Project acronym	B4B
Project full name	Brains for Building's Energy Systems
Grant No	MOOI32004
Project duration	May 1, 2021 – December 31, 2025

Deliverable 1.05b

Extension of the 4S3F HVAC B28 framework for identifying undefined end-user use and poor indoor climate quality

Developing key performance indicators for occupant-centric buildings using occupant feedback- A scoping review and methodological framework.

Authors: Karzan Mohammed (TU/e), Wei Luo a (TUe), Shalika Walker (Kropman), Rick Kramer (TUe)

Reviewers: Olivia Guerra Santin (TU/e) Martin Mosteiro Romero (TUD)

Work package	1
Result	2
Lead beneficiary	TU/e
Due Date	1 May 2025
Deliverable Status	Final
File name	B4B WP1 D1.05b Extension of the 4S3F HVAC B28 framework for identifying undefined end-user use and poor indoor climate quality FINAL.docx

The project was carried out with a Top Sector Energy subsidy from the Ministry of Economic Affairs and Climate executed by the Netherlands Enterprise Agency. The specific subsidy for this project concerns MOOI subsidy round 2020

SUMMARY

Leveraging occupant feedback in smart building control and management has been shown to enhance indoor environmental quality (IEQ) and building energy efficiency. Despite its potential, research on the collection and translation of subjective feedback into actionable key performance indicators remains limited. This study conducts a scoping review of survey-based approaches for evaluating thermal quality and indoor air quality, their computation into Subjective Key Performance Indicators (SKPIs), and their subsequent applications. We found considerable inconsistencies in survey design, survey deployment, and SKPI computation approaches, even for the same application purpose. This highlights the absence of a standardized approach for developing SKPIs. To address this gap, a methodological framework is proposed to systematize SKPI development in four steps: 1) Determining the application goals to guide SKPI development; 2) Designing surveys considering IEQ factors, survey items, question inquiries, and scale formats; 3) Deploying surveys considering temporal and spatial resolutions, as well as user interface design; 4) Computing SKPIs by defining appropriate temporal and spatial granularities alongside statistical measures. Furthermore, this framework is demonstrated for a use-case on fault diagnosis in air handling units. Lastly, the challenges associated with the SKPI development and future directions are discussed, emphasizing the need to advance validated and robust scales and explore applications in fault detection and diagnosis, and building energy flexibility. This report highlights the untapped potential of SKPIs and establishes a methodological foundation for their development and application in smart building management and controls.

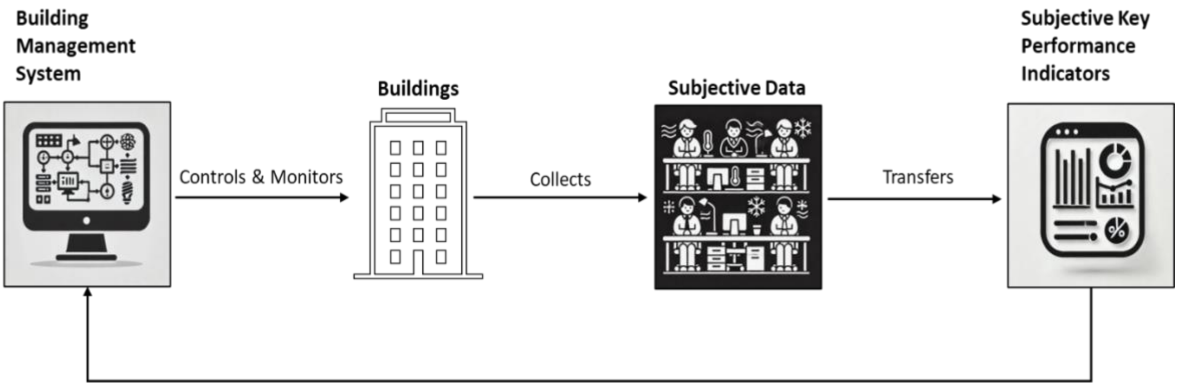

TABLE OF CONTENTS

1 INTRODUCTION

Buildings contribute to approximately 30% of global final energy consumption [1], and 26% of global energy-related CO_2 emissions, of which 50% is attributed to heating, ventilation, and air conditioning (HVAC) systems [2]. Despite this substantial energy usage, a field study of 60 office buildings in the US revealed that about 40% of occupants remain dissatisfied with the thermal environment [3]. Faults in HVAC are one of the major causes of energy waste and comfort deterioration [4]. A viable way to save energy and concurrently improve occupant comfort is to implement smart building management and control techniques [5,6]. To quantify, monitor, and optimize building energy management and control, developing and implementing effective Key Performance Indicators (KPIs) is crucial. Consequently, KPIs have attracted significant interest from researchers [7–9]. Traditional KPIs mostly focus on energy efficiency [10], which can be implemented at various hierarchical levels within buildings, including the whole-building level, the system/service level, and the component/equipment level [11]. For instance, the Energy Efficiency Index (EEI) is a widely used KPI for monitoring building energy consumption at the building level [9,12]. However, these traditional energy-related KPIs often overlook the impact of various factors, particularly factors related to the occupants [13].

Occupants, who spend over 90% of their time indoors [14], are the primary beneficiaries of building services in both residential and commercial buildingsClick or tap here to enter text.. Research indicates that occupant behavior can significantly impact building operation and indoor environmental conditions [15–19]. Conversely, Indoor Environmental Quality (IEQ) can also affect occupants' comfort, health, and performance [20]. To quantify this bi-directional impact, occupant-centric KPIs have been developed and proposed. For example, the KPI *Predicted Mean Vote* (PMV) is often used to quantify the effects of the thermal environment on occupants' comfort by integrating environmental variables including air temperature, air speed, mean radiant temperature, and relative humidity, alongside personal factors like clothing insulation and metabolic rate [21]. On the other hand, the KPI *building energy use per capita* accounts for the effects of occupancy variation on building energy consumption [22]. O'Brien et al. [23] provided guidance and outlined the required factors for developing occupant-centric KPIs. In a review paper by Li et al. [10] occupant-centric KPIs have been collected, developed, and classified into three categories: resource use, IEQ, and human-building interactions. On the same topic, Sleiman et al. [24] further highlighted how stakeholders can use these occupant-centric KPIs to support decision-making and achieve performance objectives.

The IEQ-related KPIs typically rely on objective data such as CO_2, TVOC, formaldehyde, CO, and respirable particles, illuminance, noise levels, temperature, and relative humidity to predict the effects of IEQ on occupants' comfort and health through predictive models [25]. These objective data can be obtained by simulations or measurements. However, relying solely on objective data to quantify IEQ effects imposes several challenges: 1) Objective data from simulations often fail to replicate real-world conditions; 2) Objective data obtained by sensors is often not representative or may be erroneous [26]; 3) Accurately capturing spatial differences often requires deploying many sensors, which makes it costly, difficult to implement in buildings, and prone to more errors [27]; 4) The predictive models translating objective data to occupants' perception and health may be inaccurateClick or tap here to enter text.; 5) IEQ-related KPIs are designed to evaluate indoor conditions for the "average" occupant, failing to address individual differences [30,31]. For example, the PMV model is not suitable for predicting Thermal Sensation (TS) in dynamic and non-uniform thermal conditions [28]. A study demonstrated 34% accuracy in predicting the mean TS in a real-life case [29].

It is often overlooked that occupants themselves are also valuable sensors. For example, air temperature can be sensed by the skin's thermoreceptors [32], and some air contaminants can be detected by the sense of smell [33]. Instead of relying solely on objective data, subjective data, i.e., occupant feedback, can directly reflect the impact of indoor environmental quality on occupants' comfort and health. Importantly, incorporating occupant feedback into HVAC control systems has proven highly effective, enhancing Thermal Comfort (TC) and achieving energy savings of 20%–40% in office settings [34,35]. Moreover, a comprehensive review showed a median 22% energy savings and a 34% increase in occupant satisfaction rate when smart controls integrated occupant feedback [36].

Occupant feedback can be obtained through occupant surveys, focus group meetings, structured interviews, visual records, and walkthroughs. Among these, surveys are the most widely used approach in the built environment domain [37]. However, only one review study has focused on the survey interface [37], while other aspects of the subjective measurements, such as scale and question design, have not yet been thoroughly reviewed. Therefore, this study firstly reviews the survey methods of occupant feedback and the applications of SKPIs in the literature (Section 3). Among the five IEQ factors—Thermal Quality (TQ), indoor air quality (IAQ), lighting, acoustic quality, and water quality [38]—this paper focuses on TQ and IAQ. These two factors have a direct connection to HVAC systems, which are the largest energy consumers among building services systems [2]. Furthermore, numerous studies have demonstrated the significant effects of TQ and IAQ on occupant health, comfort, and work performance [39–41]. Next, we outline a methodological framework to develop SKPIs and discuss relevant details and factors that need to be considered in survey design, survey deployment, and KPI computations (Section 4). Thirdly, we demonstrate an SKPI application example for fault diagnosis of an air handling unit (AHU) based on the proposed methodology (Section 5). Finally, the challenges associated with the methodology and future directions are discussed (Section 6).

2 METHODOLOGY

A literature search was conducted in April 2024 using Web of Science, Science Direct, and Google Scholar to identify papers published between 01/01/2015 and 30/03/2024. The search was directed to articles describing the subjective measures of TQ and IAQ perception. Any combination of the keywords from (1) and (2) below were used.

For subjective measurements on TQ, the search used the following keywords:

1) "Thermal quality" OR "Thermal sensation" OR "Thermal comfort" OR "Thermal acceptance" TOR "Thermal preference" OR "Thermal Tolerance" OR "Thermal Satisfaction " OR "Thermal pleasure";
2) “Questionnaire” OR "Survey" OR “Occupant feedback” OR "Occupant perception" OR "Subjective response".

For subjective measurements on IAQ, the following keywords were used:

1) “Indoor Air Quality” OR” IAQ" OR “Indoor Environmental Quality” OR” IEQ"

AND the search terms under (2).

This literature search identified 1961 papers for TQ and 1137 papers for IAQ after excluding the duplicates using Mendeley Version 2.129.0. Considering the large body of relevant literature, the purpose of this review (to identify the subjective measures in the research methods), and the heterogeneity of the subjective measures in the research method, we chose to conduct a scoping review as opposed to a systematic review for the sake of feasibility. When a topic hasn't been thoroughly examined before or is complicated or diverse in character, a scoping review of the literature can be especially helpful [42,43]. After scanning the papers since 2015, we reviewed 137 papers that include IAQ and TQ surveys and sourced the origin of the discovered subjective measures by the ‘reference-by-reference’ method. Standards and textbooks such as *Human Thermal Environment* [44] ANSI/ASHRAE Standard 55 [45], EN-EN16798-1 [46], ISO Standard 7730 [47] and ISO Standard 10551 [48] were also reviewed. In addition, we included relevant articles of which we are aware but were not included in the references. Moreover, we reviewed the use of subjective measurements (human as a sensor) in different application scenarios such as environment evaluation, HVAC system control and Automated Fault Detection and Diagnosis (AFDD) of HVAC. Based on the literature review, we collected factors that need to be considered for developing SKPI and propose a methodological framework.

3 MEASURING OCCUPANTS' FEEDBACK

The reviewed subjective measurements commonly include two parts: questions and scales. Questions (Figure 1a) refer to the individual prompts that specify what subjective experience is being asked about. These questions can vary widely depending on the purpose of the survey and the information being sought. Questions can be general (e.g., "How do you feel right now in this place?") or specific (e.g., "Is the environment thermally acceptable?"). Scales (Figure 1b-e) refer to a set of response options used to measure a participant's response to a particular question, incorporating verbal anchors (Figure 1) that are descriptors of subjective feelings. Five types of scales can be identified in the literature based on the verbal anchors, assigned orders/numeric values to the verbal anchors, and contiguity of the scales:

- **Nominal Scale (NS)** (Figure 1b) uses distinct categories of verbal anchors with no inherent order, e.g. Cough, Fatigue, and Headache.
- **Ordinal Scale (OS)** (Figure 1c) orders verbal anchors without specifying numerical intervals between them, e.g. the ranking of Sick Building Syndrome (SBS) symptoms: Never, Rarely, Sometimes, Often, Always.
- **Likert Scale (LS)** (Figure 1d) assigns numerical values to each verbal anchor. Respondents can choose a specific anchor, but cannot select any value in between two anchors, making it a discrete scale. For example, rating agreement levels from Strongly Unacceptable (1) to Strongly Acceptable (5).
- **Visual Analog Scale (VAS)** (Figure 1e) uses a continuous line with two endpoints, commonly ranging from 0 to 100 [49]. Respondents can choose any value between two verbal anchors.
- **Graphic Rating Scale (GRS)** (Figure 1f) is a combination of LS and VAS with verbal anchors placed at intervals along the line to assist respondents in deciding the position of their marks [50,51]. Notably, the GRS is often mistaken for VAS in the literature. In such cases, we use our defined terminology. For example, if a study used the GRS but called it VAS, we categorized it as GRS.

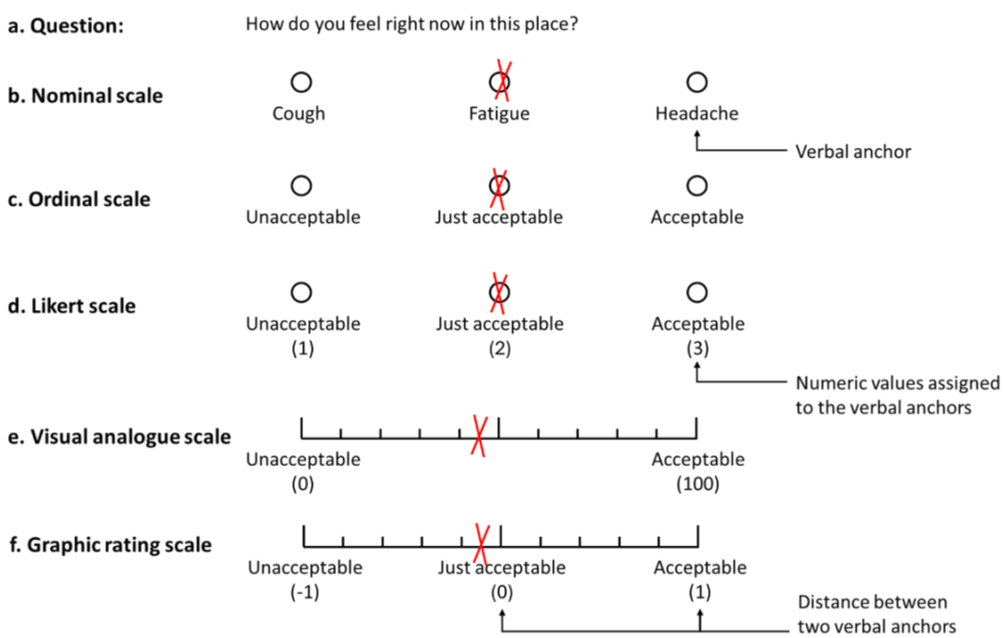

Figure 1. Example of a questionnaire: a) question; b) Nominal Scale; c) Ordinal Scale; d) Likert Scale; e) Visual Analog Scale; f) Graphic Rating Scale. Note, the numerical values in the brackets and the tick marks of the line are often not shown to respondents. The red cross indicates a possible response.

The LS and GRS have a similar structure and are often interchangeable by adjusting the scale format, see Figures 1d and 1f. Both require assigning numeric values to each anchor word. Importantly, any linear transformations applied to these numeric values—such as translation, stretching, or reflecting transformations—do not alter the psychometric properties of the scales, see Figure 2. For instance, in an original three-point acceptance scale, the words 'Unacceptable', 'Just Acceptable', and

'Acceptable' are assigned the values -1, 0, and 1, respectively. These values can be adjusted to 0, 1, 2 (Figure 2b, translation transformation), -100, 0, 100 (Figure 2c, stretching transformation), or -1, 0, 1 (Figure 2d, reflecting transformation). Despite these changes, the relative distances between verbal anchors remain consistent. This means that the interpretation of these scales remains unchanged, with only variations in numeric notation.

