Post-Occupancy Evaluation’s Applications for Improving Indoor Environment Quality

Subjects: Environmental Sciences

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To improve buildings and their characteristics, the feedback provided directly by users is generally fundamental in order to be able to adapt the technical and structural functions to the well-being of users. The post-occupancy evaluation (POE) fits perfectly into this context. The POE, through qualitative and quantitative information on the interior environment, makes it possible to identify the differences between the performances modeled in the design phase and the real performances experienced by the occupants.

post-occupancy evaluation | building performance | indoor environment quality | occupants’ comfort | literature analysis

1. Introduction

People spend a substantial proportion of their time in confined spaces. Approximately 90% of the day is spent at home, work or school, and in traveling [1], so much so that the definition of the “indoor generation” is spreading. In addition, with the advent of the COVID-19 pandemic, the entire world’s population has been forced to stay in confined spaces (especially at home) for long periods of time, which has provided the opportunity to rethink the design and operation of buildings to make them more liveable and efficient in relation to the needs of their users [2].

To improve buildings and their characteristics, the feedback provided directly by users is fundamental information to enable the technical and structural functions to be adapted to the well-being of users [3]. The post-occupancy evaluation (POE), which was introduced in the United States in the 1960s and then disseminated globally, fits perfectly into this context [4][5][6]. This assessment consists of a process of analyzing the characteristics and performance of buildings, carried out with particular attention to the perspective of the inhabitant/user of the building. The concept of the POE is that by asking users about their needs and experiences in the built environment, better spaces can be designed and used [7][8]. By building performance, researchers mean the behavior of the building system, as a whole, when used by the end user, according to their needs [8]. By allowing a “post-dwelling” evaluation, following the actual use of the spaces by the final recipients of the building, the POE makes it possible to identify any discrepancies between the performances modeled in the design phase and those experienced by the occupants. This reveals whether this discrepancy is due to failures in the building design, construction, management or misuse, and it also identifies improvements that can be made. In this way, this approach combines the information collected through the monitoring of the structural and physical parameters that characterize the living spaces and the qualitative and quantitative indications collected through questionnaires,

interviews and visits inside the buildings, directly involving the users [9]. All this makes the POE a useful tool for continuous improvement that is capable of providing useful information to all the actors involved in the life cycle of a building [10][11] and that is applicable to any type of building [12].

According to the authors of [13], the POE evaluates the performance of the analyzed environments according to three main types of aspects: functional, technical and behavioral. Functional performance elements relate to the functionality and level of efficiency of a building's features, including accessibility, adequacy of spaces and facilities, and services, etc. Behavioral performance concerns the interaction between occupant activities and the physical environment provided. Finally, the elements of the technical performance—such as hygiene and the quality of the indoor environment—represent the factors that influence the comfort, health and productivity of the occupants.

The benefits that the POE guarantees, in the short, medium and long term, are as follows [5]:

- Short-term benefits include obtaining feedback from users about problems in buildings and in identifying solutions.
- Medium-term benefits include the feed-forward of the positive and negative lessons learned into the next building cycle.
- The long-term benefits are aimed at creating databases and at updating, upgrading and generating planning and design protocols and paradigms.

The concept of the POE has evolved considerably over time, adapting to different contexts and applying increasingly complex tools for the collection, processing and combination of qualitative and quantitative data. Therefore, the methodologies for POE are different and there are many ways to conduct it, which characterizes the great flexibility of this approach [14].

As people spend most of their time indoors, indoor environmental quality (IEQ) is one of the priority factors influencing the physiological and psychological health of occupants and results in changes in their habits, well-being, and their physical and cognitive productivity [15][16]. The National Institute for Occupational Safety and Health (NIOSH) describes the IEQ as the quality of a building's environment, related to the health of occupants within it. IEQ encompasses the conditions inside a building (air quality, lighting, thermal conditions and ergonomics) and their effects on the occupants or residents.

