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Beyond Structure: Defining Inhabitable Performance in Buildings

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Abstract– Buildings are commonly assessed using structural or energy-related indicators; however, these approaches do not fully capture their capacity to support human occupation. This study addresses this gap by introducing the concept of Inhabitable Performance as an engineering-oriented framework grounded in measurable indoor conditions. A structured review of 19 calculation-based models was conducted to analyze how inhabiting conditions are quantified, focusing on their parameters, methodological structures, and applicability. Three representative models, the New Zealand Apartment Liveability Index (NZ ALI), the Healthy Housing Index (HHI), and the Building Habitability Index (Q), were selected for comparative evaluation based on their parameter coverage, indoor focus, and calculability. These models were applied to two real residential case studies in Temuco, Chile, using a consistent dataset derived from monitored indoor environmental conditions and building characteristics. Results show that differences in index values are primarily driven by how parameters are structured and weighted rather than by their inclusion alone. Performance outcomes are strongly influenced by occupancy density, envelope performance, and ventilation strategies, with the newer building exhibiting lower inhabitable performance than the older case, suggesting that occupancy and indoor environmental conditions may play a more relevant role than structural characteristics alone. The findings indicate that current models provide complementary rather than equivalent representations and underscore the importance of considering Inhabitable Performance beyond structural attributes alone. This study proposes Inhabitable Performance as a basis for integrating measurable indoor variables into engineering assessment frameworks, supporting more robust evaluation of buildings intended for human occupation.

Keywords-- Inhabitable performance, Indoor environmental quality, Building performance assessment, Habitability index

I. Introduction

Buildings are not merely physical structures but complex indoor systems where technical performance, environmental conditions, and human occupancy interact continuously. From an engineering perspective, the ability of a building to be effectively inhabited depends on its capacity to deliver adequate indoor performance over time, rather than solely on its structural integrity. Indoor thermal conditions, air quality, ventilation, moisture control, acoustic comfort, and spatial adequacy are all outcomes of design decisions, material choices, and operational strategies that directly influence occupants' well-being and the functional adequacy of the building [1], [2].

International organizations have long emphasized that buildings intended for human occupation must ensure minimum conditions that allow safe and healthy use. According to the World Health Organization (WHO), adequate housing must provide physical protection, basic services, environmental comfort, sufficient space, and safety [3]. These criteria can be interpreted not only as qualitative requirements, but as performance conditions that determine whether a building can sustain human occupation. When such conditions are not met, buildings may become sources of health risk rather than protection, exposing occupants to indoor hazards such as dampness and mould, inadequate thermal insulation leading to low indoor temperatures, insufficient ventilation, overcrowding, and poor indoor air quality [2], [4], [5]. These deficiencies have been associated with respiratory diseases, infections, injuries, and adverse mental health outcomes, including a significantly higher risk of severe psychological distress in inadequately heated indoor environments [6].

The scale of this challenge is considerable. Globally, nearly one billion people occupy buildings that fail to meet basic conditions for adequate indoor use [3]. Evidence suggests that indoor environmental conditions often have a stronger influence on occupants' satisfaction and well-being than external or urban factors [7].These issues are particularly acute in vulnerable contexts characterized by high occupancy density, insufficient insulation, energy poverty, and limited maintenance, where poor indoor performance exacerbates both physical and mental health risks [8]–[13]. Moreover, housing shortages and affordability constraints frequently force disadvantaged populations to inhabit buildings that do not comply with minimum performance thresholds required for safe and healthy use [14], [15]. This context highlights the need to move beyond descriptive definitions of habitability toward quantifiable performance-based approaches.

Over recent decades, research has progressively shifted from viewing buildings solely as static enclosures toward recognizing them as dynamic systems whose performance must be evaluated in relation to human occupation. This shift has led to the development of multiple frameworks, indices, and calculation-based models that attempt to quantify indoor conditions associated with inhabiting buildings. These models often integrate parameters related to thermal performance, indoor air quality, spatial adequacy, energy use, and environmental control, reflecting an effort to translate qualitative notions of adequate indoor conditions into measurable engineering terms [16]–[18]. However, this transition toward quantification has not resulted in methodological convergence, and existing models remain fragmented in their structure and scope.

Quantifying inhabiting conditions in buildings remains a complex challenge. Existing studies employ a wide range of assessment methods, from engineering-based calculations and monitoring campaigns to hybrid approaches that combine physical measurements with occupant feedback [18]–[20]. While some models focus primarily on technical performance indicators, others incorporate health-related or functional criteria. At the same time, many assessment frameworks originate from urban or planning contexts and emphasize external conditions, offering limited resolution of indoor building performance. Only a restricted number of models explicitly aim to calculate the level of inhabiting performance within the indoor environment itself, and these often remain partial or context-specific, lacking a consistent and transferable calculation structure [21]–[23].