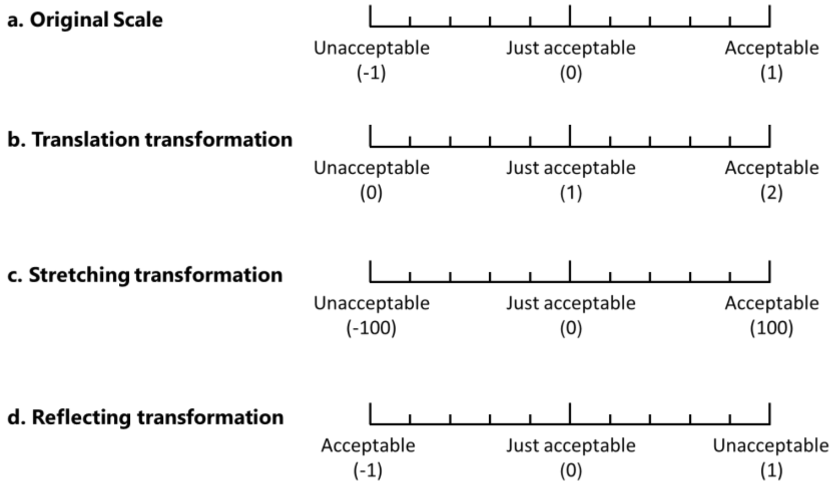

Figure 2. Invariant of a scale: (a) original scale; (b) Translation transformation; (c) Stretching transformation; (d) Reflecting transformation. These four scales are identical.

Based on the points of origin in verbal anchors, the literature also classifies the scales into two types: unipolar and bipolar.

- **Unipolar scales** have one direction starting from a single origin point, see Figure 3a.
- **Bipolar scales** are typically symmetrical, featuring two poles with a neutral point. The scale measures intensity in both directions away from this neutral point, with each direction having increasing levels of intensity, see Figure 3b.

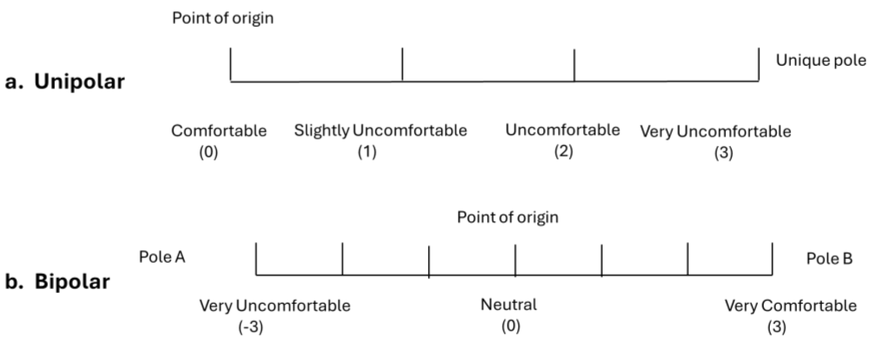

Figure 3. Examples of (a) Unipolar and (b) Bipolar scales.

The following sections summarize results into tables according to the questions and scales and their typology. For scales, any linear transformations as illustrated in Figure 2 are treated the same as the original scale. Due to the extensive number of scales reviewed, the complete list of scales and their corresponding references are provided in Appendix A. The tables in the main text mainly highlight key scales relevant to the text analysis.

3.1 Thermal Quality (TQ)

The number of items used for assessing TQ varies in the literature. Thermal Sensation, Thermal Comfort, Thermal Acceptance, and Thermal Preference are the most used items [52]. In total, the literature review identified seven items:

- Thermal Sensation (TS): The detection of the temperature of the environment, ranging from warm to cool [53].

- Thermal Comfort (TC): The condition of mind that expresses satisfaction with the thermal environment [54].
- Thermal Acceptance (TA): The willingness of individuals to tolerate and accept the thermal environment.
- Thermal Satisfaction (TSat): The overall fulfilment experienced by the subject with the thermal environment.
- Thermal Pleasure (TPle): Positive and enjoyable emotional response to (changing) thermal conditions.
- Thermal Tolerance (TT): The capacity of individuals to endure and cope with the thermal conditions.
- Thermal Preference (TP): The individual's choice for a particular thermal condition.

3.1.1 Questions

Both general and specific questions were found in the literature (Table 1). General questions cover a broad domain [55] (Table 1, General Thermal Quality category), such as 'How are you feeling at this precise moment?' [56]. In contrast, specific questions target a particular TQ items by incorporating terms related to the item (Table 1), such as asking about TC using the word 'comfort' [57]. Some questions emphasize the temporal factor by asking participants 'right now', 'current', and etc. [55–63] or stress the spatial factor[58–60], such as 'At your workspace' [60].

Table 1. Questions for subjective measures of thermal quality and indoor air quality

Question Category	Questions
General Thermal Quality	'How do you find your current thermal environment?' [55] 'How are you feeling at this precise moment?' [56] 'How do you feel, right here, right now?' [58] 'Please circle how you feel right now?' [63] 'How do you feel about the temperature right now? (please circle only one)' [62]
Thermal Sensation	'Please rate your thermal *sensation*?' on your ...[64] 'Rate your current whole body Thermal Sensation / what whole-body thermal sensations would your prefer? [57]
Thermal Comfort	'Rate your current whole-body thermal *comfort*' [57] 'Please rate the Thermal Comfort on your...' [64,65]
Thermal Acceptance	'Right now, how *acceptable* is the thermal environment at your workspace?' [59] 'Do you consider the thermal environment *acceptable*?' [66] 'How would you rate the overall acceptability of the temperature at this moment?[62]
Thermal Satisfaction	'How *satisfied* are you with the temperature in your workspace?' [60]
Thermal Preference	'Please state how you would prefer to be now' [56] 'Please indicate how you would *like to be* now' [61] 'Would you *like to be* warmer, cooler, or no change?' [62,63]
General Indoor Air Quality	'How do you judge the air quality in the room at the moment?' [67] 'How do you perceive the current quality of the air in the room? ' [68] 'How do you assess the air quality?' [69] 'How do you feel about the air freshness of your classroom at this moment?' [70] 'How is the air quality in the classroom at this moment?' [70] 'How do you feel about the air freshness of your classroom at this moment?' [70] 'Have you experienced the following perception while working in the underground shopping center in the last month:' [71] 'Overall, does the air quality in your workspace enhance or interfere with your ability to get your job done?' [72] 'How would you describe the indoor conditions in this office at this moment? Please tick one box per scale.' [73] 'How would you best describe the sources of indoor air quality discomfort?' [74]

Question Category	Questions
	'Have you been bothered during the last three months by any of the following factors at your work place? Draught, strutty "bad' air, Dry air, Unpleasant odor, Dust and dirt' [75]
Specific Indoor Air Quality Items	'Are you satisfied with indoor air quality?' [74] 'How satisfied are you with the air quality in your workspace?' [76] 'Assess odor intensity' [77] 'How strong is the odor in this room?' [78] 'How satisfied are you with the air quality in your workspace (i.e. stuffy/stale air, cleanliness, odors)?' [79] 'How acceptable is the air quality?' [80]
Sick Building Syndrome	"Which symptoms do you experience during work? Do these symptoms clear up within 1–2 hours after leaving the house?" [81] "Have you experienced the following symptom(s) while working during the last month?"[71] "In the past 12 months, have you had more than two episodes of any of the following symptoms?" [82] "Right now, I feel as follows:" [77] "Have you been bothered during the last three months by any of the following factors at your workplace?" [75] "Was your work either "somewhat" or "very'' disrupted by any experience of each of following symptoms?" [83]

3.1.2 Scales

Thermal Sensation: The verbal anchors used in TS scales are consistent (see the complete list of scales in Appendix A, Table A.1). TS measurements mostly employed GRS while LS has been used less frequently. The ASHRAE 7-point scale is the most popular scale (Table 2, Scale B). By adding anchor words 'Very Cold' and 'Very Hot' at the ends, a 9-point scale has been constructed (Table 2, Scale A). This 9-point scale is particularly used in extreme environments due to its broader range. The 5-point scale (Table 2, Scale C) covers the same range as the 9-point scale. The number of VAWs and their distribution affect the interpretation of subjective responses. Notably, the middle points of 'Very Cold' and 'Neutral' are 'Cold' on the 5-point scale, whereas it is on the 9-point scale, they are 'Cool'.

Thermal Comfort: Like the TS scales, the verbal anchors are also consistent across TC scales (see the complete list of scales in Appendix A, Table A.2). The term 'comfort' is used to structure VAWs by adding prefixes such as 'Un-', 'Very', 'Dis-', 'Fairly', 'Slightly', and 'Clearly'. However, scale spans differ between studies. Most scales end at 'Comfortable' or 'Uncomfortable', while some extended to 'Very' or 'Extremely' Comfortable or Uncomfortable. Some VAWs are used interchangeably as middle points of the scale, such as 'Indifferent', 'Neutral', 'Just comfortable / Just uncomfortable', or 'Slightly comfortable' and 'Just comfortable'. The GRS is the most common format for gauging TC. The most popular scales are the symmetric bipolar 6-point scale (Table 2, Scale D) and the unipolar 5-point scale (Table 2, Scale E). The relative distances between VAWs and the baseline vary among scales. For instance, in scale F in Table 2, the relative distance $\frac{\text{'Comfortable'} - \text{'Neutral'}}{\text{'Very comfortable'} - \text{'Neutral''}}$ equals 2/4, which differs from scale G in Table 2, where the relative distance between $\frac{\text{'Comfortable'} - \text{'Indifference'}}{\text{'Very comfortable'} - \text{'Indifference'}}$ equals 2/3. This leads to inconsistent interpretations of occupants' mean votes. When two responses are 'Very comfortable' and baseline ('Neutral' or 'Indifferent'), the mean of these two responses in Scale F is 'Comfortable', but in Scale G, it is between 'Comfortable' and 'Slightly Comfortable'.

Thermal Acceptance, Thermal Satisfaction, and Thermal Pleasure: The scales used for TA, TSat, and TPle are like those for TC evaluation (see the complete list of scales in Appendix A, Tables A.3, A.4, and A.5). The VAWs are commonly based on the word roots 'Acceptance', 'Satisfaction', and 'Pleasant' in combination with positive prefixes such as 'Totally', 'Generally', 'Just', 'Clearly', 'Very', 'Slightly', or negative prefixes such as 'Un-', and 'Not'. These scales range from 2 points to 7 points, of which the relative distances between the pairs of the same verbal anchors differ.

Thermal Preference: VAWs like "Warmer" and "Cooler" are used in the TP scales (see the complete list of scales in Appendix A, Table A.6). Researchers commonly use the 3-point scale (Scale H, Table 2) and the LS format.

Thermal Tolerance: TT includes two scales: a 2-point scale and a 5-point scale (Appendix A, Table A.7). The 5-point scale has wider and more detailed descriptions than the 2-point scale, which simply assesses whether conditions are tolerable or not.

Table 2. Examples of scale formats for measuring occupant feedback on different thermal quality items. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Items	Thermal Sensation			Thermal Comfort				Thermal Preference
Scales	A	B	C	D	E	F	G	H
Ref.	[57,84–88]	[89–92]	[93,94]	[61,95–99]	[91]	[66,100]	[101]	[59,90,91,102–104]
Scale type	GRS/LS	GRS/LS	GRS/LS	GRS/LS	GRS	LS	GRS	LS
No. of Verbal anchor words	9-point	7-point	5-point	6-point	5-point	5-point	7-point	3-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column							
4	Very hot	-		Very Comfortable				
3	Hot	Hot					Very comfortable	
2	Warm	Warm	Very hot	Comfortable		Very comfortable	Comfortable	
1	Slightly warm	Slightly warm	Hot		Comfortable	Comfortable	Slightly comfortable	Want warmer
- 0	Neutral	Neutral	Neither cool Nor warm	Just comfortable	Indifference/ Not uncomfortable	Neutral	Indifference	No change
+0				Just uncomfortable				
-1	Slightly cool	Slightly cool	Cold		Slightly uncomfortable	Uncomfortable	Slightly uncomfortable	Want warmer
-2	Cool	cool	Very cold	Uncomfortable	Uncomfortable	Very Uncomfortable	Uncomfortable	
-3	Cold	Cold			Very Uncomfortable		Very Uncomfortable	
-4	Very cold			Very uncomfortable				

3.2 Indoor Air Quality (IAQ)

The assessment of IAQ perception can be categorized into two classes: (i) Direct assessment, querying occupants about their sensory perceptions of IAQ, such as odors, humidity (indicative of mold), and overall satisfaction; (ii) Indirect evaluation by assessing symptoms associated with IAQ such as SBS.

3.2.1 Direct Evaluation of IAQ

The literature review identified four IAQ perception items: Sensation, Acceptance, Satisfaction, and Preference. The questions and scales used in this research domain are often based on the Lawrence Berkeley National Laboratory questionnaire [105].

- IAQ Sensation (IAQS): The sensation of the quality of indoor air, including factors such as humidity levels, odors, air freshness, and presence of pollutants.
- IAQ Acceptance (IAQA): The willingness of individuals to tolerate and accept the prevailing indoor air quality conditions in their environment.
- IAQ Satisfaction (IAQSat): The overall fulfilment experienced by individuals with the indoor air quality in their environment, including factors such as comfort.
- IAQ Preference (IAQP): The individual's desire for either more fresh air or no change in indoor air quality, reflecting their perceived need for ventilation adjustments.

3.2.2 Questions

Inquiries into IAQ typically fall into two broad categories: those probing the overall IAQ landscape (Table 1, “General Indoor Air Quality” category), and those focusing on specific facets such as odors, freshness, and tolerance for staleness (Table 1, “Specific Indoor Air Quality Items” category). Echoing TQ results, some questions account for temporal factors such as 'At the moment', or spatial factors such as 'At your work' or 'In your room'.

3.2.3 Scales

IAQ Sensation (IAQS): IAQS involves factors such as the sensation of humidity or odors (Table 3, Scale A and B). This assessment typically employs two types of questions (see the complete list of scales in Appendix A, Tables A.8 and A.9). The first type senses IAQ as a whole. Subjects evaluate the overall IAQ using scales with verbal anchors like "Bad," "Poor," "Good," and "Excellent" (Appendix A, Table A.8). LSs are commonly used to develop these scales. In the second type, researchers customize scales to capture occupant feedback on specific varieties of IAQS, including Odor, Humidity, and Freshness (Appendix A, Table A.9). VAWs match the varieties measured, such as "Fresh" and "Stuffy" describing air freshness. LS and GRS are commonly used.

IAQ Satisfaction (IAQSat): The IAQSat scale utilizes VAWs derived from the root word "Satisfaction". The number of VAWs and the range they cover vary across scales (see the complete list of scales in Appendix A, Table A.10). The relative distances between VAWs are also inconsistent. For example, in Scale C in Table 3, the distance between ‘Satisfied’ and ‘Neutral’ is half the distance between ‘Very satisfied’ and ‘Neutral’ ($\frac{\text{‘Satisfied’} - \text{‘Neutral’}}{\text{‘Very satisfied’} - \text{‘Neutral’}} = \frac{1}{2}$). However, in Scale D in Table 3, this relative distance is 2/3 ($\frac{\text{‘Satisfied’} - \text{‘Neither satisfied nor dissatisfied’}}{\text{‘Very satisfied’} - \text{‘Neither satisfied nor dissatisfied’}} = \frac{2}{3}$). As explained in the TC section, this leads to inconsistent interpretations of occupants’ mean vote when the submitted answers are ‘Very satisfied' and 'Neutral'. Both GRSs and LSs are employed in designing these satisfaction scales.