As indicated in [17], parameters such as thermal, acoustic, light and air quality could—also taking into account individual factors (age, sex, etc.) [18]—strongly influence well-being and health, while also playing a role in the performance of the building, such as its energy consumption. Demonstrating the direct relationship between the IEQ parameters and occupants' comfort has been the goal of many studies: [16][19][20][21][22][23]. For this reason, the POE method is an ideal approach to analyze the interaction between the factors that make up the IEQ and the users of buildings.

In [24], articles that were published between 2000 and 2015 and that identified and classified many indicators to measure the IEQ dimension within the POE's applications were analyzed. Using POE, each factor was analyzed from the following two aspects: (i) the values of this particular parameter in the environment were analyzed, and (ii) the perception that users have of this particular parameter was assessed [25].

The scientific literature appears to be very rich in articles that analyze the application of the POE approach to different reference contexts, demonstrating its effectiveness as a study tool and as a support for improving planning, management and behavior in a confined environment, both domestic and economic/productive/services.

Several reviews were also conducted, as summarized in **Table 1**, each focused on particular aspects assessed by the POE or on specific case studies. In [26] the literature on POE, with a particular focus on the origins, theories, benefits and approaches that make up POE, were reviewed by the authors. Similarly, in [27] the authors conducted a critical and exhaustive review of 146 POE projects since 2010 in order to obtain both a qualitative and quantitative benchmark on this issue. The review in [28] critically examined recent case studies of green building certification systems, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Mark and Green Star. In [29], an analysis of the POE tools to identify the methods applied for the evaluation and the metrics used to measure occupant satisfaction was conducted by the authors. The authors of [30] presented the state of the art on the links between IEQs and the well-being and comfort of occupants, with a particular focus on commercial and office buildings. In particular, the literature has analyzed indoor air quality, sick building syndrome, thermal comfort, acoustic comfort and visual comfort, with the aim of providing indications on some primary parameters that characterize the IEQ. The authors of [17] presented a review of the literature about indoor environmental quality (IEQ) and occupant comfort, identifying the most studied parameters. Similarly, review studies [24][31] identify the factors that distinguish each characteristic aspect of IEQs. In [15], the authors, in assessing the health and satisfaction of occupants in green buildings, also analyzed the design, aesthetics and ergonomics of buildings, which characterize the IEQ.

Table 1. Review articles related to POE methodology.

Paper	Objective	Consider IEQ	Paper's Contribution	Gap and Future Developments
Afroz Z. et al., 2020 [28]	POE evaluation applied to certified buildings.	Yes, as part of green building projects.	Collect a large amount of information related to post-employment data collection and analytical approaches prescribed by the certification systems reviewed.	- Discrepancies in data infrastructure and archiving practices. - In-depth policy exploration and strategies suggested by the certification schemes. -

Paper	Objective	Consider IEQ	Paper's Contribution	Gap and Future Developments
				Further research efforts in utilizing the data for advanced-level analysis.
Al Horr Y. et al., 2016 [30]	Describe the state of the art about the links between IEQs and occupant well-being and comfort.	Yes, assess the different factors that make up the IEQ.	The relationship between the IEQ and the well-being of the occupants and the relationship of IEQs amongst themselves is quite complex. Green building designs do not automatically guarantee that the building designed will be comfortable and ensure occupant well-being.	- More specific and in-depth reflections on the well-being of the occupants necessary. - Designing a potentially comfortable building is not enough. It is also necessary to monitor the performance of the building and its occupants during its operations.
Aliyu A.A. et al., 2016 [26]	Review previous literature on POE—origins, theories, benefits and approaches used in conducting POE	Not a priority	POE facilitates the detection of construction defects at an early-stage so corrective actions can be implemented as soon as possible.	- Future multidisciplinary research is recommended—deepen the social aspects. - Learn more about how occupants experience buildings. - Examine trends and patterns in building energy data. - Promote the successes of the development of social housing.
Artan D. et al., 2018 [29]	Review metrics used to measure occupant satisfaction, information	Yes	The results show that most of the existing tools are not statistically validated as a measurement construct	- Improve the way data are collected and managed.

