sustainability

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Indoor Environmental Quality Assessment Model (IEQ) for Houses

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Abstract: Housing and its indoor environment influence its inhabitants' comfort, productivity, and health. For this reason, it is becoming increasingly important to investigate the factors that affect indoor environmental quality. Thus, numerous sustainability assessment systems have been developed to evaluate building performance. This paper presents a model for evaluating the indoor environment of housing located in the Biobio region of Chile, integrating aspects that influence its overall quality. The research methodology proposes a strategy to identify appropriate evaluation criteria and contextualized standards. The application of the model made it possible to identify the level of performance of studio dwellings for each category, namely air quality, thermal comfort, acoustics, and lighting, as well as the overall evaluation of the IEQ. The results reflect that the lowest levels of performance in the three houses were with respect to the acoustic evaluation criteria, while the highest levels of performance were for the air quality evaluation criteria.

Keywords: indoor environmental quality; building sustainability assessment systems; weighted IEQ assessment scales

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Citation: Quesada-Molina, F.; Astudillo-Cordero, S. Indoor Environmental Quality Assessment Model (IEQ) for Houses. *Sustainability* **2023**, *15*, 1276. https://doi.org/10.3390/su15021276

Academic Editors: Ying Sheng and Chunxiao Su

Received: 25 October 2022
Revised: 16 December 2022
Accepted: 23 December 2022
Published: 10 January 2023

1. Introduction

Reaching sustainable development has been one of the largest concerns in the last decade, attracting academics' and professionals' work worldwide. Sustainable development is the balanced performance of social, environmental, and economic dimensions of human life for the benefit of present and future generations [1]. Therefore, the responsible management of a healthy built environment by the efficient use of ecological principles and resources has become fundamental for human impact on the environment and citizens' quality of life [2]. However, rising constantly are the construction industry's impacts over the environment, society, and economy [3], as it is an industry with high consumption of energy and natural resources and is a source of environmental pollution [4].

To face this problem, Building Sustainability Assessment (BSA) systems have been developed in order to certify the reduction of the environmental impact generated by buildings [5]. Since the appearance of the first BSA system, BREEAM certification, in 1990 and the later arrival of new international systems, it has been proven that buildings have progressed towards sustainability, introducing changes in the conventional constructive processes, improving the environmental performance, and offering a lower cost of operation with higher quality of internal environment for its habitants [6,7].

Whilst there are various BSA systems worldwide with different approaches, some authors have pointed that only certain systems have been able to excel due their influence worldwide [8,9], which are characterized for targeting three basic categories: materials, energy, and interior environmental quality (IEQ) [10]. Thus, IEQ assessment has become an important concern for sustainable development, so much so that health and social well-being depend on its quality [11,12]. Table 1 presents the BSA systems focused on residential use and their evaluation criteria.

Table 1. Evaluation criteria for residential BSA systems.

BREEAM Multi-Residential	LEED-H	VERDE NB (Residential and Commercial)	CASBEE (New Construction)	Qualitel
Natural lighting	Combustion ventilation	Toxicity in interior finishing	Sound environment	Outdoor acoustics
Views outside	Moisture control	Implementation of a process of purging	Thermal comfort	Interior acoustics
Glare control	Ventilation	The efficiency of natural ventilation	Lamps and lighting	Visual comfort
High-frequency lighting	Local extraction	Thermal comfort with natural ventilation	Air quality	Spaces and common premises
Internal and external lighting levels	Distribution of heating and cooling	Natural lighting	Service capacity	Indoor air quality
Natural ventilation potential	Air filtration	Protection against outside noise enclosures	Durability and reliability	The temperature in summer
Indoor air quality	Control of contaminants	Protection against the noise of facilities	Flexibility and adaptation	Accessibility and livability
Volatile organic compounds (VOCs)	Radon protection	Protection against noise from other rooms		Optional performance
Thermal comfort	Garage pollutant protection	The efficiency of the spaces		
Thermal zoning		Maintenance management plan		
Microbial contamination prevention		Universal accessibility		
Accessibility		Right to sunlight		
Home office		Access to private open spaces		
Acoustic isolation		Protection of views inside housing		

2. Interior Environmental Quality IEQ

People spend around 90% of their lives in indoor spaces [13], which is why they become vulnerable to any dangerous agent that could propagate in their surroundings, and currently, with the COVID-19 pandemic specifically, the IEQ has been tightly linked with people's health [14,15]. The impacts that indoor environments can have on their occupants have been studied across the globe. The World Health Organization's report attributes approximately 180,000 deaths in America and Europe to pollution of the domestic environment [16].

Usually, a deficiency in the IEQ can be the result of poor quality in residential building [17], as is the case of the residential park located in the Bío-Bío's region in Chile, where the majority of houses are detached (69.51%) [18], and diagnosis studies have determined that, either in winter or summer, indoor temperature and humidity levels are out of comfort range due to issues regarding the building's thermal envelope, causing discomfort to its habitants [19]. This poor performance in housing also generates higher demands of energy, as the houses that have higher levels of environmental humidity require more energy to heat the air [20].

Numerous studies about the effects of IEQ's poor performance have been developed. However, there's limited research about how variables that affect the IEQ of housing interact between each other [13]. Despite these limitations, it is known that the stimuli affecting the way that people perceive the internal environment are related to the thermic, visual, acoustic, and air quality variables [21].

In recent years, there have been observations involving the strong growth of experimental and numerical studies addressing the complexity of the interactions between these four stimuli, which are based upon BSA systems to propose assessment models as contributors to determine interior environment quality (IEQ) [22,23].

Models of Assessment of Interior Environment Quality IEQ

The acceptance of the IEQ is crucial for the development of sustainable buildings, as it is possible to achieve substantial savings in the construction and operation costs if housing is designed to achieve a good performance in the internal environment [24]. Therefore, it is important that the availability of assessment models are readily understood and accessible for the public and building designers, the same way as the BSA [25].