IAQ Acceptance (IAQA): The IAQA scales have less variety than TA scales and mostly use GRS and VAS for the scales (see the complete list of scales in Appendix A, Table A11).

IAQ Preference (IAQP): IAQP has a 2-point LS scale to indicate if respondents would like ‘More air’ or ‘No need to change’ [106] (see Table 3, Scale E).

Table 3 Examples of scale formats used to measure occupant feedback on direct evaluation of IAQ. Scales are indicated by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Items	IAQ Sensation		IAQ Satisfaction		IAQ Preference
Scales	A	B	C	D	E
Ref.	[77,90,107]	[77,107–109]	[110]	[76,105,108,111–115]	[106]
Scale type	LS / GRS	LS / GRS	LS	LS	LS
No. of Verbal anchor words	7-point	6-point	5-point	7-Point	2-Point
Numeric value	Verbal Anchor Words of the corresponding scales in each column				
3	Much Too humid			Very satisfied	
2	Very humid		Very satisfied	Satisfied	
1	Slightly humid		Satisfied	Slightly satisfied	More air
+ 0	Just right	No Odor	Neutral	Neither satisfied Nor dissatisfied	No need to change
- 0					
-1	Slightly dry	Slightly Odor	Dissatisfied	Slightly dissatisfied	
-2	Very dry	Moderate Odor	Very dissatisfied	Dissatisfied	
-3	Much Too dry	Strong Odor		Very dissatisfied	
-4		Very strong Odor			
-5		Overpower Odor			

3.2.4 Evaluation of Sick Building Syndrome

Most SBS questionnaires are designed based on the principles of the Örebro (MM40) Indoor Climate Questionnaire [75]. The symptoms frequently included in SBS-related questionnaires are respiratory, dermal, eyes, throat, and general symptoms [68,77,116–120] (see the complete list of symptoms items in Appendix A, Table A. 12). Headaches are the most asked symptom, followed by coughs and fatigue. Perceptions like feeling heavy-headed and experiencing dizziness are also recurrent in the literature. However, symptoms such as hoarse or dry throat, lethargy, draughts, nausea/dizziness, and irritated, stuffy, or runny nose are less common.

3.2.5 Questions

The questions of SBS normally do not inquire about a specific symptom (Table 1, Sick Building Syndrome category). Instead, the inquiries are general and ask people to select/rate a set of symptoms they experienced with temporal and spatial reference.

3.2.6 Scales

Most of the scales are structured in OS format to indicate the frequency of the symptoms. The descriptions of frequency can be a binary option with 'Yes/Often' or 'No.' (Table 4, Scale H and I) or 3-5 options with a finer granularity (Table 4, Scale J). The VAWs vary across different scales, where the popular ones are ‘Never’, ‘Sometimes’, ‘Often’, and 'Regularly'. The VAS (Table 4, Scale A and K) is less frequently used to describe these symptoms.

Table 4. Scale formats used to measure sick building syndrome. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Scales	A	B	C	D	E	F	G	H	I	J	K
Ref.	[118, 121]	[122]	[123]	[119]	[124]	[125]	[126]	[127–129]	[130]	[119,131, 132]	[68, 125]
Scale type	VAS	OS	OS	OS	OS	OS	OS	NS	OS	OS	VAS
No. of Verbal anchor words		5-point	5-point	4-point	5-point	4-point	5-point	2-point	2-point	3-point	
Numeric value	Verbal Anchor Words of the corresponding scales in each column										
	very serious	Very bad	Very often		suffer a lot		frequently	yes	Often	Yes, often (every week), or regularly	100%
		Bad	Often	often	suffer slightly	Very likely	sometimes				
		Normal	sometime	Regularly	suffer	Likely	neutral	no	No	Yes,(sometimes) occasionally	
		good	Raeley	sometime	almost never suffer	possible	rarely				0%
	never	Very good	Never	Never	never suffer	unlikely	never			No, never, or not related	

3.3 Application scenarios

This section presents an overview of the current literature on SKPI applications. Although the term "SKPI" is rarely mentioned explicitly, the concept is represented through alternative terminology across studies. SKPIs are primarily applied in environmental assessments and optimizing HVAC control. Only two studies have explored the use of SKPIs for FDD applications [133,134]. Similarly, integrating SKPIs into energy flexibility strategies has also been proposed [135–137], but this yet remains largely conceptual. For each application, the survey design and SKPIs calculation were overviewed. Survey deployment tools used in the literature include traditional, paper-based methods and technology-based interfaces, such as Tangible User Interfaces (TUIs) and/or Graphical User Interfaces (GUIs) [37].

3.3.1 Environmental Quality Assessments

Survey design

Subjective measurements in environmental assessments aim to capture occupants' perceptions of IEQ factors. The importance of each IEQ factor depends on (i) occupants’ sensitivity to that factor and (ii) the extent to which that factor impacts overall environmental satisfaction [138,139]. Frontczak and Wargocki [138] revealed that TQ has a greater impact on occupants’ overall satisfaction than visual quality, acoustic quality, and IAQ. Similarly, a field study in China showed occupants in various types of public buildings prioritized improvements in TQ and IAQ over other IEQ factors [139]. Moreover, the number of items selected to evaluate each IEQ factor varies across the studies. For example, TQ has sometimes been assessed using a single item such as TS [58,88], while others used multiple items like TS combined with TP [140].

Calculation

The most popular statistics for summarizing these subjective measures into KPIs include mean, median, percentage and intercepts of regression analysis. For instance, Z. Li et al. [103] applied non-parametric statistical methods, such as the Mann-Whitney U-test and the Kruskal-Wallis H-test to analyze group differences in human perceptions of the environment, explicitly implying the *median* of the human perceptions serves as the KPI. In another study, Ko et al. [141] utilized the *mean* differences of multiple TQ items to compare TQ perceptions between windowed and windowless conditions using permutation tests. The ASHRAE 55 standard [54] specifies a minimum of 80% TSat (*percentage*) as the KPI for evaluating TQ. Within the adaptive TC framework, the "neutral temperature" serves as a crucial indicator calculated as the *intercept* of a regression model that correlates TS with operative temperature [142].

3.3.2 HVAC Control System

Survey Design

To optimize energy consumption and ensure occupants' comfort, subjective measurements are also fed to HVAC controls to complement or replace traditional TC metrics that typically rely on indoor air temperature data [143–145]. In such cases, TQ becomes the primary IEQ factor. Some studies directly utilize individual data to develop occupants' personal TP profiles to control HVAC systems at either personal or zone level [35,146–148]. Other studies aggregate individual data into SKPIs with TS [148–153] or TP [35,154–156] serving as the input for the HVAC controls. The most widely adopted approach is using the PMV model to determine the temperature setpoint that offsets the actual TS votes, typically measured by the ASHRAE 7-point scale [149,151–153].

Calculation

The calculation of the SKPIs relies on *means* and *percentages* [149–152,155]. For instance, in the study by Erickson et. al. [149], the actual mean vote (AMV) was determined by averaging TS votes (on the ASHRAE scale) over 10-minute windows. If the sum of AMV and PMV deviated from zero, a new temperature setpoint was derived to make the sum equal to zero. Mansur et. al. [155] collected occupants' TP (warmer, colder and comfortable). The percentage of complaints was calculated relative to the number of occupants in the space. If the difference between 'warmer' and 'colder' votes exceeded 10%, the HVAC system adjusted the temperature setpoint by ±1°C, depending on the majority preference.

4 DEVELOPMENT OF SKPIS

The previous section discussed different scales and questions to obtain subjective data using survey measurements. In this section, we discuss how to translate these subjective data into SKPIs. First, we discuss the essential attributes of what makes good SKPIs. Then, we present a methodology framework for developing SKPIs.

4.1 Attributes of SKPIs

To ensure SKPIs are effective, they should have the following four critical attributes: privacy, accessibility, quantifiability, and actionability, which is in line with the literature [10,24].

- **Privacy**: prioritising privacy and data security is crucial to maintaining occupants' trust and complying with regulations. Throughout data collection and the development of SKPIs, privacy must be strictly safeguarded. Personal information should not be collected unless absolutely necessary. If collecting personal data (e.g., age or gender) is unavoidable, the information must be anonymized, and no combination of data points should allow for identifying individuals.
- **Accessibility:** The development of SKPIs should utilize user-friendly tools, such as apps or computer-based questionnaires, to facilitate data collection. Data sources and measurements should be clearly defined and understandable by occupants and stakeholders.
- **Quantifiability:** To effectively transform subjective data into actionable information, it must be quantifiable. "It cannot be effectively managed if it cannot be measured" [157]. SKPIs should convert subjective occupant data into numeric indicators.
- **Actionability:** SKPIs must effectively guide targeted solutions. For example, a TC-based SKPI cannot serve as an indicator for controlling indoor temperature, because the occupants may require either lower or higher indoor temperatures when the TC-based SKPI indicates discomfort. An actionable indicator for thermostatic control may be a TP-based SKPI, where occupants indicate that the temperature should be warmer or cooler.

4.2 Methodology Framework

The methodology framework for developing SKPIs consists of the following four steps (Figure 4):

1. **Application goal:** Determining the application goal for the SKPIs.
2. **Survey design:** Designing the survey considering the application goal.
3. **Survey deployment:** Develop survey deployment to efficiently and effectively obtain occupant feedback.
4. **SKPI computation:** Develop computation algorithms for SKPIs from subjective data.

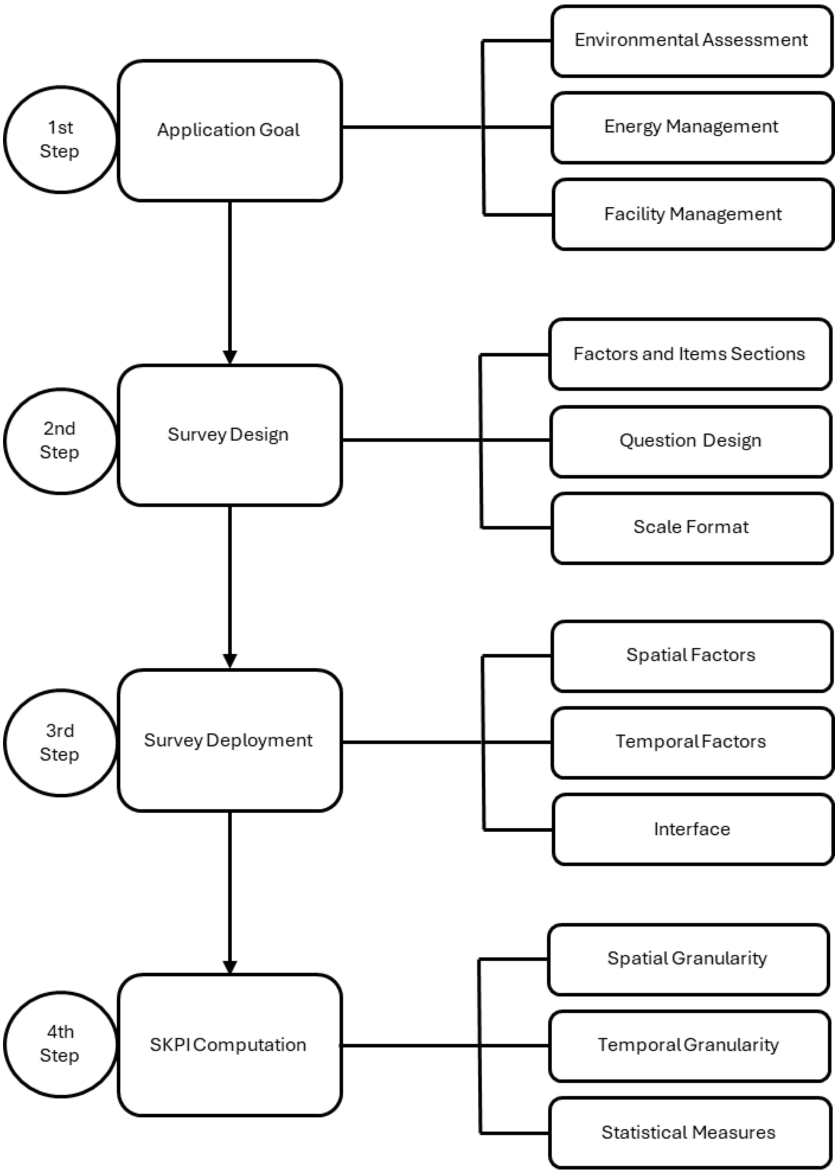

Figure 4. Steps for developing subjective key performance indicators

4.2.1 Step 1: Applications Goals

The application goal guides the development of SKPIs at each step. For example, SKPIs designed to *assess* TC differ from those developed to *control* indoor temperature. Assessing TC requires only the TC item, whereas temperature setpoint adjustments for control purposes necessitate the inclusion of the TP item. Figure 5 shows examples of application goals. It is important to note that SKPIs are mostly applicable in operational buildings, as they rely on post-occupancy feedback for data collection. However, historical SKPI data from operational buildings may also inform future building design

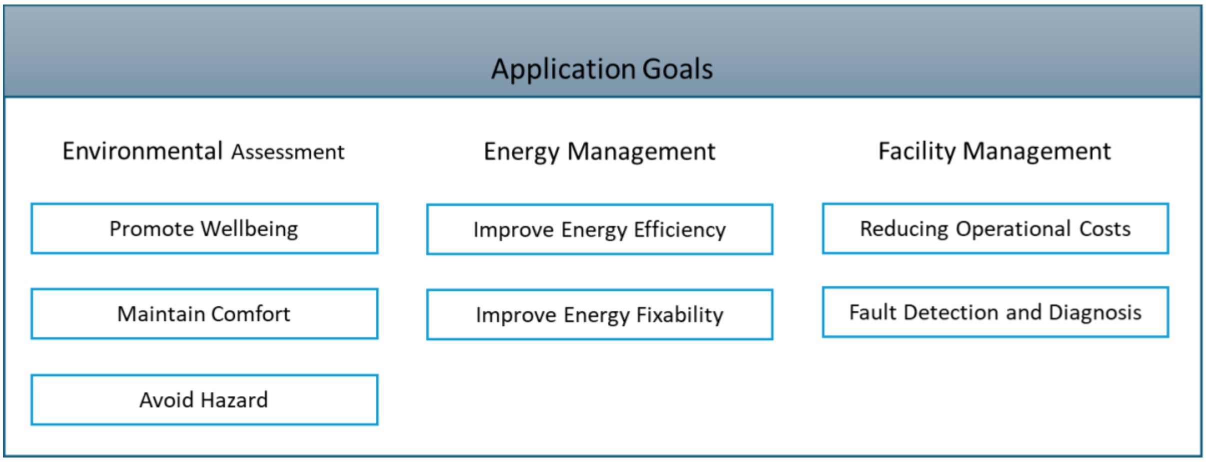

Figure 5. Application goals for developing subjective key performance indicators.

4.2.2 Step 2: Survey Design

The survey design process involves three key steps: (i) Selecting the appropriate IEQ factors, (ii) Choosing the specific items for each factor, and (iii) Tailoring the questions and scales to align the survey design with the application goal (Figure 6). Beyond content selection, surveys can also be structured to enhance efficiency and engagement by using sequential surveys and skip-logic methods that present only relevant follow-ups. For example, if respondents feel comfortable, discomfort-related questions are skipped. This dynamic survey flow minimizes redundancy, keeps respondents engaged, and improves data quality.