This fragmentation is further reinforced by disciplinary boundaries. Building engineering and environmental sciences tend to prioritize measurable indoor parameters such as temperature, ventilation rates, humidity, and pollutant concentrations, while other fields emphasize social, behavioral, or spatial aspects of occupation. As a result, existing calculation frameworks rely on disparate sets of parameters, limiting their comparability and hindering the development of integrative models capable of capturing the multidimensional nature of inhabiting buildings [2], [24]–[27]. This raises a central challenge for engineering research: how to define inhabitable performance in a way that is both measurable and comparable across contexts.

Against this background, the present study addresses the lack of a consolidated engineering-oriented framework for quantifying inhabiting conditions in buildings. The paper aims to identify and analyze existing calculation-based models that seek to quantify inhabiting performance, examining the parameters they employ and the assumptions underlying their formulation. Through a structured review of scientific literature published over the last decade, complemented by a targeted manual review of influential references, the study synthesizes current approaches and highlights key gaps in existing models.

Specifically, this paper is guided by the following research questions:

1) How are inhabiting conditions in buildings currently quantified through calculation-based models in engineering research?

2) What parameters are used in existing models to calculate inhabiting performance in buildings?

3) Which existing calculation-based models provide the most comprehensive approach to quantifying inhabiting performance in buildings, and how do their results compare when applied to real case studies?

By addressing these questions, this work moves beyond descriptive analyses by evaluating the operational performance of selected models under consistent conditions, providing a structured overview of current calculation-oriented approaches and identifying convergences and limitations across existing models. Comparative application in real residential cases enables assessing their consistency and practical applicability, while informing the development of more robust, performance-based frameworks to support engineering design and decision-making for buildings intended for human occupation.

II. METHODOLOGY

This study adopts a structured, engineering-oriented approach that combines a targeted literature analysis of calculation-based models with an applied comparative assessment in real residential case studies. The methodological approach is aligned with previous engineering syntheses of calculation-based assessment models in building science, while extending beyond review by incorporating empirical application [28], [29].

The methodology is organized in three main stages:

1) identification and analysis of existing calculation-based models,

2) data extraction, comparative analysis and selection of the most comprehensive models based on predefined criteria,

3) application and comparison of selected models in real dwellings.

A. Identification and analysis of calculation-based models

The analysis focused on peer-reviewed scientific literature published over the last ten years, complemented by a targeted backward review of frequently cited references when methodologically relevant. Literature was identified through searches in Google Scholar using combinations of keywords related to building performance, indoor conditions, and calculation-based assessment models, including ("indoor building performance" OR "indoor living conditions") (index OR score).

This strategy aimed to capture studies proposing formalized approaches for quantifying inhabiting performance. The initial search yielded 204 publications, which were screened using explicit inclusion and exclusion criteria.

Inclusion criteria: studies proposing or applying calculation-based models (e.g., equations, indices, or weighted scoring frameworks) with quantitative outputs, applicable to buildings intended for long-term human occupation, incorporating indoor-related physical or environmental parameters, and published as peer-reviewed journal articles.

Exclusion criteria: conceptual or qualitative studies without formalized calculation structures, perception-based assessments without quantitative models, and studies focused exclusively on urban-scale or external conditions.

After applying these criteria, 19 articles were included, including those identified through manual search.

B. Data extraction and comparative analysis

For each included study, key information was systematically extracted using a predefined analysis matrix. The extracted data included bibliographic information (title, year, authors, country, and source), as well as methodological and technical characteristics relevant to this study.

Specifically, the following elements were extracted and analyzed:

1) Type of index, score, or calculated indicator proposed or applied.

2) Type of metric used for quantifying inhabiting performance.

3) Scale of application (e.g., room, dwelling unit, building).

4) Parameters included in the calculation framework.

5) Relative weighting or aggregation rules applied to the parameters, when specified.

This structured extraction enabled a comparative analysis of existing models, allowing the identification of recurring parameters, common calculation structures, and methodological gaps.

In addition, the models were evaluated according to a set of engineering-oriented criteria in order to assess their level of completeness and applicability. These criteria included:

(i) coverage of relevant indoor performance variables,

(ii) clarity and robustness of the mathematical structure,

(iii) applicability at the dwelling scale, and

(iv) availability of required input data for real-world implementation.

C. Selection of representative models

Based on the comparative analysis, a subset of the most comprehensive and methodologically robust models was selected for further evaluation. The selection focused on models that demonstrated a broader integration of indoor performance parameters, a transparent and reproducible calculation structure, and practical applicability to real buildings.