Contributing to this purpose and in order to overcome the absence of universal and objective weighting of the IEQ variables (thermic, visual, acoustic comfort, and air quality), the study by Rohde, Steen Larsen [26] focused on developing a certification applicable to Danish social housing through consulting regional experts and determined the following order of priorities of the variables: noise from the building, daylight, influence from the building and materials, and temperature outside the heating season. Another study focused on the importance of the users' perception of public and private high-rise residential buildings in Hong Kong [23], which determined that IEQ variables weighting are 33.82% towards thermic comfort, 23.05% acoustic comfort, 22.90% air quality, and 20.23% odor in the environment.

For the typology of office buildings with air conditioning in the U.K., monitoring and survey methods determined that the weighting of each parameter contributing to the perceived IEQ are 34% air quality, 24% thermic comfort, 23% lighting, and 19% acoustic [27]. In the same building typology, Mujan, Licina [28], through a combination of continuous measurements and perception surveys of its occupants, determined that the average interior air quality has a weighting of 35%, followed by thermal comfort with 28.5%, acoustic 19.5%, and lighting 17%. Finally, the research of Wei, Wargocki [29], through the revision of credits that are assigned to the variables of internal environment by the BSA certification schemes for office buildings and hotels, determined that the IEQ grade for non-residential buildings has the following weightings: 27% thermic comfort, 34% air quality, 22% lighting, and 17% acoustic.

It can be observed that these investigations have tried to bridge the gap in developing an IEQ assessment methodology, as there is no registered tool for this purpose given the difficulties associated with integrating weighting to the variables, knowing that the priorities of a sustainable building vary based on each context, where its establishment depends on the historic, geographic, political, and cultural particularities of each region [4,30]; this also shows in the lack of consistency of the weightings' values from the investigations aforementioned.

3. Methods

This article's objective is to propose an IEQ assessment model for housing located in the region of Bío-Bío, Chile. Integrating variables such as thermal comfort, air quality, acoustics, and lighting, the investigation's methodological design is composed of three stages: (a) identify and define evaluation criteria and categorize them, drawing on established international systems; (b) evaluate dwellings in the region to select and contextualize the evaluation criteria; and (c) define regional priorities among the evaluation issues. These three stages have been used in similar investigations that have managed to develop tools and contextualize the evaluation [4,30–32]. It is important to point out that the data obtained by site measurements and surveys and used to determine the relative importance of each one of the contributors for IEQ were taken during the years 2013 and 2014 and have been utilized for developing the current assessment model given the pertinence of the study region, especially with the COVID-19 pandemic.

3.1. Identification of Evaluation Criteria

In order to identify IEQ evaluation criteria, the most globally recognized BSA systems' literature has been revised [8,9], and as they have regional influence [33], other international systems were therefore ruled out. The systems considered for the study are BREEAM Multi-residential [34], LEED-Home [35], Certificación Verde NB [36] (GBCe, 2012), CASBEE-New Construction [37], and Qualitel [38]. Table 1 shows the analyzed criteria.

3.2. Housing Assessment

Table 2 shows the criteria that were used for the evaluation of dwellings. The most appropriate evaluation criteria were selected and defined for reference levels leading to a qualification. The evaluation criteria for two situations were excluded as not applicable:

1. Type of housing: for example, criteria were excluded that evaluated conditions of lifts;
2. Features of the local housing: for example, criteria were excluded that assess the HVAC since 85% of homes in the study area use natural ventilation in their enclosures [39].

Table 2. Example of the analysis. Daylighting evaluation criteria.

BREEAM	VERDE	CASBEE	QH&E
Method of Evaluation			
• Calculate the daylight factor (DF). • Check % of work surface that receives direct natural light.	Check for the living room and master bedroom: • Angle of visible sky • Area illuminated by windows (depth "P") • Relationship between the surface of window and the room • Length of window and room • Light transmission of window glass	• Calculate the daylight factor (DF). • Employs angular projection factor in three dimensions (U)	• Calculation of the opening index (lo): relationship between the area of opening (including carpentry and glazing) and the floor area of room to living room, kitchen, and bedroom • Verification of aspects • Calculation of DF
Indicators			
• DF (%) • % of work surface	• Angle ° • % of surface • P = meters • Verification of conditions	• Angular projection in three dimensions U (%) factor	• Opening index (lo) • DF (%)
Requirement Level			
1: Kitchen ≥ 2.4% 2: Living rooms, dining rooms, and studies ≥ 2.4% 3: At least 80% of work surface of the kitchen, living room, dining room and study room to receive direct sunlight	1: Meet in the living room 2: Meet in the bedroom ≥50° P ≤ 4.5 m ≥20% ≥0.5 ≥0.7	1: (factor) < 0.5% 2: 0.5% ≤ (factor) < 1.0% 3: 1.0% ≤ (factor) < 1.5% 4: 1.5% ≤ (factor) < 2.0% 5: 2.0% ≤ (factor)	1: Minimum openings: • Living room lo ≥ 15% • Kitchen lo ≥ 10%. • Bedroom lo ≥ 15% 2: Quality of natural light: • Risk reduction in glare and light distribution 3: DF: • Living room DF ≥ 1.5% • Bedroom DF ≥ 2% • Kitchen lo ≥ 15%

To date, there have been few studies of this type, and many of those have generally focused on the analysis of a single style of housing [40–43]. This study focuses on three (Table 3) since similar studies have shown that the proper selection of three different housing can lead to improved results [44]. This study's analyzed dwellings were part of a group of ten homes, of which three were selected by geographic dispersion, orientation of façades, condition of housing (clean and furnished), occupation status (to ensure the opening and closing of windows), and the use of traditional means of heating in the houses of the region.