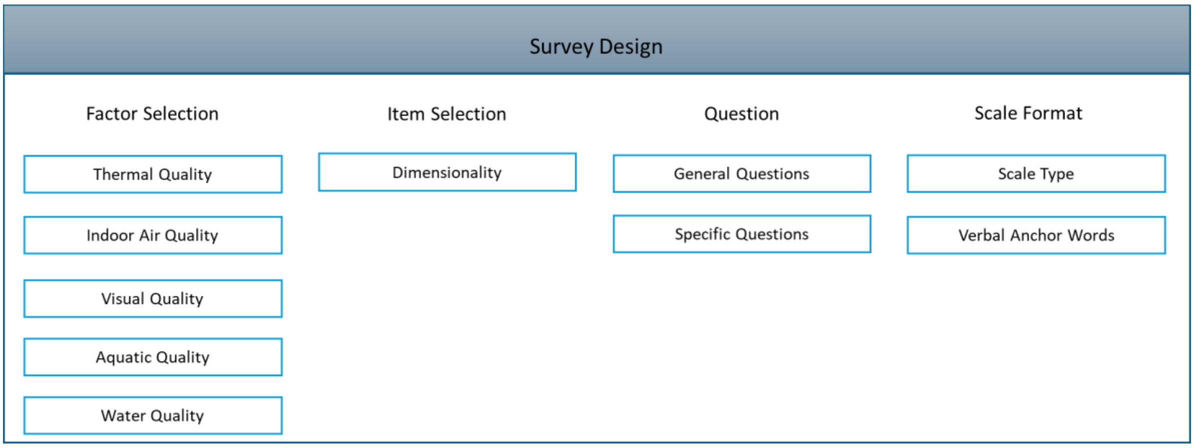

Figure 6. Important factors of survey design for developing subjective key performance indicators

IEQ factor selections: Selecting IEQ factors to develop SKPIs is relatively straightforward compared to other steps in this section. Depending on the application goals, either single or multiple IEQ factors can be utilized in the survey. For example, to develop an SKPI for evaluating indoor TQ, the TQ factor alone can be used. However, for a comprehensive assessment of the indoor environment, multiple IEQ factors such as TQ, IAQ, and acoustic quality should be included in the survey.

Item selection: Assessing each IEQ factor can be achieved through single or multiple items. However, careful consideration is necessary when selecting the appropriate items. It again should align with the application goals at hand. For example, for evaluating indoor thermal conditions, TT is less relevant, as indoor temperature hardly results in intolerable conditions. In an outdoor scenario, TT may be more of an interest. An analysis of the ASHRAE Global Thermal Comfort Database II [158] shows that TQ perception consists of at least two dimensions, with TS and TC forming the primary components in a principal component analysis. These two dimensions are also supported by other studies [48,52,158–161]. For instance, Zhang & Zhao [159] revealed that TA and TC were closely correlated under both uniform and non-uniform conditions, meaning they measure similar aspects of thermal experience rather than capturing different dimensions. On the other hand, TS responses were weakly associated with either TC or TA in non-uniform conditions [159]. Notably, while repetition can improve reliability [162], it may also introduce redundancy, leading to participant disengagement [163]. In contrast, selecting weakly correlated items (e.g., TS and TC) provides a broader understanding of occupant perception. To effectively gauge TQ perception, we recommend selecting at least two items from the following categories: Sensation (TS), Preference (TP), Appraisal (TC or TA).

Questions: To collect credible data from occupants, it's important to formulate questions that adhere to several key principles:

- Use easily understandable language: Ensure that the language used in the questions is clear and easily understandable by the survey respondents. The question text should avoid using jargon or ambiguous terms. For example, a question like "*How do you rate the temperature in your workspace?*" is clear because it directly addresses thermal environments. In contrast, a vague question like *"How are you feeling right now?"* lacks clarity because it does not specify what aspect of the subject's experience is being asked about. Additionally, when translating questions into other languages, care should be taken to ensure the translation accurately conveys the original intent and meaning. This helps maintain clarity and ensures effective communication across diverse respondents. Lastly, it is important to adapt the language complexity to the age of the respondents: Children require simpler formulations than adults.
- Avoid bias: Questions should be neutral and free from words or phrasing that might influence the respondents' answers. For instance, asking "*Do you feel cold?*" implies to the subjects that they should feel cold by including the word "*cold*". A more neutral alternative, such as "*How do you sense the room temperature at this moment?*", as suggested in ISO 10551 [48], ensures that the question is unbiased.
- Include temporal references: Incorporating temporal reference (e.g. "Right now") ensures that respondents provide feedback relevant to the specified time. Questions about past events may introduce *recall bias*, where respondents' current feelings influence their recollection of past events [164]. For example, asking *'How do you assess the thermal environment in the last season?'* may lead to recall bias, as respondents may provide answers influenced by their current feelings rather than an accurate recollection of the past season's thermal conditions.
- Include spatial references: Specify the location to help the respondents clearly understand the environment they are providing feedback about. For example, specifying a particular area within the building, such as "At the workstation," ensures clarity and context in their responses.

Scale format: Occupants use scales to convey their responses, and the type of scale plays a crucial role in translating occupant feelings into quantifiable data. As identified in Section 3, common scale types include the VAS, LS, NS, OS, and GRS. The GRS, LS, and VAS are the most popular for evaluating TQ and IAQ. The performance of these scales can be evaluated based on three criteria [160]:

- **Responsiveness:** Ability to detect important changes, even small ones.
- **Reliability:** Consistency of results over time and reproducibility under similar conditions.
- **Validity:** Accuracy in measuring what the instrument is intended to measure.

Studies have compared the responsiveness and validity of the LS and VAS. A small number of studies [165,166] found no significant difference between LS and VAS. Jaeschke et al. [166] recommended the LS for its simplicity and ease of interpretation. On the other hand, DeVellis et al. [162] highlighted that the LS is sensitive to biases, including central tendency bias (respondents avoid extreme answers and opt for middle responses) and acquiescence bias (respondents tend to agree with statements regardless of their true beliefs). Comparatively, the VAS, using a continuous line, is highly sensitive to slight changes and minimizes consistency bias since respondents are unlikely to remember their previous marks on a featureless line. Since both the LS and VAS have strengths and weaknesses, many studies combined LS and VAS to make the GRS. A study by Lee et al. [49] showed that the GRS was more in line with indoor air temperature and mean skin temperature compared to LS and VAS. Near the neutral temperature, the GRS is more sensitive in distinguishing TS than LS and VAS [49]. On the other hand, Wang et al. [160] analyzed the uncertainty in subjective TC measurement through three chamber experiments. They concluded that the LS is recommended for subjective TC measurement as GRS exaggerates intra-individual differences.

Another consideration in scale format design is the use of bipolar and unipolar formats. ISO 10551:2019 [48] recommends that bipolar format structures are more sensitive than unipolar formats in capturing occupant feedback near neutral reference points. However, there is a lack of empirical studies to support this claim. In contrast, Tzeng et al. [167] found that both formats were reliable and valid when comparing bipolar and unipolar response formats in personality assessment using data from 135 college students. However, the bipolar format was preferred among the students. Similarly, Yang et al. [168] compared four response scales to assess subjective indoor environmental sensation and perception in combined thermal and acoustic conditions with university students. The results revealed that the bipolar VAS was preferred in all conditions. The performances of the response scales were not significantly different for young university students. DeVellis et al. and Thorpe et al [49,162] emphasized that choosing between bipolar or unipolar formats depends on the logic of the research questions. Research does not conclusively determine whether bipolar or unipolar scales are more effective in collecting data; however, preference often depends on the specific conditions of the scale. Subjects tend to favor bipolar scales when the number of VAWs is equal on both sides. In contrast, unipolar scales are preferred when the scale focuses on a single continuum, where the origin is usually the opposite of the rest of the VAWs. For example, the origin might be 'Comfortable,' with the rest of the scale ranging from 'Uncomfortable' to 'Very uncomfortable'. Unipolar scales are particularly useful in applications like Automated Fault Detection and Diagnosis or Control, where the focus is on assessing the intensity of discomfort rather than comfort.

Number of VAWs: VAWs help respondents select precise responses and facilitate accurate placement along a scale, thereby improving the reliability and validity of the resulting data [169]. For instance, including intermediate VAWs like "Slightly Cool" and "Cool" between "Cold" and "Neutral" (Table 2, Scale B) provides subjects with more guidance for expressing their sensations. However, including many VAWs can introduce varying interpretations and confuse the subject as differences between anchor words become less obvious. According to Miller et al. [170] and Saaty et al. [171], humans can unambiguously identify up to seven stimuli, making seven the recommended maximum number of VAWs for judgment scales. To be more specific in the IEQ, human sensitivity to environmental changes is crucial for determining the number of VAWs on a scale, as the sensitivity to thermal variations must align with both the scale's level of detail and the mind's capacity to perceive differences [49]. For example, young adults tend to have a higher sensitivity to temperature changes compared to older adults [172]. Therefore, the effectiveness of the scale may depend on the respondents' characteristics, such as age, and the level of detail required for the specific application.

Distance between the VAWs: In the case of more than two VAWs, the (relative) distances between these words should be considered. For instance, the widely used ASHRAE 7-point TS scale (Table 2, Scale B) assumes that the verbal anchors are equidistant. However, a large international collaborative questionnaire study [173] revealed that the distances between verbal anchors in the ASHRAE scale were not interpreted as equal by the respondents. Respondents' distance perceptions were influenced by their lifetime experiences such as regional and seasonal contexts. For example, respondents from different climate regions perceived the distance between "slightly warm" and "neutral" differently compared to the distance between "slightly cool" and "neutral" despite the assumption that these distances are equal because they appear visually equal.

Translation of the VAWs: Scales in international standards like ASHRAE 55 [54] and ISO 10551 [48] are primarily in English for international communication and are often not available in many other languages. They are translated when implemented as native speakers' responses may differ from those of non-native speakers for the same questionnaire [173,174]. Thermal perceptive semantics may have different linguistic dimensions by language itself, and sometimes there is no exact equivalent for a thermal descriptor in English, or vice versa. These differences can cause confusion when interpreting thermal perceptions in different languages. [175].

For example, a study by Al-Khatri and Gadi [176] revealed issues of translating ASHRAE, Bedford, and Nicol scales into Arabic, such as irregular category widths, asymmetry, and deviations in middle category placement. For example, when translating the 7-point ASHRAE TS scale to Arabic, "cool" was translated as "Moderate," "Mild," or "Neither cool nor warm," shifting the perception of neutrality towards the cooler end of the scale. Additionally, Schweiker et al. [173] also found substantial differences in TC scales among various language versions. They observed significant differences in the distribution of responses for Arabic and Farsi, languages read from right to left, compared to languages read from left to right. While the scale is symmetrical, reading direction may influence how respondents interpret and engage with it. This could be due to cognitive biases, where respondents unconsciously anchor their attention to the starting point of the scale (the right side for right-to-left languages), potentially altering their perception of "neutral" or "middle" values.

When translating scales into languages that lack direct equivalents to English terms, like French, intensity may be adjusted by using adverbs instead of adjectives [48]. Alternatively, a VAS can be employed to reduce translation problems. Aside from the anchor words at each end, the VAS uses a continuous numeric range. This approach relies more on numerical values rather than potentially vague VAWs in the middle, reducing confusion that may arise from translation discrepancies. Thus, the numeric scale may provide a more precise and consistent measure of intensity, even when verbal anchors are challenging to translate accurately.

4.2.3 Step 3: Survey Deployment

Following the design of the survey, the next phase is deployment. During this phase, several questions should be considered (Figure 7):

– How frequently should participants fill in the survey (temporal resolution)?
– Who should fill in the survey and which locations should be considered (spatial resolution)?
– What interface should be used?

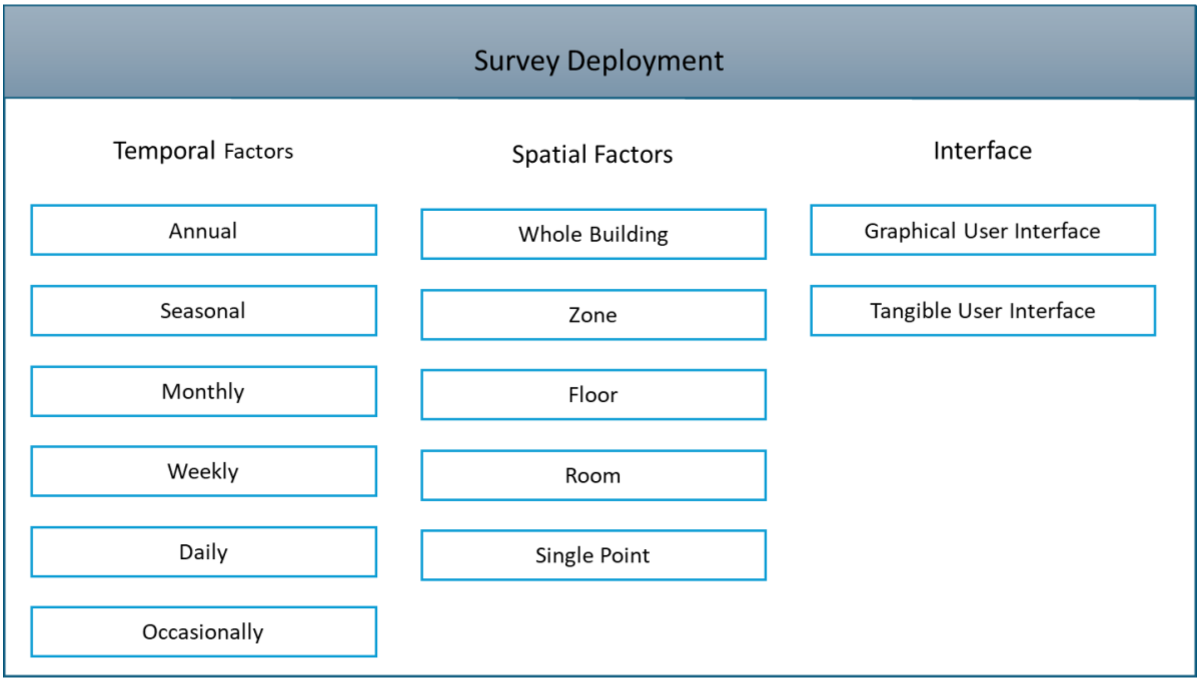

Figure 7. Important factors of survey deployment for developing subjective key performance indicators.

Temporal resolution: Common resolutions range from larger intervals like annual, occasional (e.g., after each building recommissioning) and seasonal (e.g., heating and cooling seasons), to more frequent intervals such as monthly, weekly, daily, hourly and complaint-driven (i.e., occupants can submit their feedback whenever they have a complaint). Fine data collection granularity, such as daily or hourly measurements, may lead to occupant fatigue and loss of engagement. Conversely, longer intervals, such as annual assessments, might overlook the dynamics of subjective experience. Interestingly, according to Rintala et al. [163], participant fatigue is more influenced by questionnaire length than the frequency of prompts. For example, asking occupants multiple times a day to fill in a short survey is less burdensome than asking them fewer times a day to fill in a lengthy survey.

An approach to reduce the number of surveys is proposed by utilizing targeted occupant surveys [177]. This survey platform employs real-time feedback to adjust survey requests according to specific indoor environmental conditions and ceases surveying once the necessary number of responses is obtained. This method aims to minimize occupant surveys while improving the approximation to ideal datasets compared to previous methods. In scenarios where only disfunction is of interest such as AFDD or control strategy optimization, a potential solution lies in complaint-driven approaches. It captures detailed occupant feedback only during malfunctions. Zagreus et al.

[178] also used a complaint-driven approach to inexpensively gather information on occupant satisfaction with IEQ factors.

Spatial resolution: Spatial resolution spans from entire buildings down to individual rooms and single point. When conducting surveys involving many occupants, collecting responses from the whole population becomes burdensome. A more efficient way is to sample a small group to represent the population of interest. Selecting whom to target can be challenging. To minimize error and bias while maximizing representativeness, precise sampling techniques are essential [179]. Randomization is often favored as each participant has an equal chance of being selected. Stratification considering participant characteristics (e.g. gender, age) can also help to refine the sampling strategy. Furthermore, specific locations within a larger building or zone can be considered. This includes the orientation of spaces (e.g. south-facing or north-facing) and their functional roles (e.g. office or reception area). By accounting for these details, the survey data will more accurately capture the diverse conditions present within the total environment ensuring a comprehensive and representative analysis.

