6.0 (Enterprise Edition) software programming is also used for visualizing the POE results, making it easier for the occupants to grasp what is happening [23]. Furthermore, linking performance outcomes with spatial information allows the causes of performance failure to be identified more intuitively and makes it potentially easier to communicate the POE results with architects, engineers, and facility management professionals, to engage them in a collaborative approach to continuous building performance improvement [37]. While this sector still faces obvious challenges in terms of the availability of data, selection of methods, variables, and formulation of variable weights, many studies are trying to optimize this link to make the system more transparent and intuitive.

3.1.4. Step 4: Drawing the conclusions

The final results, conclusions, and feedback provided after using the specific data analysis methods, to illustrate the final results of the green building POE project and identify impact-causing activities. The final results contain suggestions for system improvement, existing building renewal, new building design, etc. Feedback from building-in-use helps inform the design and operational process, and in developing more effective green building certification systems and regulations [38]. Ongoing and effective feedback loop systems amongst designers,
operators, and building inhabitants are recommended during the lifecycle for the transparent sharing of successes and failures [39, 40].

3.2. Green building POE projects

This last section presents a short overview of POE systems, introducing the specific steps involved. In this section, the main purpose is identify whether there is a performance gap between green buildings and traditional buildings, so we focus on previous studies that include specific POE projects and compare two types of buildings. This involves the detailed analysis of 15 articles, with GB POE projects being chosen for the use of 4 steps for deeper review, analysis, and visualization. Table 1 summarizes the content of the projects.
### TABLE 1. POE projects.

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Of the 422 publications, 49 POE projects were published between 2010 and 2020. Because nearly 1/3 of the POE systems involved are for comparison [8], the above POE projects are chosen when there is a comparison study, including actual vs. predicted performance, green vs. non-green performance, and pre vs. post-retrofit. Environmental quality, environmental load, and economic benefits constitute 68.3%, 25.0%, and 6.7%, respectively, of the frequency of purpose of POE, indicating a greater emphasis on sustainability over cost-saving. 74%, 12%, and 14%, respectively, perform better, similar, and worse than non-green buildings. In the above studies comparing green and traditional buildings, some provide a direct comprehensive conclusion of the comparisons between the two types of buildings, that is, whether green buildings perform better. However, some only compare part of the building performance. Hence, we take the results of the comparisons of partial performance as the judgment benchmark. Therefore, the comparative performance results combined in Table.1 are objective judgments based on literature’s conclusions. Several POE studies show there is a gap between the final results of POE projects and previous certification evaluation [54]; that is, GB performance during the operational stage is not meeting set goals [55]. The following section considers this aspect in more depth.

4. Gap analysis

Previous study identified three performance gaps between the predicted and actual performance of green buildings or green and conventional buildings: (i) a Prediction Gap (e.g., modeled and measured energy, water consumption); (ii) an Expectations Gap (e.g., occupant expectations in pre- and POEs); and (iii) an Outcomes Gap (e.g., thermal comfort measurements and survey results) [56]. In the absence
of any previous summary of the reasons for performance failure, we divide these into three perspectives of problems: the building, the occupants, and the POE system. The building problems comprise the challenges that appear in the entire lifecycle of the building that are caused by deficiencies in design and technology and are the most worthy of optimization; the occupant problem is mainly caused by the client’s use of construction equipment during the operation phase; while the problem of the POE system refers to deficiencies in the existing POE systems—including the subjectivity of the system and regional inapplicability—causing problems in the green building evaluation process. This system of classification also allows for the performance of future green buildings in the operation stage to be optimized from these three perspectives.

4.1. The building

4.1.1. Inadequate training leads to the inappropriate application of new technologies

Although new energy-efficient technologies seem promising, difficulties in incorporating new technologies create a gap between the design goals of new facilities and actual energy-saving efficiency and results. Workers may experience difficulties in new equipment installation, maintenance, and management, leading to more energy costs or occupant discomfort. In the POE of deep energy retrofits of residential housings, backup heating systems are not always installed or working correctly, which is probably caused by a lack of familiarity with the installation or maintenance personnel [44]. Moreover, a previous study indicates that green building is encountering similar issues related to poor as-built drawings, poor handover and guidance, problems with integrating and maintaining new technologies (heat pumps, biomass boilers, and solar thermal), lack of calibration of sub-meters, and
issues with automatic window controls [57]. Hence, due to the lack of training and understanding of energy management, issues with improper installation, commissioning, and maintenance lead to a higher risk of performance failure [11].

Therefore, careful attention is needed to ensure that installation and maintenance personnel are sufficiently educated. Technology alone does not guarantee savings, and improvements in building performance need improved user attitudes and changes in occupant behaviors and institutional consumption cultures [4] – showing that the simultaneous active and efficient participation of new technologies and users is needed to obtain the benefits of green buildings. At the same time, it is also necessary to reflect on whether existing complex green equipment can be simplified to make it easier and more convenient to use.

4.1.2. Interior design and layout influence post-occupancy satisfaction

Interior design and decoration, as an indispensable phase of a building project, have an unavoidable impact on green building performance [58]. Although such features as office layout, office furniture, cleanliness and maintenance, and indoor public space qualities have a high influence on overall satisfaction and performance, they are not included in most evaluation systems [59]. Lighting, as an IEQ factor, is clearly related to the amount and adjustability of both daylighting and electric lighting [60]. The high level of control the users have over the operation of the building contributes to their comfort and satisfaction – indicating a tendency to be satisfied despite environmental factors, and to forgive some aspects of the building that are not performing as well as they should [61]. Moreover, the research shows that occupants tended to be dissatisfied with their primary workspace when they
are dissatisfied with the acoustic conditions, furnishings, and privacy [62]. Thus, the interior design and furnishing can just be one step short of success in GB.