The equipment used for the monitoring were data sensors manufactured by Onset Computer Corporation for its HOBO applications, with the following measurement kits:

- U12-013: Data-logger 2 analogic + T°/HR internal;
- U12-012: Lux Data-logger + T°/HR internal;
- U12-006: Data-logger 4 analog ports;
- CABLE-2.5-STEREO: Cable for interface to ZW;
- BHW-PRO-CD: HOBOWare communication software.

The same monitoring equipment was installed on the first level (living room, dining room, kitchen, and outside) and on the second level (master bedroom, second bedroom, and outside). It is important to mention that the monitored data were used solely for the purpose of developing this evaluation model, and the monitoring was carried out in the following manner:

1. Monitoring of outdoor temperatures (°C), indoor temperatures (°C), surface temperatures (°C), and indoor and outdoor relative humidity (% RH), measured during two periods (summer and winter);
2. Simulation of illumination (lux) (DF) through the Autodesk software Ecotect Analysis, version 2011;
3. The estimation of noise levels through the constructive systems of housing's envelopes against the sound' impact was performed considering local regulation for acoustic isolation.

Table 3. General information about the selected housing.

	Housing 1	Housing 2	Housing 3
			
Location	Portal de San Pedro/Pasaje Lago Tintilco 293	San Pedro de la Paz/Camino Club Militar 110	Concepción/Tierras Coloradas 222
Area	65.15 m^2	88 m^2	109.38 m^2
Winter monitoring	26 September–3 October 2013	11–18 July 2012	9–16 September 2013
Summer monitoring	21–28 January 2013	3–23 September 2012	14–21 January 2013
Materiality	Concrete/Wood	Concrete/Wood/SIP Panel	Concrete/Wood

3.3. Definition of Regional Priorities

The study region was chosen by a consensus of experts of the lack of similar research in the general area [45]. To achieve this consensus, the researchers applied the methodology of Thomas Saaty's analytic hierarchy process (AHP) [46] decision-making framework, useful for its utility in identifying the interests of society [23,47]. Following the structure of the AHP method, we applied a survey questionnaire that considered 17 situations of comparison (between criteria and sub-criteria); these were evaluated using Saaty's scale. Calculations were performed on a (symmetrical) positive reciprocal matrix built with Microsoft Excel software, and importance weights were obtained by the arithmetic mean of the vectors of priorities for all respondents.

The expert panel used intentional sampling techniques and comprised members from the following interest groups and participating institutions: (a) universities: University of Bío-Bío, Pontifical Catholic University of Chile, and the University of Chile; (b) certification companies: Institute of Construction, CITEC, Efficiency Energy Certification University Higher (Temuco), and GBC Chile; and (c) public institutions: DITEC, MINVU, and SERVIU Region Bio-Bío. The total number of participants was 20: 5 academics, 7 certifiers, and 8 public officials.

4. Results and Discussion

4.1. Identification of Evaluation Criteria

The evaluation criteria that were integrated into the model were objective, feasible, measurable, and appropriate for the type of housing in the city. Because there are no tools for the identification and contextualization of evaluation criteria [33], the authors choose to impose six parameters that must be met as the evaluation criteria to be selected (Table 4):

1. The evaluation criteria are compatible with the characteristics of the dwellings;
2. The evaluation criteria contributed to overcoming problems in housing;
3. The method for evaluating was feasible to apply;
4. The requirements levels were in line with local conditions;
5. The type of evaluation performed was based on performance;
6. The evaluation criteria helped improve the comfort of dwellings.

Table 4. Selection of evaluation criteria.

Evaluation Criteria	Selection Trials					
	1	2	3	4	5	6
1. Lighting						
BREEAM						
Natural lighting	■	■	■	■	■	■
Lighting levels	■		■	■	■	■
Glare control	■		■	■		■
Views outside	■		■	■		■
VERDE						
Daylighting in primary occupation spaces	■		■	■		
CASBEE						
Natural light	■	■	■	■	■	■
Lighting levels	■		■	■	■	■
Daylight control	■		■	■		■
QH&E						
Natural lighting and visual relationship with the external environment	■	■	■	■	■	■
Artificial lighting	■		■	■		■
2. Indoor air quality						
BREEAM						
Indoor air quality	■	■		■		■
VERDE						
In spaces with natural ventilation efficiency	■	■	■	■		■
Toxicity in the interior finishing materials	■	■		■		■

Table 4. *Cont.*

Evaluation Criteria	Selection Trials					
	1	**2**	**3**	**4**	**5**	**6**
CASBEE						
Natural ventilation performance	■	■	■	■		■
3. Acoustic						
BREEAM						
Acoustic isolation	■	■	■	■	■	■
VERDE						
Protection of enclosures protected against noise	■	■	■	■	■	■
CASBEE						
Background noise levels	■	■	■	■	■	■
4. Thermal comfort						
LEED						
Distribution of heating and cooling in spaces		■				
Humidity control		■	■		■	■
BREEAM						
Thermal comfort	■	■	■	■	■	■
VERDE						
Thermal comfort in spaces with natural ventilation	■	■	■		■	■
CASBEE						
Environmental temperature	■	■	■	■	■	■
Humidity control	■	■	■	■	■	■
Perimeter performance	■	■	■	■	■	■

We selected the criteria that yielded a "yes" response to four or more of these parameters, obtaining the following: natural lighting, artificial lighting, glare control, views outside, natural ventilation, pollutants control, outdoor airborne noise, impact noises, environmental temperature, humidity control, and building envelope performance.