Interface: Traditional survey implementation, such as paper questionnaires, is known for being time-consuming and expensive. Additionally, paper surveys require occupants to invest significant time in completion [178]. In response to these limitations and the challenge of achieving continuous feedback, modern digital technologies have been adopted [180,181]. Interfaces now play a pivotal role in facilitating how occupants interact with surveys. Modern interfaces are categorized into two main types: GUIs, including smartphone apps and websites, and TUIs, like interactive panels and wearables (e.g., smartwatches) [35,37,182]. Each type offers distinct advantages depending on the application context. TUIs are user-friendly and require minimal effort from occupants making them suitable for scenarios requiring high-frequency sampling, such as monitoring dynamic environments in transition spaces [180,181]. Conversely, GUIs leverage personal devices to facilitate participatory sensing, scalability, and easier maintenance through remote software updates, unlike TUIs that require physical adjustments [183–185].

4.2.4 Step 4: SKPI computation

Once the survey is deployed and data is collected, it will undergo statistical analysis to convert data with different spatial and temporal resolutions into SKPIs. SKPIs can be computed across both spatial and temporal dimensions at varying levels of *granularity*. Aggregating data across individuals (*spatial granularity*) reduces variance caused by inter-individual differences in subjective perceptions allowing the observation of temporal dynamics by analyzing aggregated KPIs over time. Conversely, aggregating data over time (*temporal granularity*) mitigates the uncertainty inherent in intra-individual subjective judgments allowing the identification of spatial variations in the environment. By combining spatial and temporal aggregations at appropriate granularities, it is possible to reveal both temporal and spatial patterns while simultaneously reducing uncertainty in subjective assessments. A variety of statistical measures can further support the development of robust SKPIs:

- **Measures of central tendency** like mean, median, and mode can help develop SKPIs that reflect the average IEQ. The median is preferred over the mean when: 1) The distribution contains extreme data points; 2) Some data points have undetermined values; 3) The data distribution is open-ended; 4) The data are measured on an ordinal scale [186]. For nominal data, the mode is the preferred measure of central tendency [186].
- **Measures of variability**, such as range, interquartile range, standard deviation and variance, help to reveal the individual differences and dynamics of the SKPI. Range is highly sensitive to outliers. Variance and standard deviations are suitable for normally distributed data, while interquartile range focuses on the middle 50% of the distribution and is suitable for skewed data or if outliers are present. Moreover, the maximum or minimum values can capture the extremes and highlight specific spatial locations and time intervals that need attention.
- **Measures of frequency**, such as count and percent, show how often a response occurs. For example, standards such as ISO 7730 [47] and ASHRAE 55 [54] stipulate that the TS rate of occupants should be at least 80%.
- **Measures of shapes of the distribution** include symmetry, skewness and kurtosis. These metrics can detect distribution shifts of subjective measures over time or space within individuals or a population.

- **Measures of correlations**, such as the Pearson correlation coefficient, Spearman's rank correlation coefficient and Cronbach's Alpha may be used to analyze relationships between different IEQ factors or among items within a factor. For instance, correlating similar (repetitive) items can help identify and eliminate careless responses when working with survey data, thereby improving the reliability and validity of the analysis.

5 CASE EXAMPLE OF THE PROPOSED FRAMEWORK

This section demonstrates a use case of SKPI development using the proposed framework in four steps: (i) establishing the objective of the SKPI, (ii) survey design, (iii) survey deployment, and (iv) translating the data into actionable indicators.

Step 1: Application goal

Fault diagnosis plays a critical role in enhancing the performance of HVAC systems by reducing energy waste, maintaining indoor air quality, and ensuring TC. A common fault in such systems is stuck heating coil valves, which frequently results in overheating or underheating the conditioned building zones. This case application is to develop an SKPI for diagnosing stuck heating coil valves of air handling units (AHUs) in office buildings during winter.

Step 2: Survey Design

Based on the proposed framework, the survey design for developing an SKPI needs to consider the following critical factors: (i) IEQ factor selection, (ii) item selections, (iii) question formulation, and (iv) scale formulation.

- *IEQ factor selection*: AHU heating coil valves control the air temperature and therefore a stuck heating coil valve will result in abnormal variations in air temperature. Hence, the KPI for this application case will be based on TQ.
- *Item selection*: Three items—TS, TC, and TP—are selected to assess TQ. The TC item is used to detect the existence of the fault. If the occupants feel comfortable, the HVAC operation achieves its comfort goal in the office building and, therefore, there might be no faults. Uncomfortable conditions imply potential faults in HVAC systems. The TS item may inform the 'direction' of the fault. The heating coil value may be stuck at a higher open position when occupants perceive 'hot', while the heating coil value may be stuck at a lower open position or closed position when occupants perceive 'cold'. In addition, the TP item can be used to rule out some special scenarios and to double check the subjective feedback. For example, one may vote 'slightly uncomfortable' and 'slightly warm' but may still prefer warmer conditions. This may be caused for example by the transition from the cold outdoors into the indoors or by mistakes made during filling out the surveys, instead of the heating valve faults. Since only uncomfortable conditions are relevant for fault diagnosis, a skip-logic approach is employed to address these three items: follow-up questions on TS and TP are triggered only when discomfort is reported.
- *Question*: Three specific questions were designed for TC, TS and TP by incorporating terms like 'comfortable', 'sensation' and 'prefer'. The question stresses "at this moment" and "in this place" to avoid recall bias as discussed in section 4. In addition, asking "at the moment" enables the possibility of the high-granularity measurement to detect the temporal dynamics of heating coil valves stuck. The spatial term "in this place" helps to identify which heating coil valve has faults in the case of multi-zone air distribution.
- *Scale*: A unipolar scale format is chosen for TC, as the intensity of discomfort reveals diagnostic information while the intensity of comfort is less relevant for fault diagnosis. For TS and TP, both sides of the neutral point are essential for diagnosing the severity of the faults and, therefore, bipolar scale formats are chosen. The GRS scale format is selected for all measurements due to its advantages in high sensitivity. To potentially address the equal distance assumption in GRS, numerical values are assigned to each VAW on the scale (e.g., -1 for "Slightly Cool", 0 for "Neutral", +1 for "Slightly Warm"). This may help occupants to assume equal spacing between VAWs. For the number of VAWs, we take seven anchor words for TS and TP, as suggested in section 4. For the unipolar TC scale, four VAWs are used to describe discomfort (Figure 8).

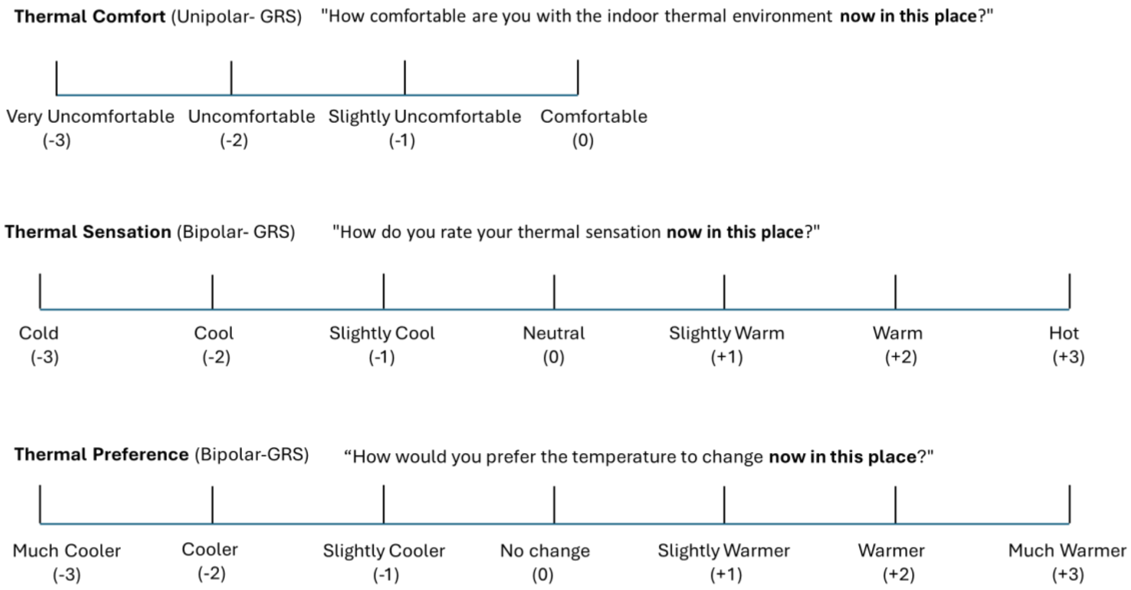

Figure 8. Survey design for diagnosing heating coil valve faults.

Step 3: Deployment of the survey

Surveys will be distributed to all occupants to establish a baseline reference under normal operating conditions when no faults exist in the heating coils. Since discomfort indicates stuck heating coil valves, a complaint-driven approach is used (*temporal resolution*). Occupants only submit their complaints when they feel uncomfortable. This complaint-driven method reduces the survey burden on participants compared to a fixed-interval survey approach. Human thermal perceptions are influenced by inter- and intra-individual factors beyond ambient air temperature. On top of that, temperature spatial differences also exist within the conditioned zone. As a result, collecting sufficient feedback is essential to derive reliable SKPIs. To address this, if the percentage of occupants submitting complaints exceeds a predefined threshold (indication of the faulty conditions), additional *diagnostic* survey requests can be issued. These surveys may target either all occupants or a random sample in the targeted zone (*spatial resolution*). A GUI is selected to implement the proposed deployment method as it enables seamless communication with occupants and is easily accessible via personal smartphones.

Step 4: SKPI calculation

The collected data consists of individual votes from various rooms within the heating zone (spatial resolution) in either the reference survey or diagnostic survey (temporal resolutions). The window of SKPI calculation can be in each reference and diagnostic survey (temporal dimension) and at the room level and zone level (spatial dimensions). The *differences* in subjective perceptions at the zone-level between the diagnostic and reference surveys help identify the occurrence of the heating valve being stuck. The *variations* at room level can distinguish between localized and central faults. For example, high variance (one room is comfortable while others are not) suggests a local fault such as a variable air volume (VAV) valve problem. Low variance (all rooms are uncomfortable) indicates a stuck heating coil valve in the central AHU. The SKPI to diagnose heating valve issues includes:

- Discomfort ratio: This is calculated as the *percentage* of individuals reporting discomfort based on the diagnostic survey. It implies potential heating coil malfunctions as previously mentioned.
- Median of TS, TC and TP: The median is used to assess the severity of faults because it is robust against outliers, unlike the mean, and more applicable than the mode for continuous data. Using central tendency measures also helps reduce uncertainties associated with inter- and intra-individual variations in subjective responses.
- Pearson correlation between TS and TP: This identifies outliers and helps exclude specific cases. For example, a positive Pearson correlation between TS and TP might indicate occupants transitioning from cold outdoor environments into offices, which could skew diagnostic interpretations.

6 DISCUSSION AND CONCLUSIONS

Using humans as sensors in building smart controls and management systems has demonstrated significant potential to enhance IEQ and building energy efficiency. In this deliverable, existing research on occupant feedback measurement has been reviewed, a structured methodological framework to convert subjective data into SKPIs has been developed, and a practical application of the proposed framework has been presented. However, several limitations should be acknowledged: Firstly, a systematic literature review was not conducted due to the extensive volume of relevant studies. As a result, the scales and questions collected may not encompass every approach in the existing literature. Nonetheless, the review shows clear inconsistencies in scale and question design within the surveyed body of work. Secondly, this study only focused on two IEQ factors: TQ and IAQ. Other domains, such as indoor acoustic quality, and visual quality were not explored. While the proposed methodology is tailored to TQ and IAQ, future studies may extend the framework to address subjective measures and applications in these additional domains.

The findings of this study highlight several critical gaps and questions that necessitate future research for SKPI development:

– *How to design efficient yet effective surveys?* Efficient surveys should minimize item redundancy while capturing essential subjective dimensions of the indoor environment. Existing studies have investigated TQ dimensions, but research into the dimensionality of IAQ experiences remains limited. Further work is needed to develop concise, comprehensive surveys that reflect these complex experiences.
– *How to design validated and robust scales?* The literature review shows that different studies used different scales to measure the same subjective perceptions, e.g. TS scales in section 3. This impedes comparability across different studies and may confound their research findings. Many existing scales in the TQ and IAQ domain lack rigorous validation, and concerns have also arisen recently regarding the equal-distance issues in the ASHRAE scales [173]. Future research should focus on the development of validated, psychometrically robust scales. These efforts should consider: 1) Optimal scale format (types and VAWs) tailored to different respondent characteristics and application scenarios; 2) The strengths and limitations of various scale formats across diverse contexts and populations; 3) Effective translation of scales across languages while preserving their psychometric properties.
– *What sample size is sufficient?* Subjective judgements are prone to inter- and intra-individual variation in nature. Therefore, reliable SKPIs need sufficient samples to balance this variation. Further work is required to investigate how large the sample size should be to reduce the intra-individual and inter-individual noise to an acceptable extent.
– *What are the potential areas for the SKPI applications?* The literature primarily highlights SKPI applications in environmental assessment and HVAC control. However, SKPIs can extend to other domains requiring indoor environmental sensing, including HVAC fault detection and diagnosis, building energy management, building commissioning, building certifications, and building energy flexibility using adaptive temperature setpoints.

The key conclusions of this study are as follows:

– Significant inconsistency exists across the literature in survey design, survey deployment and SKPI computation strategies, even for the same application purpose. This inconsistency manifests in the selection of IEQ factors, the design of survey questions and scales, data collection methods, and data aggregation strategies. However, the rationale for these variations is often unclear, often based on arbitrary decisions.
– Inconsistent terminology in TQ is evident; for example, TC is often used to describe TS in the literature. The most commonly used items for assessing TQ are TS, TC, TA, and TP. The literature suggests that TQ perception consists of at least two dimensions and using at least two items, such as TS and TC, provides a more comprehensive assessment of TQ. However, unlike TQ, a clear classification of items and dimensions for IAQ does not currently exist.
– There is no "one method fits all"; instead, the survey design, survey deployment and SKPI computation strategies should align with specific application goals. Hence, this study proposed a methodological framework to systematize SKPI development encompassing four generally applicable steps.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Netherlands Enterprise Agency (project number MOOI32004) and the Netherlands' Ministry of Economic Affairs and Climate (project number 202103101) for their financial support. Special thanks to Professor Emeritus Wim Zeiler for his guidance during the early stages of this work. Additionally, we acknowledge the sharing of knowledge provided by IEA EBC Annex 81.

REFERENCES

[1] International Energy Agency (IEA), Energy System: Buildings, (2023). https://www.iea.org/energy-system/buildings.

[2] International Energy Agency (IEA), CO2 Emissions in 2022, (2023). https://www.iea.org/reports/co2-emissions-in-2022.

[3] C. Karmann, S. Schiavon, L.T. Graham, P. Raftery, F. Bauman, Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings, Build Environ 126 (2017) 431–441. https://doi.org/10.1016/J.BUILDENV.2017.10.024.

[4] K.W.; W.D.; F.M.Y.; L.P.; Q.L. Roth, Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential., (2005).

[5] C. van Dronkelaar, M. Dowson, C. Spataru, D. Mumovic, A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings, Front Mech Eng 1 (2016). https://doi.org/10.3389/fmech.2015.00017.

[6] P. Wilde, Building Performance Analysis, Wiley, 2018. https://doi.org/10.1002/9781119341901.

[7] A. Kylili, P.A. Fokaides, P.A. Lopez Jimenez, Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review, Renewable and Sustainable Energy Reviews 56 (2016) 906–915. https://doi.org/10.1016/J.RSER.2015.11.096.

[8] H. ALwaer, D.J. Clements-Croome, Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings, Build Environ 45 (2010) 799–807. https://doi.org/10.1016/j.buildenv.2009.08.019.