Rather than aiming to identify a single "best" model, this stage prioritizes the selection of representative models that capture different methodological approaches while maintaining sufficient completeness to allow meaningful comparison. To support this process, additional evaluative attributes were defined and later used for comparative analysis in the Results section. These attributes include level of indoor focus, data requirements, and level of applicability, which were qualitatively classified by the authors using three levels (high, medium, low).

The level of indoor focus reflects the extent to which the parameters included in each model are associated with indoor conditions at the dwelling or building level. Models classified as high are primarily based on indoor-related parameters, medium indicates a combination of indoor and broader contextual parameters, and low corresponds to models predominantly oriented toward urban, structural, or aggregated conditions. The data requirements indicate the level of information needed to apply each model. Models with high data requirements rely on detailed inspections, measurements, or expert-based assessments; medium corresponds to models that use standard or commonly available datasets; and low refers to models that can be applied using simplified or perception-based inputs. The level of applicability represents the degree to which a model can be directly implemented in real case studies using available data. Models classified as high are fully calculable and operational, with clearly defined inputs and procedures. Medium applicability indicates that the model can be applied with certain assumptions or adaptations, while low corresponds to models that are not directly calculable or depend on perception-based or statistical structures that limit their practical implementation.

These criteria provide a consistent basis for selecting representative models and enable a structured comparison of their performance in real residential case studies.

D. Application in real residential case studies

The selected models were applied to two real residential case studies located in the city of Temuco, Chile (38.74° S, 72.60° W, temperate rainy climate - Cfb), for which detailed indoor environmental and building performance data were available.

Case 1 corresponds to a private dwelling (77.0 m², built in 2010) with low occupancy density (38.5 m²/person), masonry construction, and a relatively high level of envelope insulation. This case also presents comparatively favorable indoor environmental conditions, including moderate thermal performance and controlled humidity levels. In contrast, Case 2 corresponds to a more recent social dwelling (48.5 m², built in 2016) with higher occupancy density (16.2 m²/person), timber-frame construction, and a medium-to-low level of envelope performance, resulting in less favorable indoor environmental conditions, particularly in terms of humidity and thermal stability. These contrasting characteristics provide a relevant basis for evaluating the sensitivity of the selected models under different physical and operational conditions.

Both case studies correspond to dwellings intended for long-term human occupation and present contrasting characteristics in terms of construction, operation, and indoor environmental conditions. The same input dataset was used across all selected models in order to ensure consistent boundary conditions.

This application enables a direct comparison of model outputs under identical conditions, providing insights into:

(i) the consistency of results across models,

(ii) their sensitivity to input parameters, and

(iii) their capacity to represent inhabiting performance in practice.

A detailed description of both case studies is provided in the Appendix A (Table VI), including their physical, environmental, and operational characteristics.

III. RESULTS

A. Overview of identified calculation-based models

A total of 19 models for assessing inhabiting conditions in buildings were identified and analyzed. These models exhibit considerable heterogeneity in their methodological approach, reflecting the coexistence of engineering-based indices, rating frameworks, and perception-oriented assessments within the field. Table I presents the main characteristics of the identified models, including their geographical context, model type, scale of application, and abbreviation.

TABLE I
OVERVIEW AND CLASSIFICATION OF MODELS FOR ASSESSING INHABITING CONDITIONS IN BUILDINGS

N	Year	Authors	Ref.	Country	Model / assessment name	Model Type	Abb.
1	2024	Aristondo et al.	[30]	Spain	Overall Discomfort Index	Composite synthetic index	ODI
2	2024	Ashraf	[31]	India	Resident Satisfaction Score	Resident-based satisfaction score	RSS
3	2021	Behr et al.	[3]	Nigeria	Adequate Housing Index	Composite synthetic index	AHI
4	2010	Bennett	[32]	New Zealand	New Zealand Apartment Liveability Index	Composite synthetic index	NZ ALI
5	2018	Garay et al.	[33]	Chile	Índice Integrado de Seguridad y Sust.	AHP-based rating framework	IISS
6	2025	Garrison et al.	[21]	USA	Housing Quality Metric	Composite synthetic index	HQM
7	2007	Keall et al.	[34]	New Zealand	Healthy Housing Index	Expert inspection–based synthetic index	HHI
8	2010	Keall et al.	[35]	New Zealand	Housing Health & Safety Rating System	Rating system	HH& SRS
9	2017	Liu	[36]	China	Habitable Housing Index	AHP-based livability rating / scoring system	S
10	2021	Mercader-Moyano et al.	[37]	Mexico	Socially Lagging Housing	Composite synthetic index	SLH
11	2025	Musiitwa et al.	[38]	Kenya	Severity Index	Synthetic index	SI
12	2013	Orellana et al.	[39]	Chile	Índice de Calidad de Vida Urbana	Composite synthetic index with rating	ICVU
13	2020	Peña-Barrera et al.	[40]	Mexico	Índice de Habitabilidad y Cohesión Social	Composite synthetic index	IHaCoS
14	2018	Roh et al.	[41]	Korea	The Building Habitability Index	Composite synthetic index	Q