4.2. Housing Assessment Results

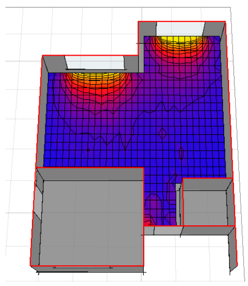
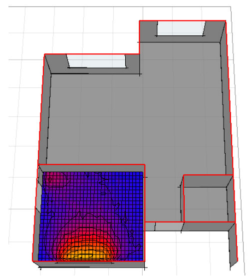
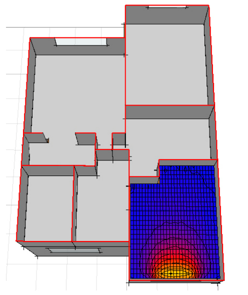
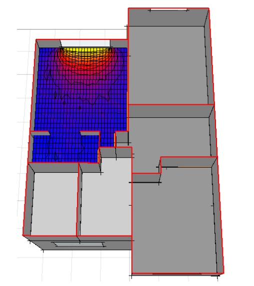
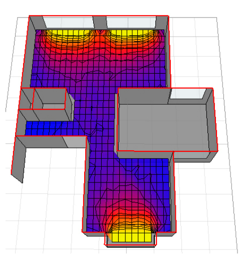
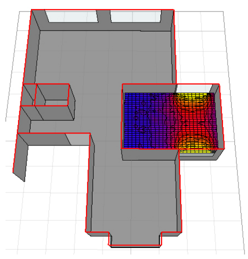
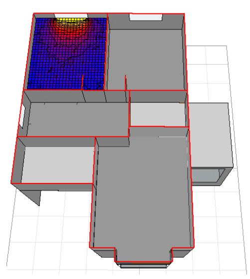
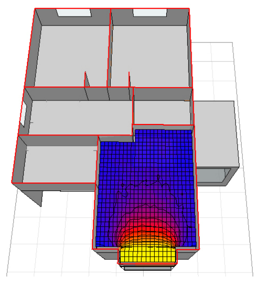
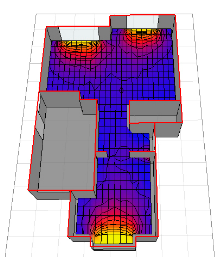
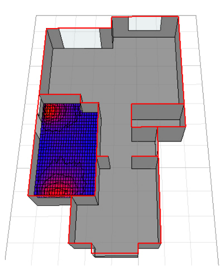
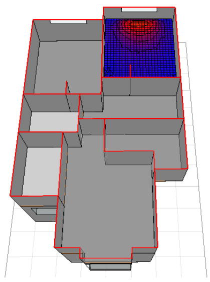
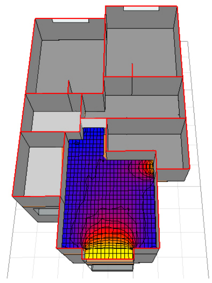
4.2.1. Natural Lighting

The international systems assessed this through the "daylight factor" (DF), with ranks ranging from 0.5% to 2.4%, according to the method and required compliance for living room, kitchen, and bedrooms. Evaluated dwellings obtained values higher than 2.4% DF (Table 5).

4.2.2. Artificial Lighting

Noncompulsory national standards set a temperature of 3500 k maximum color and an index of chromatic yield of no less than 70 for LEDs and no less than 80 for the rest of the luminaires. International systems evaluate by checking points of lighting available in the rooms. It was found that the study homes complied with these requirements.

Table 5. Simulation of the factor daylight to the main rooms.

Scale DF	Living Room—Dining Room	Kitchen	Second Bedroom	Master Bedroom
Housing 1 	DF = 4.75% / LUX = 354.41 	DF = 4.91% / LUX = 365.92 	DF = 3.53% / LUX = 265.08 	DF = 4.01% / LUX = 298.89 
Housing 2 	DF = 7.23% / LUX = 542.14 	DF = 7.57% / LUX = 585.94 	DF = 4.16% / LUX = 312.05 	DF = 5.59% / LUX = 418.42 
Housing 3 	DF = 5.38% / LUX = 404.15 	DF = 3.53% / LUX = 249.75 	DF = 3.11% / LUX = 232.33 	DF = 5.80% / LUX = 434.97 

4.2.3. Environmental Temperature

International systems establish temperature ranges for master bedrooms based on systems of cooling and heating ranging from 18 °C to 24 °C for winter and from 23 °C to 28 °C in summer. National thermal regulations have established minimum values within the concept of heating degree days (a measure of how warm or cold a region is) annually, defining its standard as 15 °C and providing a comfort level between 18 °C and 20 °C, with normal operating regime gains and solar earnings for the winter season [48]. The winter season results for the main rooms of houses 1 and 3 showed average temperature values, with the highest percentage of hours for the ranges between 18 °C to 20 °C and 18 °C to 24 °C. For the summer season results, the same spaces showed average temperature values; however, the highest percentage of hours fell outside the range from 23 °C to 28 °C (see Table 6).

4.2.4. Humidity Control

International systems define reference levels by ranges of relative humidity in the interior through dehumidification systems. LEED requires a level less than or equal to 60%, which could be met in winter by the spaces of housing 1, while in summer, the spaces in housing 2 and 3 obtained better performance, with spaces in housing 2 room being the only ones that did not meet the specifications (Table 7). CASBEE sets a range between 40 and

70%, which is not met by spaces in housing 2 in winter. National regulations on the subject do not exist; however, the official technical guides establish an interior level between 30 and 60%.

Table 6. Monitoring of temperature in summer and winter.