[9] J. Al Dakheel, C. Del Pero, N. Aste, F. Leonforte, Smart buildings features and key performance indicators: A review, Sustain Cities Soc 61 (2020). https://doi.org/10.1016/j.scs.2020.102328.

[10] H. Li, Z. Wang, T. Hong, Occupant-Centric key performance indicators to inform building design and operations, J Build Perform Simul 14 (2021) 814–842. https://doi.org/10.1080/19401493.2021.1876771.

[11] H. Li, T. Hong, S.H. Lee, M. Sofos, System-level key performance indicators for building performance evaluation, Energy Build 209 (2020). https://doi.org/10.1016/j.enbuild.2019.109703.

[12] N.N. Abu Bakar, M.Y. Hassan, H. Abdullah, H.A. Rahman, M.P. Abdullah, F. Hussin, M. Bandi, Energy efficiency index as an indicator for measuring building energy performance: A review, Renewable and Sustainable Energy Reviews 44 (2015) 1–11. https://doi.org/10.1016/j.rser.2014.12.018.

[13] S. Wang, Making buildings smarter, grid-friendly, and responsive to smart grids, Sci Technol Built Environ 22 (2016) 629–632. https://doi.org/10.1080/23744731.2016.1200888.

[14] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants, J Expo Anal Environ Epidemiol 11 (2001) 231–252. https://doi.org/10.1038/sj.jea.7500165.

[15] M. Jia, R.S. Srinivasan, A.A. Raheem, From occupancy to occupant behavior: An analytical survey of data acquisition technologies, modeling methodologies and simulation coupling mechanisms for building energy efficiency, Renewable and Sustainable Energy Reviews 68 (2017) 525–540. https://doi.org/10.1016/J.RSER.2016.10.011.

[16] I.M. de Alegría Mancisidor, P. Díaz de Basurto Uraga, I. Martínez de Alegría Mancisidor, P. Ruiz de Arbulo López, European Union's renewable energy sources and energy efficiency policy review: The Spanish perspective, Renewable and Sustainable Energy Reviews 13 (2009) 100–114. https://doi.org/10.1016/J.RSER.2007.07.003.

[17] Z. Ma, S. Wang, Building energy research in Hong Kong: A review, Renewable and Sustainable Energy Reviews 13 (2009) 1870–1883. https://doi.org/10.1016/J.RSER.2009.01.006.

[18] S. Chen, G. Zhang, X. Xia, Y. Chen, S. Setunge, L. Shi, The impacts of occupant behavior on building energy consumption: A review, Sustainable Energy Technologies and Assessments 45 (2021) 101212. https://doi.org/10.1016/J.SETA.2021.101212.

[19] J. Kim, T. Hong, J. Jeong, C. Koo, M. Kong, An integrated psychological response score of the occupants based on their activities and the indoor environmental quality condition changes, Build Environ 123 (2017) 66–77. https://doi.org/10.1016/J.BUILDENV.2017.06.046.

[20] A. Tomaschek, S.S.L. Lanfer, M. Melzer, U. Debitz, G. Buruck, Measuring work-related psychosocial and physical risk factors using workplace observations: a validation study of the "Healthy Workplace Screening," Saf Sci 101 (2018) 197–208. https://doi.org/10.1016/j.ssci.2017.09.006.

[21] P.O. Fanger, Thermal Comfort, Copenhagen, Danish Technical Press., Copenhagen : Danish Technical Press, 1970.

[22] X. Yuan, W. Long, "Per Capita Building Energy Consumption Occupied Space(PCEOS)" for Assessment of Building Energy Consumption, in: 2009 International Conference on Management and Service Science, IEEE, 2009: pp. 1–4. https://doi.org/10.1109/ICMSS.2009.5304217.

[23] W. O'Brien, I. Gaetani, S. Carlucci, P.J. Hoes, J.L.M. Hensen, On occupant-centric building performance metrics, Build Environ 122 (2017) 373–385. https://doi.org/10.1016/j.buildenv.2017.06.028.

[24] S. Sleiman, M. Ouf, W. Luo, R. Kramer, W. Zeiler, E. Borkowski, T. Hong, Z. Nagy, Z. Chen, Overview of occupant-centric KPIs for building performance and their value to various building stakeholders, Energy Build 322 (2024) 114704. https://doi.org/10.1016/j.enbuild.2024.114704.

[25] P. Li, T.M. Froese, G. Brager, Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review, Build Environ 133 (2018) 187–202. https://doi.org/10.1016/J.BUILDENV.2018.02.024.

[26] H.Y. Teh, A.W. Kempa-Liehr, K.I.-K. Wang, Sensor data quality: a systematic review, J Big Data 7 (2020) 11. https://doi.org/10.1186/s40537-020-0285-1.

[27] K. Mohammed, V. Krishnan, H. Zheng, Shalika S.W. Walker, Rick P. Kramer, Wim Zeiler, Low cost-effective measurements for schools. , in: Marcel Schweiker, Christoph Van Treeck, Dirk Mueller, Janina Fels, T Kraus, Hannah Pallubinsky (Eds.), Healthy Buildings Europe 2023, ISIAQ International, Aachen, 2023.

[28] M. Schweiker, G.M. Huebner, B.R.M. Kingma, R. Kramer, H. Pallubinsky, Drivers of diversity in human thermal perception – A review for holistic comfort models, Temperature 5 (2018) 308–342. https://doi.org/10.1080/23328940.2018.1534490.

[29] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, Build Environ 153 (2019) 205–217. https://doi.org/10.1016/J.BUILDENV.2019.01.055.

[30] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, Energy Build 105 (2015) 178–205. https://doi.org/10.1016/j.enbuild.2015.07.047.

[31] G.S. Brager, R.J. De Dear, Thermal adaptation in the built environment: a literature review, Energy Build 27 (1998) 83–96. https://doi.org/10.1016/S0378-7788(97)00053-4.

[32] D.D. McKemy, The molecular and cellular basis of cold sensation, ACS Chem Neurosci 4 (2013) 238–247. https://doi.org/10.1021/cn300193h.

[33] M. Obrist, A.N. Tuch, K. Hornbæk, Opportunities for odor: Experiences with smell and implications for technology, in: Conference on Human Factors in Computing Systems - Proceedings, Association for Computing Machinery, 2014: pp. 2843–2852. https://doi.org/10.1145/2556288.2557008.

[34] Y. Murakami, M. Terano, K. Mizutani, M. Harada, S. Kuno, Field experiments on energy consumption and thermal comfort in the office environment controlled by occupants' requirements from PC terminal, Build Environ 42 (2007) 4022–4027. https://doi.org/10.1016/J.BUILDENV.2006.05.012.

[35] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, Human-Building Interaction Framework for Personalized Thermal Comfort-Driven Systems in Office Buildings, Journal of Computing in Civil Engineering 28 (2014) 2–16. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000300.

[36] D. Sheikh Khan, J. Kolarik, Can occupant voting systems provide energy savings and improved occupant satisfaction in buildings?—a review, Sci Technol Built Environ 28 (2022) 221–239. https://doi.org/10.1080/23744731.2021.1976017.

[37] D. Sheikh Khan, J. Kolarik, P. Weitzmann, Design and application of occupant voting systems for collecting occupant feedback on indoor environmental quality of buildings – A review, Build Environ 183 (2020). https://doi.org/10.1016/j.buildenv.2020.107192.

[38] M.G.L.C. Loomans, A. Huovila, P.-H. Lefebvre, J. Porkka, P. Huovila, J. Desmyter, A. Vaturi, Key Performance Indicators For The Indoor Environment, APA, 2011. www.tue.nl/taverne.

[39] P. Wolkoff, K. Azuma, P. Carrer, Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation, Int J Hyg Environ Health 233 (2021) 113709. https://doi.org/10.1016/j.ijheh.2021.113709.

[40] I. Mujan, A.S. Anđelković, V. Munćan, M. Kljajić, D. Ružić, Influence of indoor environmental quality on human health and productivity - A review, J Clean Prod 217 (2019) 646–657. https://doi.org/10.1016/j.jclepro.2019.01.307.

[41] L.-R. Jia, J. Han, X. Chen, Q.-Y. Li, C.-C. Lee, Y.-H. Fung, Interaction between Thermal Comfort, Indoor Air Quality and Ventilation Energy Consumption of Educational Buildings: A Comprehensive Review, Buildings 11 (2021) 591. https://doi.org/10.3390/buildings11120591.

[42] M.T. Pham, A. Rajić, J.D. Greig, J.M. Sargeant, A. Papadopoulos, S.A. Mcewen, A scoping review of scoping reviews: Advancing the approach and enhancing the consistency, Res Synth Methods 5 (2014) 371–385. https://doi.org/10.1002/jrsm.1123.

[43] Z. Munn, M.D.J. Peters, C. Stern, C. Tufanaru, A. McArthur, E. Aromataris, Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach, BMC Med Res Methodol 18 (2018). https://doi.org/10.1186/s12874-018-0611-x.

[44] K. Parsons, Human Thermal Environments, CRC Press, 2014. https://doi.org/10.1201/b16750.

[45] ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy, 2017. https://www.ashrae.org.

[46] EN 16798-1:2019, Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6, 2019.

[47] ISO 7730 : 2005, Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 2005. https://www.iso.org/standard/39155.html?utm_source=chatgpt.com.

[48] ISO 10551:2019, Ergonomics of the physical environment — Subjective judgement scales for assessing physical environments, 2019. https://www.iso.org/standard/67186.html.

[49] J.Y. Lee, E.A. Stone, H. Wakabayashi, Y. Tochihara, Issues in combining the categorical and visual analog scale for the assessment of perceived thermal sensation: Methodological and conceptual considerations, Appl Ergon 41 (2010) 282–290. https://doi.org/10.1016/J.APERGO.2009.07.007.

[50] M.D. Tesler, M.C. Savedra, W.L. Holzemer, D.J. Wilkie, J.A. Ward, S.M. Paul, The word-graphic rating scale as a measure of children's and adolescents' pain intensity, Res Nurs Health 14 (1991) 361–371. https://doi.org/10.1002/nur.4770140507.

[51] M.E. Wewers, N.K. Lowe, A critical review of visual analogue scales in the measurement of clinical phenomena, Res Nurs Health 13 (1990) 227–236. https://doi.org/10.1002/nur.4770130405.

[52] M. Schweiker, X. Fuchs, S. Becker, M. Shukuya, M. Dovjak, M. Hawighorst, J. Kolarik, Challenging the assumptions for thermal sensation scales, Building Research and Information 45 (2017) 572–589. https://doi.org/10.1080/09613218.2016.1183185.

[53] L.A. Jones, H.-N. Ho, Warm or Cool, Large or Small? The Challenge of Thermal Displays, IEEE Trans Haptics 1 (2008) 53–70. https://doi.org/10.1109/TOH.2008.2.

[54] ANSI/ASHRAE, ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy, The American Society of Heating Refrigerating and Air-Conditioning Engineers (2017).

[55] F. Zhang, S. Haddad, B. Nakisa, M.N. Rastgoo, C. Candido, D. Tjondronegoro, R. de Dear, The effects of higher temperature setpoints during summer on office workers' cognitive load and thermal comfort, Build Environ 123 (2017) 176–188. https://doi.org/10.1016/J.BUILDENV.2017.06.048.

[56] S.Q. da S. Hirashima, E.S. de Assis, M. Nikolopoulou, Daytime thermal comfort in urban spaces: A field study in Brazil, Build Environ 107 (2016) 245–253. https://doi.org/10.1016/J.BUILDENV.2016.08.006.

[57] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Build Environ 45 (2010) 29–39. https://doi.org/10.1016/j.buildenv.2009.02.016.

[58] R. de Dear, J. Kim, T. Parkinson, Residential adaptive comfort in a humid subtropical climate—Sydney Australia, Energy Build 158 (2018) 1296–1305. https://doi.org/10.1016/J.ENBUILD.2017.11.028.

[59] H. Zhang, E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y. Zhai, M. Pigman, Using footwarmers in offices for thermal comfort and energy savings, Energy Build 104 (2015) 233–243. https://doi.org/10.1016/J.ENBUILD.2015.06.086.

[60] C. Huizenga, S. Abbaszadeh, L. Zagreus, E. Arens, Air Quality and Thermal Comfort in Office Buildings: Results of a Large Indoor Environmental Quality Survey, 2006. http://cbe.berkeley.edu.

[61] S.G. Hodder, K. Parsons, The effects of solar radiation on thermal comfort, Int J Biometeorol 51 (2007) 233–250. https://doi.org/10.1007/s00484-006-0050-y.

[62] N.H. Wong, S.S. Khoo, Thermal comfort in classrooms in the tropics, Energy Build 35 (2003) 337–351. https://doi.org/10.1016/S0378-7788(02)00109-3.

[63] R. de Dear, J. Kim, C. Candido, M. Deuble, Adaptive thermal comfort in Australian school classrooms, Building Research & Information 43 (2015) 383–398. https://doi.org/10.1080/09613218.2015.991627.

[64] H. Zhang, E. Arens, C. Huizenga, T. Han, Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort, Build Environ 45 (2010) 399–410. https://doi.org/10.1016/j.buildenv.2009.06.020.

[65] E. Arens, H. Zhang, C. Huizenga, Partial- and whole-body thermal sensation and comfort— Part I: Uniform environmental conditions, J Therm Biol 31 (2006) 53–59. https://doi.org/10.1016/J.JTHERBIO.2005.11.028.

[66] S. Liu, B. Cao, Y. Zhu, Experimental study on comparison of indoor and multiple outdoor thermal environments excluding visual and acoustic interference, Sustain Cities Soc 94 (2023). https://doi.org/10.1016/j.scs.2023.104564.

[67] G. Torriani, G. Lamberti, F. Fantozzi, F. Babich, Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools, Journal of Building Engineering 63 (2023). https://doi.org/10.1016/j.jobe.2022.105419.

[68] I. Mujan, D. Licina, M. Kljajić, A. Čulić, A.S. Anđelković, Development of indoor environmental quality index using a low-cost monitoring platform, J Clean Prod 312 (2021) 127846. https://doi.org/10.1016/J.JCLEPRO.2021.127846.

[69] P. Wargocki, Perceived air quality, sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads, Indoor Air 9 (1999) 165–179. https://doi.org/10.1111/j.1600-0668.1999.t01-1-00003.x.

[70] F. Ma, C. Zhan, X. Xu, Investigation and Evaluation of Winter Indoor Air Quality of Primary Schools in Severe Cold Weather Areas of China, Energies (Basel) 12 (2019) 1602. https://doi.org/10.3390/en12091602.

[71] J. Kim, M. Jang, K. Choi, K. Kim, Perception of indoor air quality (IAQ) by workers in underground shopping centers in relation to sick-building syndrome (SBS) and store type: A cross-sectional study in Korea, BMC Public Health 19 (2019). https://doi.org/10.1186/s12889-019-6988-6.

[72] G. Brager, L. Baker, Occupant satisfaction in mixed-mode buildings, Building Research & Information 37 (2009) 369–380. https://doi.org/10.1080/09613210902899785.