Paper	Objective	Consider IEQ	Paper's Contribution	Gap and Future Developments
	collected for each parameter and mechanisms adopted to process the data collected.		and that there is no consensus on occupant satisfaction measures, as well as on the information that should be collected by the operator/ occupant for each parameter	
Brambilla A. and Capolongo S., 2019 [32]	Compare and review recent tools able to assess the built environment of the hospital	Yes	The most recent tools analyzed by the document show a tendency to increase the percentage of indicators related to health rather than sustainability.	- Understand the effectiveness of those tools in practice.
Durosaiye I.O. et al., 2019 [6]	Describe the state the art of POE in the UK building procurement process.	Not a priority.	POE can be used to make important strategic decisions. Facility managers can use information from this POE repository to make strategic decisions.	n.a.
Esfandiari M. et al., 2017 [17]	Analyze IEQ parameters and their relationship to occupant satisfaction.	Yes.	Identify IEQ parameters that have a strong influence on occupant comfort. The thermal, acoustic, light and air quality could strongly influence the comfort and health of people, playing a critical role in the energy consumption of buildings. There is a complicated relationship between IEQ parameters, which makes it difficult for a designer to find a balance between them.	- Simultaneously identify full satisfaction and IEQ parameters.
Fantozzi F. and Rocca	Collect indicators for occupant health and	Yes.	Human health risk assessment and	- Simultaneously identify full satisfaction and IEQ

Paper	Objective	Consider IEQ	Paper's Contribution	Gap and Future Developments
M., 2020 [31]	comfort assessment in IEQ assessments.		comfort assessment indicators are specified.	parameters.
Galasiu A.D. and Veitch J.A., 2006 [33]	Occupant preferences and satisfaction with lighting environment and control systems in daylight offices.	Yes, for daylight.	The paper reveals the limitations in the current knowledge about how people react to daylight and, in particular, how they react to lighting and shading controls. Improving the energy efficiency of commercial buildings' lighting should include better use of daylight, but this will require the development of control systems.	- Systematically study the lighting conditions created by individuals using manual lighting and shading control systems. - Make systematic comparisons. - Widen the range of light conditions studied. - Study the relationship between discomfort and glare ratios.
Geng Y. et al., 2019 [25]	Review published research on post-occupancy performance of green buildings in terms of energy consumption, IEQ and occupant satisfaction.	Yes, with special attention to green buildings.	The energy performance of green buildings was, on average, better than that of conventional buildings. A significant discrepancy was found between planned and operational power consumption. It was not possible to observe a clear relationship between the actual energy consumption and the level of certification of sustainable construction. Current IEQ conditions of green buildings were not comparable in different countries. Green buildings generally have a higher level of occupant	- New data collection technologies. - Global performance optimization.

Paper	Objective	Consider IEQ	Paper's Contribution	Gap and Future Developments
			satisfaction than conventional buildings.	
Ilter D.A. et al., 2016 [24]	Collect indicators for assessing occupant satisfaction in IEQ evaluations.	Yes.	Evaluation indicators.	- Identify and solve existing issues that impede occupant satisfaction and guide the design of retrofits in office buildings to maximize building performance and user needs.
Lee J.W. et al., 2020 [34]	Implement a web-based building occupant tracking system that incorporates the new approaches, based on a geographic information system (GIS) tool and open source spatial information.	Yes.	Define a detailed system framework	- Conduct research on IEQ factors. - Analyze occupant satisfaction and display the visualization vertically. - Carry out a case study of the occupants of a real building to propose a direction for statistical analysis with 3D visualization.
Li P. et al., 2018 [27]	Qualitative and quantitative introduction of POE.	Yes.	Emerging research topics related to visualization of POE results, occupant survey database analysis, and occupancy measurement.	- Five directions for future POE development and applications, as follows: from ad hoc to ongoing, from high-level to detailed, owner-/occupant-oriented researcher-oriented, from academia to industry, and from independent to integrated.