	Winter	**Summer**	**International Systems**				**National Regulations**	
			Winter Range 18–24 °C (% hours)		**Summer Range 23–28 °C (% hours)**		**Winter Range 18–20 °C (% hours)**	
	Average (°C)		**Outside**	**Inside**	**Outside**	**Inside**	**Outside**	**Inside**
Housing 1:								
Living room (°C)	20.5	20.3	0.0	100.0	95.9	4.1	75.0	25.0
Master bedroom (°C)	20.1	21.1	0.0	100.0	88.3	11.7	48.0	52.0
Second bedroom (°C)	20.4	21.0	0.0	100.0	92.4	7.6	62.0	38.0
Kitchen (°C)	19.0	20.9	30.0	70.0	91.9	8.1	67.0	33.0
Outside temperature (°C)	11.3	18.3						
Housing 2:								
Living room (°C)	16.4	17.6	100.0	0.0	99.6	0.4	100.0	0.0
Master bedroom (°C)	16.7	20.7	71.9	28.1	95.2	4.8	75.4	24.6
Second bedroom (°C)	15.9	18.5	92.8	7.2	99.6	0.4	92.8	7.2
Kitchen (°C)	16.6	19.2	79.6	20.4	99.7	0.3	79.6	20.4
Outside temperature (°C)	10.9	13.2						
Housing 3:								
Living room (°C)	18.8	21.2	36.9	63.1	71.6	28.4	53.0	47.0
Master bedroom (°C)	18.4	21.9	43.5	56.5	73.2	26.8	70.2	29.8
Second bedroom (°C)	20.0	21.6	9.5	90.5	70.7	29.3	58.9	41.1
Kitchen (°C)	18.6	21.5	46.4	53.6	100.0	0.0	59.5	40.5
Outside temperature (°C)	10.0	19.2						

Table 7. Monitoring relative humidity in summer and winter.

	Exterior (%)	**Living Room (%)**	**Master Bedroom (%)**	**Kitchen (%)**
Winter				
Housing 1	65.63	45.35	49.92	48.12
Housing 2	87.13	81.10	72.06	71.00
Housing 3	77.19	59.96	66.21	58.56
Summer				
Housing 1	70.59	65.56	59.15	62.28
Housing 2	71.01	62.44	57.36	58.77
Housing 3	64.64	59.03	59.64	59.49

4.2.5. Air Quality

For the evaluation of natural ventilation, international systems provide different levels of reference. For example, VERDE requires window openings to be a minimum of 5% of the floor area of the rooms and the distances between two openings of opposite façades to be a maximum of five times the height of the room. All three dwelling satisfactorily fulfilled this requirement. BREEAM requires the minimum surface of windows to be one-eighth of the usable area in the main rooms, while CASBEE sets a range from one-tenth to one-sixteenth for the window opening with respect to the area of the room. This level could not be reached by the three houses in this study. National regulations for this criterion establish minimum conditions requiring the use of windows for the different areas of the house and, under certain conditions, the use of ventilation ducts or air conditioning systems. However, official technical guides for the prevention of diseases establish minimum levels of exchanges of air from the outside between 3.0 and 3.6 m^3/h per m^2 of premises.

4.2.6. Acoustics

For aerial noise from outside, international systems establish levels that exceed local standards in a range of 3 to 10 dB(A). The national regulations require only elements that separate or divide housing units, establishing a sound-reduction index minimum of 45 dB(A) [49]. Impact noise levels are required to overcome the local rules in a range from 3 to 15 dB. Domestic regulations set a maximum of 75 dB normalized impact sound pressure level. None of the three housing exceeded the national levels.

The results of the evaluations showed that international systems do not evaluate all of the factors that influence the indoor environment and that their evaluation criteria have different levels of demand. The study found that it was not possible to apply all the assessment criteria due to the characteristics of the houses of the region. Therefore, the dwellings obtained different performances depending on the system applied (Figure 1).

The results of the evaluations showed that there were different levels of performance, which could be awarded allocation for compliance as follows [50]:

- Standard practices: 1 point;
- Best practices: 3 points;
- Superior practices: 5 points.

With this scale of linear scores, qualifying the level of performance of the houses, we worked on two aspects to define reference levels (benchmarks) for each evaluation criterion. First, for the standard reference level, we used the requirements laid down in the national regulatory framework and standards for different technical documents that, although not mandatory, were identified by institutions or the government as expected and socially accepted, as in the case of the code of the sustainable construction for housing [51]. Second, based on the critical analysis of the evaluation of dwellings described and for the purpose of guiding sustainable practices, we set benchmarks for best practices and superior practices. By way of example, Figure 2 shows the benchmarks for the evaluation criteria of natural lighting, environmental temperature, humidity control, and natural ventilation.

4.3. Definition of Regional Priorities

The expert panel issued different values for each factor that influences the IEQ and evaluation criteria (Table 8), indicating that some things were viewed as more important than others.

The values of the weights that each group of experts issued were similar (Figure 3) and thus represented a consensus on the priorities and interests for the IEQ of dwellings. The order of priorities and the values of the weights were as follows: (a) air quality 0.37; (b) thermal comfort 0.32; (c) acoustics 0.16; and (d) illumination 0.15. These results are consistent with those of similar studies of office buildings [27]. With respect to the evaluation criteria, it seems logical that natural ventilation (0.2294), the performance of the envelope (0.1568), and control of contaminants (0.1406) would represent 53% of the total value of the weightings; therefore, these criteria were considered to have the greatest influence on the quality of the indoor environment.