TABLE I (Continued)
OVERVIEW AND CLASSIFICATION OF MODELS FOR ASSESSING INHABITING CONDITIONS IN BUILDINGS

N	Year	Authors	Ref.	Country	Model / assessment name	Model Type	Abb.
15	2021	Salazar & Ley	[42]	Mexico	Índice de Vivienda Inadecuada	Composite synthetic index	IVINA
16	2025	Sarkar et al.	[43]	India	Decent Living Standars	Latent composite score	DLS
17	2022	Ugás et al.	[44]	Peru	Índice de Habitabilidad	Multidimensional synthetic index	IH
18	2018	UN-Habitat	[45]	Kenya	The Housing Rights Index	policy / expert-based composite index	HRI
19	2021	Vima-Grau et al.	[46]	Spain	Global Habitability Index	Composite synthetic index	GHI

The results show a clear predominance of composite synthetic indices, which constitute the most common approach for quantifying inhabiting conditions. These models typically aggregate multiple variables into a single indicator, generally through additive or weighted structures. In contrast, a smaller group of models adopts alternative approaches, including AHP-based frameworks, expert-based rating systems, latent statistical models, and resident-based satisfaction scores, which differ in their level of formalization and calculability.

In terms of scale, the models are distributed across multiple spatial levels. While a significant proportion operates at the dwelling scale, several models are defined at urban or national levels, and others combine multiple scales, integrating dwelling-level and neighborhood-level dimensions. This dispersion reveals the absence of a consistent scale for assessing inhabiting performance and reflects differing interpretations of habitability across disciplines.

Geographically, the models are distributed across diverse regions, including Europe, Latin America, Asia, and Africa, indicating a broad international interest in the quantification of inhabiting conditions. However, this diversity is also associated with variability in methodological approaches and contextual priorities.

Finally, although most models produce quantitative outputs in the form of indices, scores, or ratings, their structure varies considerably. While some models are fully calculable and suitable for engineering applications, others rely on qualitative assessments or perception-based data, limiting their direct comparability and operational use.

B. *Comparative analysis of calculation-based models*

To enable a structured comparison of the identified models, a set of analytical attributes was defined, including model type, scale of application, level of indoor focus, data requirements, number of dimensions, number of parameters, and parameter coverage. These attributes allow a systematic evaluation of the methodological structure, scope, and applicability of each model.

The parameter-related indicators (number of dimensions, number of parameters, and parameter coverage) were calculated based on a standardized set of 21 parameters identified across the reviewed models. These parameters correspond to those repeated in at least three different studies, ensuring consistency in the comparison. Although several models originally included a larger number of parameters, only those aligned with this common set were considered in this analysis. Consequently, the number of parameters reported for each model reflects only the subset of parameters shared across the reviewed literature.

Parameter coverage was defined as the proportion of these 21 common parameters included in each model. For example, a model originally composed of 15 parameters may include only 10 parameters from the standardized set; therefore, it is reported as having 10 parameters and a parameter coverage of 48% (10/21). This approach allows a consistent comparison of the relative completeness of each model.

The 21 identified parameters were grouped into four main dimensions: functional (10 parameters), environmental (9 parameters), material condition (1 parameter), and economic (1 parameter), reflecting the multidimensional structure of inhabiting performance. The detailed composition of parameters and dimensions for each model is provided in Appendix.

TABLE II
COMPARATIVE ANALYSIS OF CALCULATION-BASED MODELS FOR INHABITING PERFORMANCE IN BUILDINGS

N	Model	Type	Scale	I. Focus	Data	Appl.	Dim.	P.	P. Cov.
1	ODI	Index	D	H	M	H	2	6	29%
2	RSS	Score	D/U	M	L	L	2	9	43%
3	AHI	Index	N	L	M	L	3	5	24%
4	NZ ALI	Index	D/U	M	M	H	3	16	76%
5	IISS	Rating	D	M	H	M	2	3	14%
6	HQM	Index	U/N	L	H	L	2	8	38%
7	HHI	Index	D	H	H	H	3	9	43%
8	HH&S RS	Rating	D	H	H	M	2	10	48%
9	S	Rating	D	H	M	M	2	5	24%
10	SLH	Index	U/N	L	M	L	2	7	33%
11	SI	Index	D/U	M	M	M	2	8	38%
12	ICVU	Index	U	L	M	L	1	1	5%
13	IHaCo S	Index	D/U	M	M	M	3	8	38%