Paper	Objective	Consider IEQ	Paper's Contribution	Gap and Future Developments
Meir I.A. et al., 2009 [5]	Describe POE's conceptual and methodological context, its interaction with other issues related to sustainable design and its growing "canonization" as a method.	Yes	POE is an important and probably inevitable step to make buildings more sustainable.	n.a.
Mirzaei P. et al., 2020 [15]	Examine the relationship between buildings and health	Yes	Identification of important IEQ factors, including building design, aesthetics and ergonomics, which were less valued in previous research. Occupants of green buildings enjoy higher IEQ, satisfaction and health than occupants of non-green buildings.	- More buildings to accurately assess the indicators cited. [25]
Roberts C.J. et al., 2019 [35]	Analyze POE literature on building operations and performance as a way to holistically map the body of existing knowledge	Yes	A stronger community of practice is needed to ensure a consistent approach to POE.	- Expand current research study and generate broader debate among practitioners and scholars.

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The authors of [41] compared the expected and actual energy performance of non-residential buildings and applied the POE to produce more accurate energy performance models. The authors of [41] used the POE to prioritize maintenance work to achieve the maximum occupant satisfaction. The authors of [42] aimed to improve the accuracy of buildings' energy simulation, through the evaluation of occupant behaviors. The authors of [43] evaluated the functional performance of entrance spaces in apartments in the Kurdistan region of Iraq.

With respect to the physical parameters, the analyzed authors described whether or not the evaluation of the POE was completed by in situ measurements, or whether the evaluation was carried out solely by qualitative assessments and judgments, provided by the users of the spaces investigated. In this case, there was a greater balance: 43% expected physical measurements, while 57% of the authors only made qualitative assessments. Some case studies that complemented the POE surveys with field measurements were as follows: [44], alongside the questionnaires, the authors also measured the temperature, relative humidity, noise, light, and CO2 concentrations in the case study of Universiti Teknologi PETRONAS' new academic complex; the authors of [45] measured the brightness of highly glazed modern buildings, which require solar protection to ensure the visual and thermal comfort of the occupants; the authors of [46] detected the temperature and relative humidity trends in houses in the hot and humid tropical climate of Darwin; the authors of [47] measured the brightness in collective

housing in Algeria; the authors of [48] measured different physical parameters (temperature, relative humidity, noise, light and CO2 concentrations) for a comparative study on green and conventional malls in Beijing, China; the authors of [49] focused on noise measurements to improve the acoustic performance of residential buildings in Turkey.

Conversely, some authors only carried out qualitative evaluations, as follows: the authors of [50] analyzed the relationship between defects and occupant satisfaction and loyalty in build-then-sell houses; the authors of [51] assessed how maintenance features might affect occupant satisfaction; the authors of [52] analyzed the demand for space in the common areas of student residences in Iran; the authors of [53] applied the POE to understand how occupants perceive wood in built environments; the authors of [54] analyzed how the social dimension of physical space in educational contexts can explain a student's academic achievement.

Considering only the 157 articles that provided qualitative and/or quantitative assessments of IEQ's physical parameters, **Table 2** reports the frequency of analysis of the four categories proposed in [25]: thermal comfort, indoor air quality, lighting and acoustics. For each variable investigated, the main types of tools used for measurement were also reported, as support elements for the design of measurement campaigns, which are useful for the use of the POE methodology.

Table 2. IEQ categories considered.