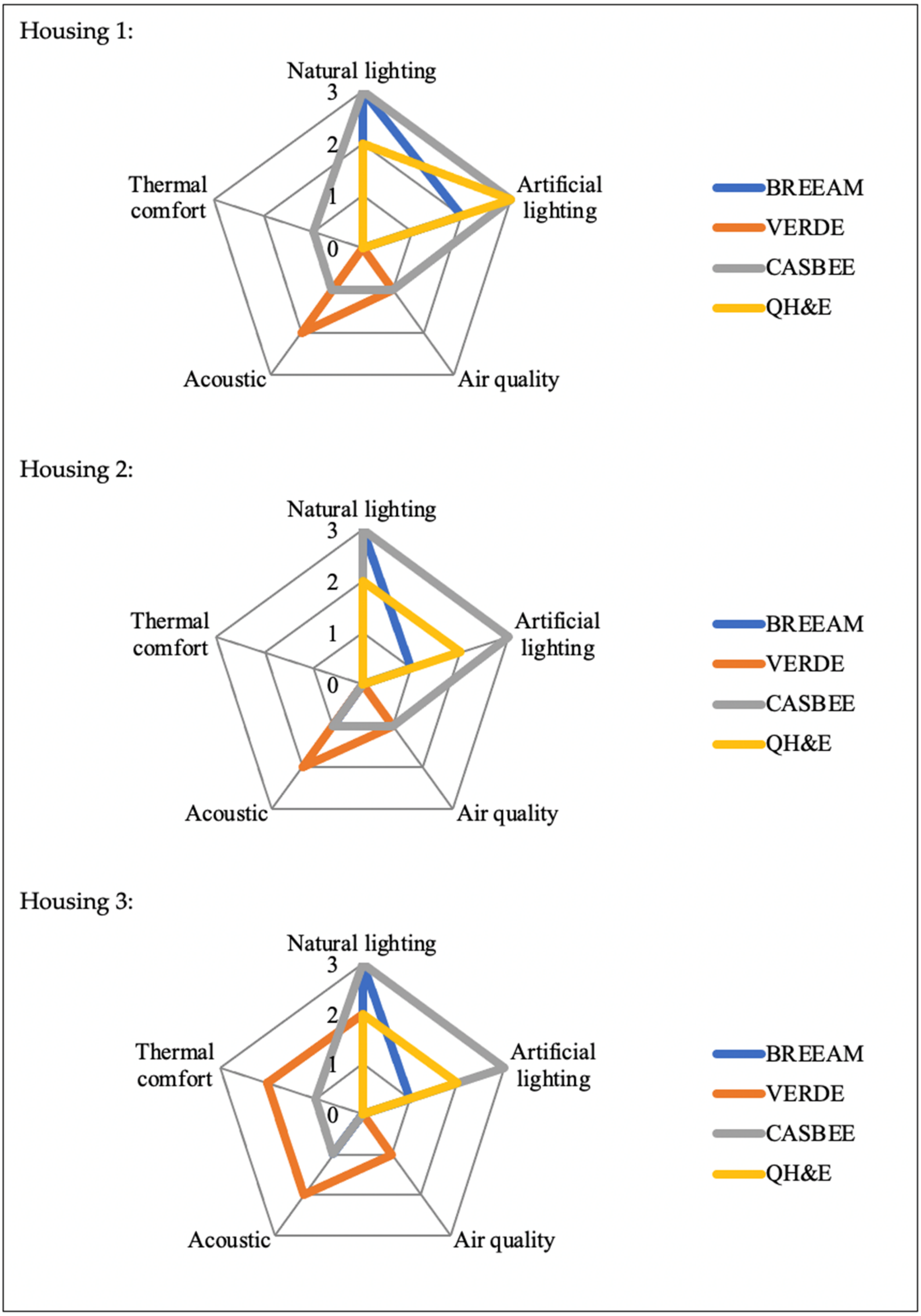


Figure 1. Comparison of the performance levels of the housing in the most representative evaluation criteria.