[73] W. Angell, U. Hannu Arvela, F. James Axley, U. Sandra Baldacci, I. Michael Berry, U. Jonny Bjurman, S. Peter Blom, N. Malcolm Blumenthal, U. Michael Brauer, C. Niels Breum, D. Harriet Burge, U. William Cain, U. Neil Carlson, U. Marilou Cheple, U. Per Clausen, D. Keith Cliff, U. Maurizio De-Bortoli, I. Robert Dumont, C. Lars Ekberg, S. Annika Ekstrand-Tobin, S. Helmut Feustel, U. Don Figley, C. Jordan Fink, U. William Fisk, U. Karin Foarde, U. Robert Gehrig, S. Diana Godish, U. Zhishi Guo, H. Gustafsson, S.D. Bruce Henschel, U. Eeva-Liisa Hintikka, F. Michael Hodgson, U. Beverly Hooper, A. Ling-ling Hung, U. Mar-itta Jaakkola, F.B. Rikke Jorgensen, N. Helmut Knoppel, I. Neil Leslie, U. Karsten Levs-en, R. Menzies, C. Philip Morey, U. Gary Nelson, U. Daniel Norback, S. Malcolm Orme, U. Rein Otson, M. Pearce, U. Anthony Pickering, U.T. A E Platts-Mills, U. James Ramsey, U. Gary Raw, U. Claude-Alain Roulet, S. Ragnar Rylander, S. Tunga Salthammer, G. Max Sherman, U. Bruce Tichenor, U. Gene Tucker, U. Sylvia Von Machensen, G. James Walker, U. George - Walton, U. Charles Weschler, U. James White, C. Timothy Whitley, U. David Wolbrink, U. Peder Wolkoff, D. Hiroshi Yoshino, P.M. Bluyssen, E. DE Oliveira Fernandes, L. Groes, G. Clausen, C.A. Bernhard, C.A. RouLET, European Indoor Air Quality Audit Project in 56 Office Buildings, Indoor Air 6 (1996) 221–238.

[74] H. Tang, Y. Ding, B.C. Singer, Post-occupancy evaluation of indoor environmental quality in ten nonresidential buildings in Chongqing, China, Journal of Building Engineering 32 (2020) 101649. https://doi.org/10.1016/J.JOBE.2020.101649.

[75] K. Andersson, Epidemiological Approach to Indoor Air Problems, Indoor Air 8 (1998) 32–39. https://doi.org/10.1111/j.1600-0668.1998.tb00005.x.

[76] J. Kim, R. de Dear, C. Cândido, H. Zhang, E. Arens, Gender differences in office occupant perception of indoor environmental quality (IEQ), Build Environ 70 (2013) 245–256. https://doi.org/10.1016/J.BUILDENV.2013.08.022.

[77] P. Wargocki, The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity, Indoor Air 10 (2000) 222–236. https://doi.org/10.1034/j.1600-0668.2000.010004222.x.

[78] L. Gunnarsen, P.O. Fanger, ADAPTATION TO INDOOR AIR POLLUTION, 1992.

[79] J. Kim, R. de Dear, Nonlinear relationships between individual IEQ factors and overall workspace satisfaction, Build Environ 49 (2012) 33–40. https://doi.org/10.1016/J.BUILDENV.2011.09.022.

[80] M. Frontczak, R.V. Andersen, P. Wargocki, Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing, Build Environ 50 (2012) 56–64. https://doi.org/10.1016/J.BUILDENV.2011.10.012.

[81] Indoor Air Quality Assessment and Health impact in context to Household conditions in Lucknow, Global NEST Journal (2019). https://doi.org/10.30955/gnj.003105.

[82] Air quality management -- Congresses, Indoor air pollution -- Health aspects -- Congresses, Housing and health -- Congresses, in: Espoo, Finland : Indoor Air '93, 1993.

[83] A. Hedge, W.A. Erickson, G. Rubin, PREDICTING SICK BUILDING SYNDROME AT THE INDIVIDUAL AND AGGREGATE LEVELS, 1996.

[84] D.I. Bogatu, J. Shinoda, J.J. Aguilera, B.W. Olesen, F. Watanabe, Y. Kaneko, O.B. Kazanci, Human physiology for personal thermal comfort-based HVAC control – A review, Build Environ 240 (2023) 110418. https://doi.org/10.1016/J.BUILDENV.2023.110418.

[85] Y. Xie, J. Niu, H. Zhang, S. Liu, J. Liu, T. Huang, J. Li, C.M. Mak, Development of a multi-nodal thermal regulation and comfort model for the outdoor environment assessment, Build Environ 176 (2020) 106809. https://doi.org/10.1016/J.BUILDENV.2020.106809.

[86] W. Liu, Y. Zhang, Q. Deng, The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate, Energy Build 128 (2016) 190–197. https://doi.org/10.1016/J.ENBUILD.2016.06.086.

[87] Z. Fang, Z. Lin, C.M. Mak, J. Niu, K.T. Tse, Investigation into sensitivities of factors in outdoor thermal comfort indices, Build Environ 128 (2018) 129–142. https://doi.org/10.1016/J.BUILDENV.2017.11.028.

[88] Y. He, H. Zhang, E. Arens, A. Merritt, C. Huizenga, R. Levinson, A. Wang, A. Ghahramani, A. Alvarez-Suarez, Smart detection of indoor occupant thermal state via infrared thermography, computer vision, and machine learning, Build Environ 228 (2023) 109811. https://doi.org/10.1016/J.BUILDENV.2022.109811.

[89] W. Luo, R. Kramer, M. Kompier, K. Smolders, Y. de Kort, W. van Marken Lichtenbelt, Effects of correlated color temperature of light on thermal comfort, thermophysiology and cognitive performance, Build Environ 231 (2023) 109944. https://doi.org/10.1016/J.BUILDENV.2022.109944.

[90] T. Chaudhuri, D. Zhai, Y.C. Soh, H. Li, L. Xie, Random forest based thermal comfort prediction from gender-specific physiological parameters using wearable sensing technology, Energy Build 166 (2018) 391–406. https://doi.org/10.1016/J.ENBUILD.2018.02.035.

[91] X. Jia, S. Li, Y. Zhu, W. Ji, B. Cao, Transient thermal comfort and physiological responses following a step change in activity status under summer indoor environments, Energy Build 285 (2023). https://doi.org/10.1016/j.enbuild.2023.112918.

[92] T. Xu, R. Yao, C. Du, B. Li, Outdoor thermal perception and heatwave adaptation effects in summer – A case study of a humid subtropical city in China, Urban Clim 52 (2023) 101724. https://doi.org/10.1016/J.UCLIM.2023.101724.

[93] Nikolopoulou, RUROS: Rediscovering the Urban Realm and Open Spaces. Final Project Report for EU, Section 6, (2011).

[94] Pantavou K., Lykoudis S., Delibasis K. K., Tseliou A., Koletsis I., Nikolopoulou M., Tsiros I.X.1, The integration of three field survey datasets in Athens, Greece: transformation of five-point to seven-point thermal sensation scale, 2019. http://alpha.cres.gr/ruros/.

[95] R. Rawal, M. Schweiker, O.B. Kazanci, V. Vardhan, Q. Jin, L. Duanmu, Personal comfort systems: A review on comfort, energy, and economics, Energy Build 214 (2020). https://doi.org/10.1016/j.enbuild.2020.109858.

[96] E. Arens, H. Zhang, C. Huizenga, Partial- and whole-body thermal sensation and comfort - Part I: Uniform environmental conditions, in: J Therm Biol, 2006: pp. 53–59. https://doi.org/10.1016/j.jtherbio.2005.11.028.

[97] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Build Environ 45 (2010) 29–39. https://doi.org/10.1016/j.buildenv.2009.02.016.

[98] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, Q. Meng, Human comfort and perceived air quality in warm and humid environments with ceiling fans, Build Environ 90 (2015) 178–185. https://doi.org/10.1016/j.buildenv.2015.04.003.

[99] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, Indoor Air 20 (2010) 273–283. https://doi.org/10.1111/j.1600-0668.2010.00657.x.

[100] Z. Xie, B. Cao, Y. Zhu, A novel wind comfort evaluation method for different airflows by considering dynamic characteristics of wind direction and velocity, Build Environ 246 (2023). https://doi.org/10.1016/j.buildenv.2023.110976.

[101] S. Li, X. Jia, B. Cao, Y. Zhu, Improvement of thermal perceptions and physiological responses using torso heating under short-term cold exposure, Science of the Total Environment 892 (2023). https://doi.org/10.1016/j.scitotenv.2023.164491.

[102] X. Jia, B. Cao, Y. Zhu, A climate chamber study on subjective and physiological responses of airport passengers from walking to a sedentary status in summer, Build Environ 207 (2022) 108547. https://doi.org/10.1016/j.buildenv.2021.108547.

[103] Z. Li, Q. Zhang, O.B. Kazanci, F. Fan, B.W. Olesen, Investigation of group differences in human perceptions of indoor environment in open-plan offices in a severe cold region, Build Environ 213 (2022) 108855. https://doi.org/10.1016/J.BUILDENV.2022.108855.

[104] Z. Li, D. Loveday, P. Demian, Nudging and usage of thermal comfort-related systems, Energy Build 252 (2021) 111480. https://doi.org/10.1016/J.ENBUILD.2021.111480.

[105] C. Huizenga, L. Zagreus, E. Arens, D. Lehrer, UC Berkeley Indoor Environmental Quality (IEQ) Title Measuring indoor environmental quality: a web-based occupant satisfaction survey Publication Date Measuring Indoor Environmental Quality: A Web-based Occupant Satisfaction Survey, 2003.

[106] M. Kong, B. Dong, R. Zhang, Z. O'Neill, HVAC energy savings, thermal comfort and air quality for occupant-centric control through a side-by-side experimental study, Appl Energy 306 (2022) 117987. https://doi.org/10.1016/j.apenergy.2021.117987.

[107] P.M. Bluyssen, European indoor air quality audit project in 56 office buildings, Indoor Air 6 (1996) 221–238. https://doi.org/10.1111/j.1600-0668.1996.00002.x.

[108] S. Altomonte, S. Schiavon, Occupant satisfaction in LEED and non-LEED certified buildings, Build Environ 68 (2013) 66–76. https://doi.org/10.1016/J.BUILDENV.2013.06.008.

[109] A.K. Kaushik, M. Arif, M.M.G. Syal, M.Q. Rana, O.T. Oladinrin, A.A. Sharif, A.S. Alshdiefat, Effect of Indoor Environment on Occupant Air Comfort and Productivity in Office Buildings: A Response Surface Analysis Approach, Sustainability (Switzerland) 14 (2022). https://doi.org/10.3390/su142315719.

[110] F. Ma, C. Zhan, X. Xu, Investigation and evaluation ofwinter indoor air quality of primary schools in severe cold weather areas of China, Energies (Basel) 12 (2019). https://doi.org/10.3390/en12091602.

[111] Y.S. Lee, S. Kim, Indoor environmental quality in LEED-certified buildings in the U.S., Journal of Asian Architecture and Building Engineering 7 (2008) 293–300. https://doi.org/10.3130/jaabe.7.293.

[112] T. Cheung, S. Schiavon, L.T. Graham, K.W. Tham, Occupant satisfaction with the indoor environment in seven commercial buildings in Singapore, Build Environ 188 (2021) 107443. https://doi.org/10.1016/J.BUILDENV.2020.107443.

[113] L. Wang, D. Zheng, Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation, Build Environ 182 (2020) 107014. https://doi.org/10.1016/J.BUILDENV.2020.107014.

[114] L. Wang, D. Zheng, Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation, Build Environ 182 (2020) 107014. https://doi.org/10.1016/J.BUILDENV.2020.107014.

[115] H.H. Liang, C.P. Chen, R.L. Hwang, W.M. Shih, S.C. Lo, H.Y. Liao, Satisfaction of occupants toward indoor environment quality of certified green office buildings in Taiwan, Build Environ 72 (2014) 232–242. https://doi.org/10.1016/J.BUILDENV.2013.11.007.

[116] A.H. Abdullah, Y.Y. Lee, E. Aminudin, Y.H. Lee, INDOOR AIR QUALITY ASSESSMENT FOR A MULTI-STOREY UNIVERSITY OFFICE BUILDING IN MALAYSIA, n.d. http://meridian.allenpress.com/jgb/article-pdf/14/4/93/2403383/i1943-4618-14-4-93.pdf.

[117] D. Jung, Y. Choe, J. Shin, E. Kim, G. Min, D. Kim, M. Cho, C. Lee, K. Choi, B.L. Woo, W. Yang, Risk Assessment of Indoor Air Quality and Its Association with Subjective Symptoms among Office Workers in Korea, Int J Environ Res Public Health 19 (2022). https://doi.org/10.3390/ijerph19042446.

[118] Y. Wu, Y. Lu, D.C. Chou, Indoor air quality investigation of a university library based on field measurement and questionnaire survey, International Journal of Low-Carbon Technologies 13 (2018) 148–160. https://doi.org/10.1093/ijlct/cty007.

[119] P.M. Bluyssen, EPIQR and IEQ: indoor environment quality in European apartment buildings, Energy Build 31 (2000) 103–110. https://doi.org/10.1016/S0378-7788(99)00024-9.

[120] S.N. Nazli, A.Z. Ul-Saufie, A. Abd Razak, M. Elbayoumi, Assessment of Indoor Air Quality in Small and Medium Food Industries and Effects towards Perceived IAQ Symptoms, Sustainability (Switzerland) 15 (2023). https://doi.org/10.3390/su15054065.

[121] Y. Shang, B. Li, A.N. Baldwin, Y. Ding, W. Yu, L. Cheng, Investigation of indoor air quality in shopping malls during summer in Western China using subjective survey and field measurement, Build Environ 108 (2016) 1–11. https://doi.org/10.1016/J.BUILDENV.2016.08.012.

[122] M.F. Silva, S. Maas, H.A. de Souza, A.P. Gomes, Post-occupancy evaluation of residential buildings in Luxembourg with centralized and decentralized ventilation systems, focusing on indoor air quality (IAQ). Assessment by questionnaires and physical measurements, Energy Build 148 (2017) 119–127. https://doi.org/10.1016/J.ENBUILD.2017.04.049.

[123] F. Haghighat, G. Donnini, Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings, Build Environ 34 (1999) 479–503. https://doi.org/10.1016/S0360-1323(98)00034-1.

[124] J. Awad, C. Jung, Evaluating the indoor air quality after renovation at the Greens in Dubai, United Arab Emirates, Buildings 11 (2021). https://doi.org/10.3390/buildings11080353.

[125] K.W. Cheong, K.Y. Chong, Development and application of an indoor air quality audit to an air-conditioned building in Singapore, Build Environ 36 (2001) 181–188. https://doi.org/10.1016/S0360-1323(99)00064-5.

[126] J. Kim, M. Jang, K. Choi, K. Kim, Perception of indoor air quality (IAQ) by workers in underground shopping centers in relation to sick-building syndrome (SBS) and store type: A cross-sectional study in Korea, BMC Public Health 19 (2019). https://doi.org/10.1186/s12889-019-6988-6.

[127] P. Kuurola, T. Raunima, J. Ketko, O. Toyinbo, J. Vinha, U. Haverinen-Shaughnessy, Reduced night ventilation did not impair indoor air quality for occupants in a sample of Finnish school and daycare buildings, Energy Build 297 (2023) 113470. https://doi.org/10.1016/J.ENBUILD.2023.113470.

[128] A. Norhidayah, C.K. Lee, M.K. Azhar, S. Nurulwahida, Indoor Air Quality and Sick Building Syndrome in Three Selected Buildings, Procedia Eng 53 (2013) 93–98. https://doi.org/10.1016/J.PROENG.2013.02.014.

[129] K. Nordström, D. Norbäck, G. Wieslander, Subjective Indoor Air Quality in Geriatric Hospitals, Indoor and Built Environment 8 (1999) 49–57. https://doi.org/10.1177/1420326X9900800105.

[130] Z. Cheng, N. Lei, Z. Bu, H. Sun, B. Li, B. Lin, Investigations of indoor air quality for office buildings in different climate zones of China by subjective survey and field measurement, Build Environ 214 (2022). https://doi.org/10.1016/j.buildenv.2022.108899.

[131] H.F. Alomirah, H.M. Moda, Assessment of indoor air quality and users perception of a renovated office building in manchester, Int J Environ Res Public Health 17 (2020). https://doi.org/10.3390/ijerph17061972.

[132] K. Tähtinen, S. Lappalainen, K. Karvala, J. Remes, H. Salonen, Association between four-level categorisation of indoor exposure and perceived indoor air quality, Int J Environ Res Public Health 15 (2018). https://doi.org/10.3390/ijerph15040679.