TABLE II (Continued)
COMPARATIVE ANALYSIS OF CALCULATION-BASED MODELS FOR INHABITING PERFORMANCE IN BUILDINGS

N	Model	Type	Scale	I. Focus	Data	Appl.	Dim.	P.	P. Cov.
14	Q	Index	D	H	M	H	2	6	29%
15	IVINA	Index	U	M	M	L	3	5	24%
16	DLS	Score	D	M	H	L	2	6	29%
17	IH	Index	D/U	M	M	M	2	2	10%
18	HRI	Index	U/N	M	H	L	4	12	57%
19	GHI	Index	D	M	M	M	2	6	29%

Note: D: Dwelling, U: Urban, N: National, H: High, M: Medium, L: Low, I. Focus: Indoor Focus, Appl.: Applicability, Dim.: Dimension, P: Parameters, P. Cov.: Parameter Coverage.

The results show a heterogeneous distribution of models across different spatial scales, including dwelling, urban, national, and multi-scale approaches. While several models operate at the dwelling level, a considerable number extend their scope to broader spatial contexts or combine multiple scales within the same framework.

The level of indoor focus varies across models. A subset of models presents a high indoor focus, meaning that their parameter sets are primarily associated with indoor conditions at the dwelling or building level. In contrast, other models incorporate parameters related to broader spatial contexts, resulting in medium indoor focus classifications. Additionally, some models show a low indoor focus, as their parameter sets are predominantly oriented toward urban or aggregated conditions rather than indoor environments. This distribution indicates that the consideration of indoor conditions is not consistent across existing models.

Differences in data requirements reflect varying levels of complexity and applicability. Models with high data requirements typically depend on detailed inspections, measurements, or structured assessment procedures, while those with medium requirements rely on standardized datasets or commonly available information. Models with low data requirements are generally based on simplified or perception-driven inputs, enabling easier implementation but with reduced technical depth. The number of dimensions considered by the models ranges from one to four, indicating different levels of conceptual integration. Similarly, the number of parameters varies considerably across models. However, parameter coverage remains limited in most cases, with only a small number of models incorporating more than half of the identified common parameters. This suggests that most models address only a partial subset of the parameters associated with inhabiting performance.

Overall, the results highlight substantial variability in model structure, scope, and level of detail, particularly in relation to scale, indoor focus, data requirements, and parameter coverage. These differences provide the basis for the selection of representative models presented in the following section.

C. Application to real case studies

Based on the comparative analysis presented in the previous section, a subset of three representative models was selected for application in real residential case studies. The selection was guided by four main criteria: (i) relatively high parameter coverage, ensuring a broader representation of inhabiting performance; (ii) medium or lower data requirements, allowing practical implementation without excessive data constraints; (iii) high or justified medium indoor focus, prioritizing models centered on indoor conditions; and (iv) a calculable structure, enabling direct application through explicit equations or scoring procedures.

Following these criteria, the selected models were: the New Zealand Apartment Liveability Index (NZ ALI), the Healthy Housing Index (HHI), and the Building Habitability Index (Q).

The NZ ALI was selected due to its high parameter coverage (76%), representing the most comprehensive integration of the identified parameters among the analyzed models. Although it presents a medium indoor focus, its structure incorporates a broad range of parameters associated with dwelling conditions, making it suitable for comparative purposes.

The HHI was selected as a representative model with high indoor focus and relatively high parameter coverage (43%), combined with a structured and calculable framework. Its emphasis on dwelling-level conditions and systematic assessment approach allows a detailed evaluation of indoor-related conditions from a health-risk perspective.

The Building Habitability Index (Q) was selected due to its high indoor focus and explicit calculable structure based on weighted aggregation. Unlike inspection-based or hierarchical frameworks, Q provides a direct and flexible formulation that can be adapted to measurable indoor parameters. Although its parameter coverage is moderate (29%), its methodological clarity and compatibility with quantitative data make it suitable for application in monitored residential environments.

Together, these models represent different methodological approaches, levels of parameter integration, and data requirements, enabling a comparative assessment of their performance under consistent conditions.

Although the New Zealand Apartment Liveability Index (NZ ALI) is originally conceived as a multi-dimensional rating framework, a reduced version is proposed here based on parameters directly measurable and relevant to indoor conditions. This adaptation focuses on Indoor Environmental Quality, spatial conditions, and building-related aspects that can be consistently applied to the available case study data.

It is important to note that, although several parameters are shared across the three models, the resulting index values are not directly equivalent. Differences arise from the relative weighting assigned to each parameter, which reflects the underlying conceptual focus of each model, such as overall performance, health-related risk, or multidimensional habitability.