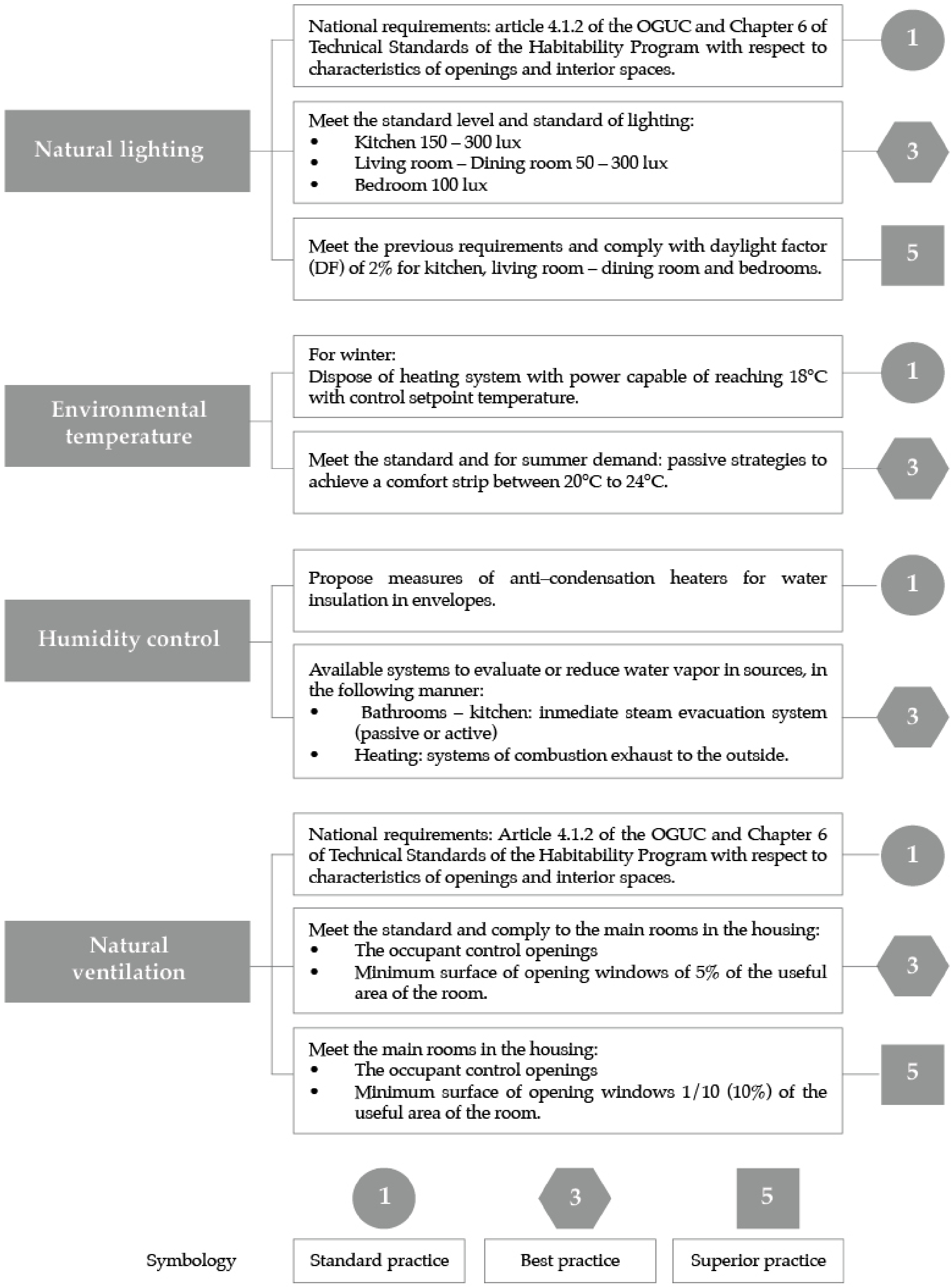


Figure 2. Example of reference for the evaluation criteria levels.

Table 8. Overall results of weightings.

Category	Weighting	Evaluation Criteria	Weighting
L: Lighting	15%	NL: Natural Lighting	0.42
		AL: Artificial Lighting	0.24
		GC: Glare Control	0.15
		VO: Views Outside	0.19
AQ: Air Quality	37%	NV: Natural Ventilation	0.62
		PC: Pollutants Control	0.38
A: Acoustic	16%	OAN: Outdoor Airborne Noise	0.67
		IN: Impact Noise	0.33
TC: Thermal Comfort	32%	ET: Environmental Temperature	0.23
		HC: Humidity Control	0.28
		BEP: Building Envelope Performance	0.49

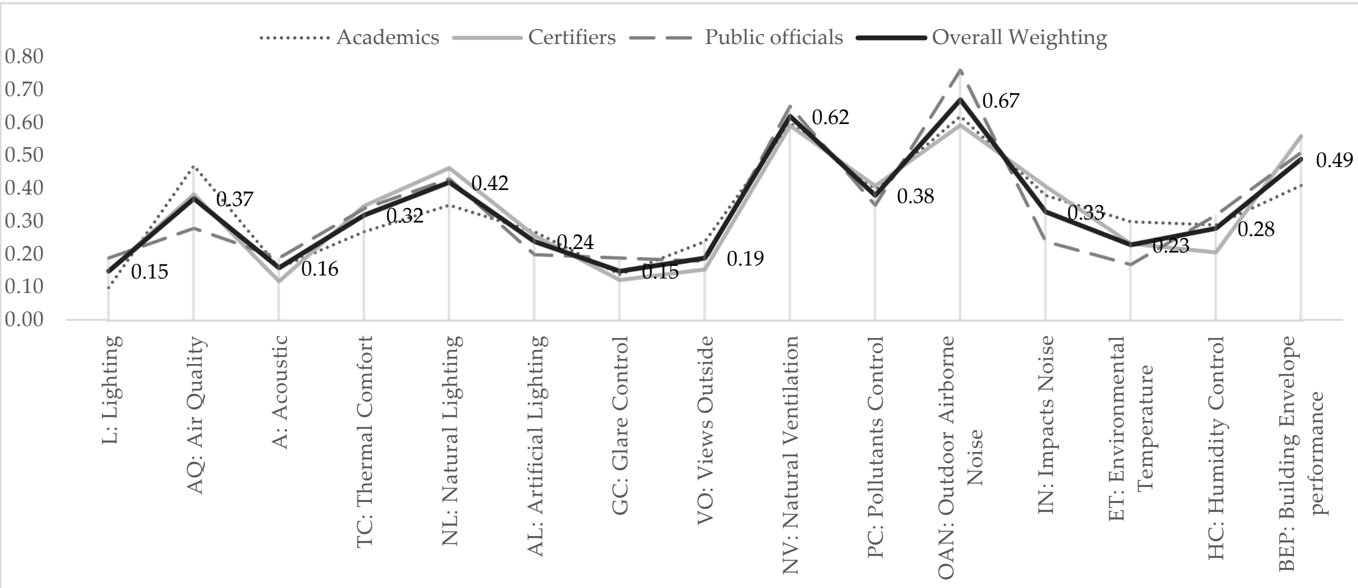


Figure 3. Comparisons of values of weights by interest group.

4.4. Proposed Assessment Model

The proposed model has a hierarchical structure in which the factors influencing the IEQ (categories) group the evaluation criteria and, on the basis of the model of Ncube and Riffat [27], establish a relationship between the perception of the quality and the categories. The proposed evaluation model is expressed by a function that integrates the four categories of IEQ and is explained by means of a formula or mathematical expression (1). The model is based on the linear relationship between the fulfillment of the requirements for each category through the allocation of score [49] and the perceived importance (Table 8 weights) (2). That is, the objective of the model is expressed by the air quality (3); thermal comfort (4); acoustics (5); and lighting (6), as shown in the following expressions:

$$IEQ = \sum \alpha i \omega i \quad (1)$$

$\alpha 1$–$\alpha 4$ are scores based on the level of performance of the four categories of the indoor environment, and ω is the weighting assigned as the coefficient of importance. Therefore, the quality of the indoor environment can be expressed using a multivariate model in the following way:

$$IEQ = (AQ \times 0.37) + (TC \times 0.32) + (A \times 0.16) + (L \times 0.15) \quad (2)$$

where AQ is air quality, TC is thermal comfort, A is acoustics, and L is lighting. These categories are fed by expressions composed of scores based on the reference level of each evaluation criterion (Table 8) and its weighting in the following way:

$$AQ = (NV \times 0.62) + (PC \times 0.38) \quad (3)$$

$$TC = (ET \times 0.23) + (HC \times 0.28) + (BEP \times 0.49) \quad (4)$$

$$A = (OEN \times 0.67) + (IN \times 0.33) \quad (5)$$

$$L = (NL \times 0.42) + (AL \times 0.24) + (GC \times 0.15) + (VO \times 0.19) \quad (6)$$

where NV is natural ventilation, PC is pollutants control, ET is environmental temperature, HC is humidity control, BEP is the building envelope performance, OEN is outdoor airborne noise, IN is impact noise, NL is natural lighting, AL is artificial lighting, GC is glare control, and VO is views outside.