Category	Number of Papers	Frequency (%) of Articles that Analyze this Category, Compared to those that Do Not	Main Variables Measured	Main Instruments Used for the Sampling/Measurement
Thermal comfort	134	85%	Temperature	HOBO and Tinytag sensors; Raspberry-Pi-based sensors; Kestral 4000 m; DT-172 logger; and HWM Ecosense temperature loggers
			Humidity	HOBO and Tinytag sensors; Raspberry-Pi-based sensors; Kestral 4000 m; and DT-172 logger
			Air pressure	HOBO and Tinytag sensors
			Air velocity	T-DCI-F900-S-O
Indoor air quality	100	64%	CO	HD21AB/HD21AB17
			Particulate matter, PM10 and PM2.5	Optical particle counters
			NO_2	Passive Difram100 Rapid air monitor

Category	Number of Papers	Frequency (%) of Articles that Analyze this Category, Compared to those that Do Not	Main Variables Measured	Main Instruments Used for the Sampling/Measurement
Lighting	112	71%	Total volatile organic compounds (TVOC)	RadielloTM Cartridge Adsorbents; 98,519
			Formaldehyde	Passive devices
			CO_2	Raspberry-Pi-based sensors; 98,123 J; HD21AB/HD21AB17; Vaisala CO_2 sensor
			Lighting	TM-203 Datalogging; Digital Light Meter and Lutron-YK2005LX; illuminance sensors
			Glare	Camera-based imaging luminance photometer
			Views from windows [55]	Two-dimensional color analyzer
Acoustic environment	97	62%	Noise [56]	Sound level meter and tapping machine. Solo 1092 01dB-METRAVIB [57]

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performance of an agri-food building in Italy, they measured the indoor heat levels in hot and cold seasons. In two studies, [16][59], the authors measured the thermal conditions in green office buildings in Jordan.

In [60], evaluating 20 office buildings, they measured the lighting levels as a factor in visual comfort and workplace productivity. The authors of [61] analyzed the internal conditions of the Arts Tower (Sheffield, UK), also through light measurements. The authors of [62] analyzed the physical quantities of lighting in an open plan office to assess the layout of the environment and the effect on the occupants. The authors of [63] compared green office buildings with different levels of energy consumption intensity, using light measurement as a rating indicator. The authors of [64] analyzed the IEQ of platinum, green-certified office buildings in Malaysia, assessing thermal comfort, indoor air quality, acoustics, lighting, furnishings and cleanliness.

The authors of [65], by monitoring the performance of four social housing units certified to the Code for Sustainable Homes level, measured CO_2 levels as a representative parameter of indoor air quality. Likewise, the authors of [66] applied CO_2 measurements as an air quality indicator to assess energy-certified buildings. The authors of [67] also used this indicator to assess the quality of office space at an Australian urban university. In [68], the authors verified occupants' satisfaction with the indoor environment at work, through the qualitative assessment of indoor air quality. In [69], for the assessment of green office buildings, they measured many air pollutants, such as CO_2,

PM2.5, CO and formaldehyde. The authors of [70], in a zero-carbon building, measured CO_2 and PM2.5 concentrations.

Finally, noise was analyzed in 62% of the papers collected. The authors of [71] quantified several key factors influencing occupant satisfaction in higher education institutions in the USA and Lebanon, considering acoustic quality as one of them. The authors of [72] analyzed the environments of university buildings in Chongqing, China, through questionnaires and occupant measurements. The authors of [73] analyzed the office plan of the Land Rover/Ben Ainslie Racing (LR/BAR) team's headquarters in Portsmouth, UK. A comparison was made between the measurements with the occupants' perception of comfort with respect to the same parameters. The authors of [74] examined occupant satisfaction in three excellent BREEAM-certified buildings at Coventry University, in the UK. Qualitative assessments were carried out on the perceptions of the occupants, evaluating the thermal environment, indoor air quality, as well as the visual and acoustic environment. The authors of [11] analyzed satisfaction in the office buildings of the University of Southampton (UK), by measuring and evaluating the thermal, acoustic and air quality of the indoor environment.

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