TABLE III
ADAPTED NZ ALI CALCULATION AND RESULTS FOR THE CASE STUDIES

Parameter		Weight	Score	
			1	2
1	Overcrowding	15%	1.00	0.50
2	Lighting	5%	1.00	1.00
3	Ventilation	10%	1.00	0.75
4	Humidity	15%	0.75	0.25
5	Temperature	20%	0.25	-
6	CO_2	20%	0.50	0.50
7	Condition of materials	15%	1.00	0.50
NZ ALI			**0.71**	**0.41**

Each parameter was evaluated using monitored or derived data and normalized into a score ranging from 0 to 1, representing the level of performance or compliance. The final NZ ALI score was calculated as a weighted aggregation of the selected parameters, preserving the relative importance assigned within the adapted framework.

The Healthy Housing Index (HHI) is originally based on inspection-derived indicators focused on identifying health-related risks in dwellings. In this study, an adapted version is implemented using measurable indoor and building-related parameters, allowing its application to the available case study data. This adaptation maintains the original focus on health and risk conditions while translating them into quantifiable indicators associated with indoor environmental performance, spatial conditions, and building state. Each parameter was evaluated using monitored or derived data and expressed as a normalized score between 0 and 1. The final HHI value was calculated as a weighted aggregation of the selected parameters, enabling a consistent comparison with the other applied models. The resulting HHI values for the two case studies are presented in Table IV.

TABLE IV
ADAPTED HHI CALCULATION AND RESULTS FOR THE CASE STUDIES

Parameter		Weight	Score	
			1	2
1	Overcrowding	15%	1.00	0.50
2	Ventilation	10%	1.00	0.75
3	Humidity	15%	0.75	0.25
4	Temperature	15%	0.25	-
5	Mold	10%	1.00	1.00
6	CO2	20%	0.50	0.50
7	Condition of materials	15%	1.00	1.00
HHI			**0.75**	**0.54**

The Building Habitability Index (Q) is formulated as a weighted aggregation model combining multiple dimensions of building performance. In this study, an adapted version is applied using measurable parameters aligned with indoor environmental conditions, spatial aspects, and energy performance. This approach preserves the original structure of the model while enabling its direct application to the available case study data. Each parameter was evaluated using monitored or derived data and normalized into a score between 0 and 1, representing the level of performance. The final Q value was calculated as a weighted aggregation of the selected parameters, allowing a direct comparison with the other applied models. The resulting Q values for the two case studies are presented in Table V.

TABLE V
ADAPTED Q CALCULATION AND RESULTS FOR THE CASE STUDIES

	Parameter	Weight	Score	
			1	2
1	Overcrowding	20%	1.00	0.50
2	Humidity	10%	0.75	0.25
3	Temperature	15%	0.25	-
4	Mold	10%	1.00	1.00
5	CO_2	15%	0.50	0.50
6	Heating demand	30%	1.00	-
	Q		**0.79**	**0.30**

The results obtained from the three applied models reveal differences in the magnitude and distribution of index values across the two case studies. A detailed interpretation of these differences is provided in the following section.

IV. DISCUSSION

A. *Evolution and nature of calculation-based models*

The results indicate that the quantification of inhabiting conditions is characterized by the coexistence of multiple methodological approaches rather than a unified framework. Although composite synthetic indices are the most prevalent, their structures, parameter selections, and underlying assumptions vary considerably, reflecting different disciplinary perspectives.

This heterogeneity is also evident in the range of application scales, from dwelling-level to urban and national contexts. The absence of a consistent spatial reference suggests that habitability is still interpreted differently depending on the intended scope of analysis, which limits comparability and transferability across models.

Finally, differences in calculability reveal a clear distinction between models designed for direct application using measurable parameters and those relying on qualitative or perception-based inputs. This divergence indicates that, despite the apparent convergence toward index-based approaches, the operationalization of habitability remains fragmented and context-dependent.

B. *Comparative structure and applicability of models*

The comparative analysis highlights that differences between models are not only associated with the number of parameters included, but also with how these parameters are structured, weighted, and operationalized. As shown in the comparative framework (see Table II) , models with similar parameter sets can produce substantially different outcomes due to variations in their aggregation logic and conceptual emphasis. This indicates that methodological structure plays a more decisive role than parameter presence alone.

A clear distinction emerges between models with high applicability and those with limited operational use. While some models provide explicit calculation structures compatible with measurable indoor data, others rely on qualitative inputs or broader contextual variables, restricting their direct implementation. This reveals a gap between theoretically comprehensive models and those that can be effectively applied in real-case assessments.

Parameter coverage across models remains generally limited, with only a few approaches incorporating a large proportion of the identified common parameters. Most models therefore capture only partial aspects of inhabiting performance, prioritizing specific dimensions or parameter groups. This reinforces the need for more integrated approaches that balance parameter coverage, indoor relevance, and practical applicability.