4.2. The occupants

4.2.1. Occupant behavior affects actual performance in the operation phase

The biggest difference between POE and building design evaluation is that POE is carried out during the use phase, when occupant behavior is one of the most important factors influencing a building’s performance, such as its energy and resource efficiency [63]. However, living in green buildings does not necessarily promote green behavior [64], its natural increase tending to be small so that occupants require motivation and socialization for living green [65]. Moreover, to be active participants, occupants generally need to receive effective feedback on their adaptive behavior (engaging with building controls and complaints) [66]. At the same time, studies also show that green education needs to be conducted by a third party, rather than from the green building itself [67]. However, there is no research showing the relationship between green behaviors and households that have received higher green education. Likewise, the extent to which green behavior improves the green efficiency of buildings is also worthy of study. For building operators, how to strengthen the guidance of the residents’ green education and green behavior in the future is also particularly critical, as well as design teams ensuring that easy-to-understand user guides are made available to facilities managers and occupants before handover [57].
4.2.2. Impact of user demographics on research results

Since surveys of user satisfaction are subjective, there will be some errors. Gender, age, work year, and weekly work hours could have an impact on occupant satisfaction with IEQ [68]. Perceptions of green buildings vary differently between people. For example, “…employees perceive green buildings spaces as better in comparison with conventional buildings employee’s perception, but customers of both groups cannot tell differences between those edifices” [69]; employee satisfaction is affected by workstation size, window access, and office type (open-plan versus private) [30]; occupants with higher levels of environmental concern are more forgiving of their buildings [70]; occupants sharing a concern for energy conservation are more amenable to slightly deficient IEQ [71]; and if occupants recognize that a building is a GB, they will be more tolerant of IEQ, which has an impact on its subjective evaluation [19].

4.3. The POE system

4.3.1. POE performance indicators

The POE indicator formulation process can cause problems with the evaluation results, such as a lack of clarity in the indicator. Some indicators influence each other [72], the conventional scoring method used by the existing green rating tools is not effective in dealing with standards with interactive characteristics [73], and industry experts’ opinions are not necessarily included in the process of determining indicators used [34] – causing the selection of specific indicators and the determination of weights to be too subjective. Byrd and Rasheed also state that IEQ criteria for building design are unrepresentative of how occupants perceive the environment [49] and, hence, the achievement of
specific IEQ credits does not substantively increase satisfaction with the corresponding IEQ factor [74], highlighting the need for the better integration of ergonomic design into green buildings, the rating certification, and POE system [55, 75].

Another concern with the indicator system is that indicators are often established only for a specific problem, rather than the overall framework, and cannot define the sustainability of the entire building. Jane Jacobs, for instance, criticized the simplification method in the 1960s for trying to turn systematic and complex problems into simple problems that can be solved independently of each other [76].

4.3.2. POE lacks real-time analysis

As mentioned earlier, POE needs to be a continuous process rather than evaluation at a certain moment of GB: the POE model using contextual information related to feedback in real-time and the analysis conducted continuously [31], while providing an effective mechanism for integrating occupant feedback into the building model for the visualization and query of feedback items [34]. This can be achieved by BIM in the operation stage, as its use can effectively improve the operation organization’s work efficiency, improve the quality of service to customers, and reduce the waste of resources [77]. Therefore, GB POE should also use real-time analytics and optimization to acquire green benefits over the entire lifecycle of the building.

5. Conclusion

Evaluation of the actual performance of green buildings is crucial to their lifecycle management. The green building evaluation process contains a complex framework and correlations between
indicators and building characteristics. Different stakeholders in the fields of SLEPT (Social, Legal, Economic, Political, Technology, etc.) also have different needs and, hence, if they participate in the evaluation of green buildings, the evaluation needs to be based on a consensus framework. However, considering the uniqueness of each project evaluation (geographical location, type, scale, evaluation period, etc.), a universal ‘one-size-fits-all’ system is unlikely to be appropriate. Therefore, a green building certification does not guarantee it can achieve the expected performance throughout its lifecycle.

To further analyze such performance gap, this study first establishes the four-step POE framework of (i) carrying out the research purpose/goal; (ii) determining the research objectives; (iii) conducting data collection, analysis, and visualization; and (iv) obtaining the results and drawing conclusions. The research purpose includes the three aspects of (i) evaluation of the decrease in environmental load, (ii) evaluation of improvement in environmental quality, and (iii) evaluation of green building economic benefits. Then, it is critical to identify targeted research projects in the time, spatial, and object dimensions.

Following the four-step framework, 15 research projects are reviewed, showing that most POE studies aim to analyze the environmental quality of existing GB, while few consider the impact of season, time scale, or other dimensions – highlighting the lack of a specific POE system development strategy.

In general, 74%, 12%, and 14% of the POE projects perform better, similar, and worse than their non-green counterparts. Future GB POE projects can be optimized from the perspective of the building, user, and POE system. To optimize green building actual performance, careful attention needs to be
paid to ensure the sufficient education of the installation and maintenance personnel, and occupant green behavior. Finally, interior design and decoration, user demographics, and POE performance indicators are shown to be key factors to introduce into GB design strategies and lifecycle evaluation systems.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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