The rating is obtained in a unique value by applying the model that represents the overall performance of the indoor environment of the housing and is grouped by rating ranges. The ranges are obtained by the points that issue the evaluation criteria at the three performance levels by their weighting. In order to obtain thresholds with integers greater than 100 points for the value of the coefficient ω in each rating range, it was decided to replace its percentage value with its integer (called weight). The threshold score for each reference range is:

- Standard practice: 100 points;
- Best practices: 240 points;
- Superior practices: 330 points.

Using the proposed model, we assessed the study dwellings to obtain the overall IEQ rating. Table 9 presents the results of housing 1, 2, and 3. The grades obtained ranged from 176.52 to 198.60 points, placing them at the level of standard practice. You can see that housing 1 and 3 obtained better performance. In addition, it is observed that the lowest levels of performance in the three houses were with respect to the acoustics evaluation criteria, while the highest levels of performance were for the air quality evaluation criteria.

Table 9. Results of the qualification of housing.

			Housing 1	Housing 2	Housing 3
Air Quality	NV	Points	3	3	3
		Weighting		0.62	
	PC	Points	1	1	1
		Weighting		0.38	
	Weight Category			37	
	The Category Qualification		82.88	82.88	82.88
Thermal Comfort	ET	Points	3	0	3
		Weighting		0.23	
	HC	Points	3	3	3
		Weighting		0.28	
	BEP	Points	0	0	0
		Weighting		0.49	
	Weight Category			32	
	The Category Qualification		48.96	26.88	48.96

Table 9. *Cont.*

			Housing 1	**Housing 2**	**Housing 3**
Acoustic	OAN	Points	1	1	1
		Weighting		0.67	
	IN	Points	3	3	3
		Weighting		0.33	
	Weight Category			16	
	The Category Qualification		26.56	26.56	26.56
Lighting	NL	Points	5	5	5
		Weighting		0.42	
	AL	Points	1	1	1
		Weighting		0.24	
	GC	Points	1	1	1
		Weighting		0.15	
	VO	Points	1	1	1
		Weighting		0.19	
	Weight Category			15	
	The Category Qualification		40.20	40.2	40.2
QUALIFICATION IEQ			198.60	176.52	198.60

5. Conclusions

After evaluating the BSA systems, it was possible to observe that the assessment criteria varies from one system to another due the way each poses its levels of exigency and performs its assessments. For that reason, during the application of the BSA's assessment criteria into the case studies, different results were obtained for a single criteria according to the BSA. Secondly, systems such as BREEAM, VERDE, and CASBEE were the ones that could apply their assessment criteria into the case studies.

From the BSA evaluation, eleven assessment criteria were identified along with their proper performance levels for the existing housing in the region of Bío-Bío. Additionally, through the consensus with experts, it was possible to define local priorities for the IEQ assessment in order to establish categories such as air quality (AQ) and thermal comfort (TC) and assessment criteria such as natural ventilation (NV), building envelope performance (BEP), and outdoor airborne noise (OAN), which altogether have more importance and influence on the quality of the internal environment of the region's houses.

On the basis of those results, we propose a model of evaluation of indoor environment quality (IEQ) that integrates performance and weights the importance of the different evaluation categories. In this sense, the model is a tool for predicting the future performance of an indoor environment and provides support for residential architectural design.

As regards the methodology of investigation used, since there is no international agreement on the process to be followed for the generation of BSA, this research proposes an approach for the development and contextualization of BSA systems to be structured in three stages:

1. Identify evaluation criteria within an international framework;
2. Select and contextualize evaluation criteria through field assessments;
3. Define regional priorities with the participation of experts.

Future efforts should continue to conduct and refine this type of research to contribute to the objective of sustainable housing. It is important to define how IEQ contributes to the goal of sustainability and at the same time to integrate energy efficiency without compromising its standards. In addition, future research must continue to develop and improve methodologies that enable building assessment schemes and other spatial scales to be placed in different contexts.

Author Contributions: Conceptualization, F.Q.-M.; Methodology, F.Q.-M.; Investigation, F.Q.-M.; Writing—original draft, F.Q.-M.; Writing—review & editing, F.Q.-M. and S.A.-C.; Project administration, F.Q.-M. and S.A.-C.; Funding acquisition, S.A.-C. All authors have read and agreed to the published version of the manuscript.

Funding: The project "Contextualization of Sustainable Indicators for Neighborhoods in the city of Cuenca-Ecuador" was funded by the Vice-rectorate of Research of the University of Cuenca, Cuenca-Ecuador. Grant number 2040000 07 1636. And The APC was funded by the Vice-rectorate of Research of the University of Cuenca.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors wish to express their gratitude to the University of Cuenca and its Research Vice-rectorate (VIUC) for providing the necessary funds for the research project "Contextualization of Sustainable Indicators for Neighborhoods in the city of Cuenca-Ecuador". Moreover, we thank Rodrigo García for the opportunity to collaborate on his project.

Conflicts of Interest: The authors declare no conflict of interest.

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