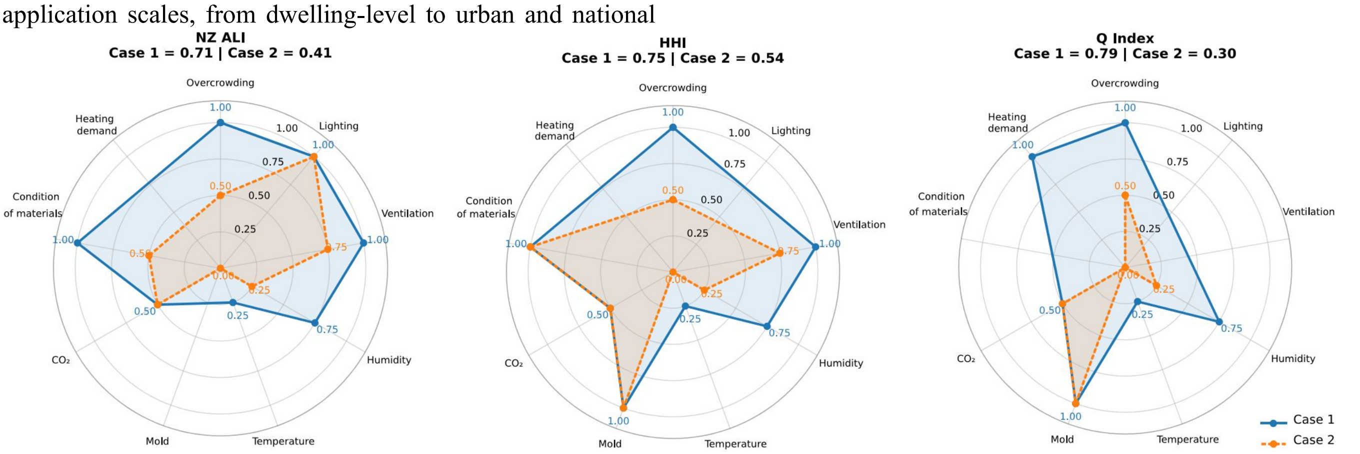

Fig. 1 Variable-level Scores by Case and Index.

C. Insights from application in case studies

The application of the three selected models to the same case studies shows that differences in resulting index values are primarily driven by how parameters are structured and weighted rather than by their inclusion alone. Fig. 1 illustrates these differences at the variable level, presenting normalized scores across the three indices with consistent parameter positions to enable direct comparison. The figure highlights that variations in occupancy, ventilation, and humidity-related parameters are key drivers of performance differences, particularly in Case 2.

In addition to these methodological differences, the results also reflect the underlying physical and operational characteristics of each case study. Case 2 consistently shows lower scores in humidity-related parameters across all models, which can be associated with its higher occupancy density, lower airtightness, and absence of mechanical-assisted ventilation. These conditions favor moisture accumulation and reduced environmental control, directly affecting its performance in humidity-related indicators. In contrast, Case 1 benefits from lower occupancy density, higher envelope insulation, and the presence of mechanical-assisted ventilation, resulting in more stable indoor environmental conditions.

Similarly, differences in overcrowding-related indicators are directly linked to the available floor area per occupant, with Case 1 presenting significantly higher spatial availability (38.5 m^2/person) compared to Case 2 (16.2 m^2/person). This translates into better performance in indicators associated with spatial adequacy and occupancy conditions.

This becomes particularly evident when comparing models with different conceptual orientations. The NZ ALI emphasizes a broader, multidimensional perspective, the HHI prioritizes health-related risk conditions, and the Q index focuses on performance-based evaluation. As a result, each model captures different aspects of the same dwelling conditions, reinforcing that the interpretation of habitability is inherently dependent on the underlying methodological framework.

These differences indicate that the selection of a model is not neutral, as it directly influences the assessment outcome. Rather than converging toward a single representation of inhabiting performance, the results suggest that current models provide complementary perspectives, each reflecting specific priorities and assumptions regarding indoor conditions and building performance.

V. Conclusions

The analysis of existing models confirms that the quantification of inhabiting conditions has evolved toward index-based approaches; however, this evolution has not led to methodological convergence. Current models reflect different disciplinary perspectives, resulting in heterogeneous structures, scales of application, and levels of formalization.

The comparative evaluation shows that differences between models are not primarily explained by the parameters they include, but by how these parameters are structured and weighted. Even when similar parameters are considered, variations in aggregation logic and conceptual focus lead to different representations of inhabiting performance. Across the reviewed models, parameters related to indoor environmental conditions, such as temperature, humidity, ventilation, air quality, and spatial adequacy, are consistently present, although their integration remains partial and uneven.

The application to real case studies demonstrates that these differences are not only methodological but also linked to the physical and operational characteristics of the dwellings. Variations in occupancy density, envelope performance, and ventilation strategies directly influence key indicators, particularly those related to humidity and spatial adequacy. This confirms that performance outcomes cannot be interpreted independently from the building context.

A particularly relevant finding emerges from the direct comparison of the two case studies. Despite being a more recent construction, Case 2 consistently exhibits lower inhabitable performance across all applied indices compared to Case 1, which corresponds to an older dwelling. This contrast suggests that building age or structural condition alone may not determine inhabiting performance. Instead, factors such as occupancy density, ventilation strategy, and indoor environmental conditions appear to play a more decisive role in shaping overall performance outcomes.

The comparison of selected models (NZ ALI, HHI, and Q index) shows that each framework emphasizes different aspects of inhabiting conditions, ranging from health risk to multidimensional and performance-based perspectives, resulting in complementary, rather than equivalent, assessments.

In this context, the results support the need to move beyond structure-based evaluations toward the definition of Inhabitable Performance as an engineering-oriented concept grounded in measurable indoor conditions. Rather than being inferred from structural or design attributes alone, inhabitable performance must be understood as the outcome of the interaction between building characteristics and actual patterns of occupation and operation.

From this perspective, the study supports the need to move beyond structure-based evaluations toward the definition of Inhabitable Performance as an engineering-oriented concept grounded in measurable indoor conditions. This concept enables a more consistent interpretation of building performance by linking calculation-based models with the actual physical and operational characteristics of dwellings.

The main contribution of this work lies in integrating a structured comparison of calculation-based models with their application to real residential cases under consistent input conditions. This combined approach not only reveals methodological differences across models but also demonstrates how these differences translate into distinct performance assessments in practice.

Future research should expand the number of analyzed cases and advance toward integrated frameworks that combine key parameters, consistent weighting structures, and performance-based criteria to improve the evaluation of inhabiting conditions in buildings intended for human occupation.

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APPENDIX A

Table VI presents the main physical, environmental, and operational characteristics of the two analyzed residential case studies. The information includes building features, construction systems, indoor environmental conditions, and occupancy patterns, providing the necessary context for the interpretation of the model outputs. In particular, the table summarizes key performance-related variables used as inputs for the selected models, allowing a consistent comparison between both cases.

TABLE VI
CASE STUDY CHARACTERISTICS

Category	Parameter	Case 1	Case 2
Building Characteristics	Building type	Privat House	Social House
	Construction year	2010	2016
	Floor area (m²)	77.0	48.5
	Number of occupants	2	3
	Occupancy density (m²/pers)	38.5	16.2
Construction System	Main structure	Masonry	Timber frame
	Envelope insulation level	High	Medium
	Window type	DVH Low e / PVC frame	SG / PVC frame
	Airtightness (qualitative)	Medium	Low
Energy	Energy demand (kWh/m² year)	49.5	114.9
Building Condition	Presence of mold	No	No
	Condition of materials	Good	Regular
Indoor Environmental Conditions	Temperature (% time within 18–24 °C)	$35\% < \%t_t < 50\%$	$\%t_t < 35\%$
	Relative humidity (% time below 80% RH)	$50\% < \%t_{RH} < 80\%$	$35\% < \%t_{RH} < 50\%$
	CO_2 (% time above 1,000ppm)	$10\% < \%t_{CO2} < 25\%$	$10\% < \%t_{CO2} < 25\%$
	Ventilation	Mechanical-assisted	Natural
	Lighting	Natural and artificial	Natural and artificial

The characteristics presented in Table VI were categorized into defined ranges and subsequently transformed into normalized scores for their use in Tables III, IV, and V, which form the basis for the calculation of the selected indices. Indoor environmental and operational variables were quantified using a scoring system based on the percentage of monitored time within or outside established thresholds. For temperature, the score is based on the percentage of time within the 18–24 °C range (<35% = 0; 35–50% = 0.25; 50–80% = 0.75; >80% = 1). For relative humidity, the score is based on the percentage of time below 80% RH using the same thresholds. For CO_2, the score is based on the percentage of time above 1,000 ppm (>50% = 0; 25–50% = 0.25; 10–25% = 0.50; <10% = 1). Ventilation performance is classified according to the presence of mechanical or mixed systems and the availability of adequate window opening (no system and insufficient openings = 0; no system but sufficient openings = 0.5; presence of ventilation system and sufficient openings = 1). Lighting conditions are evaluated based on compliance with natural lighting requirements and the presence of artificial lighting (insufficient natural lighting and no artificial lighting = 0; artificial lighting without sufficient natural lighting = 0.5; sufficient natural and artificial lighting = 1).

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