[133] M. Monsberger, D. Koppelhuber, V. Sabol, H. Gursch, A. Spataru, O. Prentner, An innovative user feedback system for sustainable buildings, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2019. https://doi.org/10.1088/1755-1315/323/1/012123.

[134] S. Lazarova-Molnar, H.P. Logason, P.G. Andersen, M.B. Kjærgaard, Mobile crowdsourcing of data for fault detection and diagnosis in smart buildings, in: Proceedings of the 2016 Research in Adaptive and Convergent Systems, RACS 2016, Association for Computing Machinery, Inc, 2016: pp. 12–17. https://doi.org/10.1145/2987386.2987416.

[135] K.O. Aduda, T. Labeodan, W. Zeiler, G. Boxem, Y. Zhao, Demand side flexibility: Potentials and building performance implications, Sustain Cities Soc 22 (2016) 146–163. https://doi.org/10.1016/j.scs.2016.02.011.

[136] P. Morales-Valdés, A. Flores-Tlacuahuac, V.M. Zavala, Analyzing the effects of comfort relaxation on energy demand flexibility of buildings: A multiobjective optimization approach, Energy Build 85 (2014) 416–426. https://doi.org/10.1016/j.enbuild.2014.09.040.

[137] F. Sehar, M. Pipattanasomporn, S. Rahman, A peak-load reduction computing tool sensitive to commercial building environmental preferences, Appl Energy 161 (2016) 279–289. https://doi.org/10.1016/J.APENERGY.2015.10.009.

[138] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Build Environ 46 (2011) 922–937. https://doi.org/10.1016/j.buildenv.2010.10.021.

[139] Y. Miao, Y. Ding, Indoor environmental quality in existing public buildings in China: Measurement results and retrofitting priorities, Build Environ 185 (2020) 107216. https://doi.org/10.1016/J.BUILDENV.2020.107216.

[140] R. De Dear, J. Kim, M. Deuble, C. Candido, Summertime thermal comfort in Australian school classrooms, 2014. http://nceub.org.uk.

[141] W.H. Ko, S. Schiavon, H. Zhang, L.T. Graham, G. Brager, I. Mauss, Y.W. Lin, The impact of a view from a window on thermal comfort, emotion, and cognitive performance, Build Environ 175 (2020). https://doi.org/10.1016/j.buildenv.2020.106779.

[142] Richard de Dear and Gail Brager, Developing an adaptive model of thermal comfort and preference, Center for the Built Environment 104 (1998) 145–167.

[143] L. Hang, D.H. Kim, Enhanced model-based predictive control system based on fuzzy logic for maintaining thermal comfort in IoT smart space, Applied Sciences (Switzerland) 8 (2018). https://doi.org/10.3390/app8071031.

[144] J. Kim, F. Bauman, P. Raftery, E. Arens, H. Zhang, G. Fierro, M. Andersen, D. Culler, Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers, Build Environ 148 (2019) 348–360. https://doi.org/10.1016/J.BUILDENV.2018.11.012.

[145] X. Chen, Q. Wang, J. Srebric, Model predictive control for indoor thermal comfort and energy optimization using occupant feedback, Energy Build 102 (2015) 357–369. https://doi.org/10.1016/j.enbuild.2015.06.002.

[146] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings, Energy Build 70 (2014) 398–410. https://doi.org/10.1016/j.enbuild.2013.11.066.

[147] A. Ghahramani, F. Jazizadeh, B. Becerik-Gerber, A knowledge based approach for selecting energy-aware and comfort-driven HVAC temperature set points, Energy Build 85 (2014) 536–548. https://doi.org/10.1016/j.enbuild.2014.09.055.

[148] Q. Zhao, Y. Zhao, F. Wang, Y. Jiang, Y. Jiang, F. Zhang, Preliminary study of learning individual thermal complaint behavior using one-class classifier for indoor environment control, Build Environ 72 (2014) 201–211. https://doi.org/10.1016/j.buildenv.2013.11.009.

[149] V.L. Erickson, A.E. Cerpa, Thermovote, in: Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings, ACM, New York, NY, USA, 2012: pp. 9–16. https://doi.org/10.1145/2422531.2422534.

[150] S. Purdon, B. Kusy, R. Jurdak, G. Challen, Model-free HVAC control using occupant feedback, in: 38th Annual IEEE Conference on Local Computer Networks - Workshops, IEEE, 2013: pp. 84–92. https://doi.org/10.1109/LCNW.2013.6758502.

[151] S.R. West, J.K. Ward, J. Wall, Trial results from a model predictive control and optimisation system for commercial building HVAC, Energy Build 72 (2014) 271–279. https://doi.org/10.1016/J.ENBUILD.2013.12.037.

[152] D.A. Winkler, A. Beltran, N.P. Esfahani, P.P. Maglio, A.E. Cerpa, FORCES: Feedback and control for occupants to refine comfort and energy savings, in: UbiComp 2016 - Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Association for Computing Machinery, Inc, 2016: pp. 1188–1199. https://doi.org/10.1145/2971648.2971700.

[153] A.H.Y. Lam, Y. Yuan, D. Wang, An occupant-participatory approach for thermal comfort enhancement and energy conservation in buildings, in: E-Energy 2014 - Proceedings of the 5th ACM International Conference on Future Energy Systems, Association for Computing Machinery, 2014: pp. 133–143. https://doi.org/10.1145/2602044.2602067.

[154] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings, Energy Build 70 (2014) 398–410. https://doi.org/10.1016/J.ENBUILD.2013.11.066.

[155] V. Mansur, P. Carreira, A. Arsenio, A Learning Approach for Energy Efficiency Optimization by Occupancy Detection, in: 2015: pp. 9–15. https://doi.org/10.1007/978-3-319-19656-5_2.

[156] F. Jazizadeh, F.M. Marin, B. Becerik-Gerber, A thermal preference scale for personalized comfort profile identification via participatory sensing, Build Environ 68 (2013) 140–149. https://doi.org/10.1016/j.buildenv.2013.06.011.

[157] P. Drucker, The Practice of Management, Routledge, 2012. https://doi.org/10.4324/9780080942360.

[158] Z. Wang, J. Wang, Y. He, Y. Liu, B. Lin, T. Hong, Dimension analysis of subjective thermal comfort metrics based on ASHRAE Global Thermal Comfort Database using machine learning, Journal of Building Engineering 29 (2020) 101120. https://doi.org/10.1016/J.JOBE.2019.101120.

[159] Y. Zhang, R. Zhao, Overall thermal sensation, acceptability and comfort, Build Environ 43 (2008) 44–50. https://doi.org/10.1016/J.BUILDENV.2006.11.036.

[160] J. Wang, Z. Wang, R. de Dear, M. Luo, A. Ghahramani, B. Lin, The uncertainty of subjective thermal comfort measurement, Energy Build 181 (2018) 38–49. https://doi.org/10.1016/J.ENBUILD.2018.09.041.

[161] S. Liu, N. Nazarian, J. Niu, M.A. Hart, R. de Dear, From thermal sensation to thermal affect: A multi-dimensional semantic space to assess outdoor thermal comfort, Build Environ 182 (2020) 107112. https://doi.org/10.1016/J.BUILDENV.2020.107112.

[162] Robert F. DeVellis, Carolyn T. Thorpe., Robert F.DeVellis & amp; Carolyn T.Thorpe. (2022) Scale development: Theory and applications. California: SAGE Publications, Inc., 320 pages, $60.00 softcover, Pers Psychol 75 (2022) 243–244. https://doi.org/10.1111/peps.12499.

[163] A. Rintala, M. Wampers, G. Lafit, I. Myin-Germeys, W. Viechtbauer, Perceived disturbance and predictors thereof in studies using the experience sampling method, Current Psychology 42 (2023) 6287–6301. https://doi.org/10.1007/s12144-021-01974-3.

[164] S.S. Coughlin, Recall bias in epidemiologic studies, J Clin Epidemiol 43 (1990) 87–91. https://doi.org/10.1016/0895-4356(90)90060-3.

[165] G.H. Guyatt, M. Townsend, L.B. Berman, J.L. Keller, A comparison of Likert and visual analogue scales for measuring change in function, J Chronic Dis 40 (1987) 1129–1133. https://doi.org/10.1016/0021-9681(87)90080-4.

[166] R. Jaeschke, J. Singer, G.H. Guyatt, A comparison of seven-point and visual analogue scales: Data from a randomized trial, Control Clin Trials 11 (1990) 43–51. https://doi.org/10.1016/0197-2456(90)90031-V.

[167] O.C.S. Tzeng, R. Ware, N. Bharadwaj, Comparison between Continuous Bipolar and Unipolar Ratings of the Myers-Briggs Type Indicator, Educ Psychol Meas 51 (1991) 681–690. https://doi.org/10.1177/0013164491513019.

[168] W. Yang, H.J. Moon, J.Y. Jeon, Comparison of response scales as measures of indoor environmental perception in combined thermal and acoustic conditions, Sustainability (Switzerland) 11 (2019). https://doi.org/10.3390/su11143975.

[169] J.W. Beckstead, On measurements and their quality. Paper 4: Verbal anchors and the number of response options in rating scales, Int J Nurs Stud 51 (2014) 807–814. https://doi.org/10.1016/J.IJNURSTU.2013.09.004.

[170] G.A. Miller, The magical number seven, plus or minus two: Some limits on our capacity for processing information., Psychol Rev 63 (1956) 81–97. https://doi.org/10.1037/h0043158.

[171] T.L. Saaty, M.S. Ozdemir, Why the magic number seven plus or minus two, Math Comput Model 38 (2003) 233–244. https://doi.org/10.1016/S0895-7177(03)90083-5.

[172] G.S. Anderson, G.S. Meneilly, I.B. Mekjavic, Passive temperature lability in the elderly, Eur J Appl Physiol Occup Physiol 73 (1996) 278–286. https://doi.org/10.1007/BF02425488.

[173] M. Schweiker, M. André, F. Al-Atrash, H. Al-Khatri, R.R. Alprianti, H. Alsaad, R. Amin, E. Ampatzi, A.Y. Arsano, E. Azar, B. Bannazadeh, A. Batagarawa, S. Becker, C. Buonocore, B. Cao, J.H. Choi, C. Chun, H. Daanen, S.A. Damiati, L. Daniel, R. De Vecchi, S. Dhaka, S. Domínguez-Amarillo, E. Dudkiewicz, L.P. Edappilly, J. Fernández-Agüera, M. Folkerts, A. Frijns, G. Gaona, V. Garg, S. Gauthier, S.G. Jabbari, D. Harimi, R.T. Hellwig, G.M. Huebner, Q. Jin, M. Jowkar, J. Kim, N. King, B. Kingma, M.D. Koerniawan, J. Kolarik, S. Kumar, A. Kwok, R. Lamberts, M. Laska, M.C.J. Lee, Y. Lee, V. Lindermayr, M. Mahaki, U. Marcel-Okafor, L. Marín-Restrepo, A. Marquardsen, F. Martellotta, J. Mathur, I. Mino-Rodriguez, A. Montazami, D. Mou, B. Moujalled, M. Nakajima, E. Ng, M. Okafor, M. Olweny, W. Ouyang, A.L. Papst de Abreu, A. Pérez-Fargallo, I. Rajapaksha, G. Ramos, S. Rashid, C.F. Reinhart, M.I. Rivera, M. Salmanzadeh, K. Schakib-Ekbatan, S. Schiavon, S. Shooshtarian, M. Shukuya, V. Soebarto, S. Suhendri, M. Tahsildoost, F. Tartarini, D. Teli, P. Tewari, S. Thapa, M. Trebilcock, J. Trojan, R.B. Tukur, C. Voelker, Y. Yam, L. Yang, G. Zapata-Lancaster, Y. Zhai, Y. Zhu, Z.S. Zomorodian, Evaluating assumptions of scales for subjective assessment of thermal environments – Do laypersons perceive them the way, we researchers believe?, Energy Build 211 (2020). https://doi.org/10.1016/j.enbuild.2020.109761.

[174] K. Pantavou, I. Koletsis, S. Lykoudis, E. Melas, M. Nikolopoulou, I.X. Tsiros, Native influences on the construction of thermal sensation scales, Int J Biometeorol 64 (2020) 1497–1508. https://doi.org/10.1007/s00484-020-01927-8.

[175] J.-Y. Lee, Y. Tochihara, H. Wakabayashi, E.A. Stone, Warm or Slightly Hot? Differences in Linguistic Dimensions Describing Perceived Thermal Sensation, J Physiol Anthropol 28 (2009) 37–41. https://doi.org/10.2114/jpa2.28.37.

[176] H. Al-Khatri, M.B. Gadi, Investigating the behaviour of ASHRAE, Bedford, and Nicol thermal scales when translated into the Arabic language, Build Environ 151 (2019) 348–355. https://doi.org/10.1016/J.BUILDENV.2019.01.051.

[177] C. Duarte Roa, S. Schiavon, T. Parkinson, Targeted occupant surveys: A novel method to effectively relate occupant feedback with environmental conditions, Build Environ 184 (2020) 107129. https://doi.org/10.1016/J.BUILDENV.2020.107129.

[178] L. Zagreus, C. Huizenga, E. Arens, D. Lehrer, Listening to the occupants: a Web-based indoor environmental quality survey, Indoor Air 14 (2004) 65–74. https://doi.org/10.1111/j.1600-0668.2004.00301.x.

[179] S. Tyrer, B. Heyman, Sampling in epidemiological research: issues, hazards and pitfalls, BJPsych Bull 40 (2016) 57–60. https://doi.org/10.1192/pb.bp.114.050203.

[180] J. Berquist, M.M. Ouf, W. O'Brien, A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort, Build Environ 150 (2019) 88–98. https://doi.org/10.1016/J.BUILDENV.2018.12.064.

[181] K.S. Konis, Leveraging ubiquitous computing as a platform for collecting real-time occupant feedback in buildings, Intelligent Buildings International 5 (2013) 150–161. https://doi.org/10.1080/17508975.2013.781499.

[182] O. Shaer, Tangible User Interfaces: Past, Present, and Future Directions, Foundations and Trends® in Human–Computer Interaction 3 (2009) 1–137. https://doi.org/10.1561/1100000026.

[183] L.A. Hang-yat, D. Wang, Carrying My Environment with Me, in: Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings, ACM, New York, NY, USA, 2013: pp. 1–8. https://doi.org/10.1145/2528282.2528286.

[184] K. Konis, M. Annavaram, The Occupant Mobile Gateway: A participatory sensing and machine-learning approach for occupant-aware energy management, Build Environ 118 (2017) 1–13. https://doi.org/10.1016/J.BUILDENV.2017.03.025.

[185] O. Shaer, Tangible User Interfaces: Past, Present, and Future Directions, Foundations and Trends® in Human–Computer Interaction 3 (2009) 1–137. https://doi.org/10.1561/1100000026.

[186] M. S., Measures of central tendency: Median and mode, J Pharmacol Pharmacother 2 (2011) 214–215. https://doi.org/10.4103/0976-500X.83300.

APPENDIX A

Table A1. Scale formats used to measure occupant feedback on thermal sensation. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Scales	A	B	C	D	E	F	G	H
Ref.	[1–6]	[7–10]	[11,12]	[13]	[14]	[15]	[16]	[17]
Scale type	GRS/LS	GRS/LS	GRS/LS	LS	GRS	LS	LS	VAS
No. of Verbal anchor words	9-point	7-point	5-point	11-Point	7-Point	13-Point	13-Point	3-Point
Numeric value	Verbal Anchor Words of the corresponding scales in each column							
-6						So cold I am helpless	Unbearably cold	
-5				Completely Certain Cold		Numb with cold	Extremely cold	The coldest I have ever been
-4	Very cold	-				Very cold	Very cold	
-3	Cold	Cold			Cold	Cold	Cold	
-2	Cool	Cool	Very cold			Uncomfortably cold	Cool	
-1	Slightly cool	Slightly cool	Cold			Cool but fairly comfortable	Slightly cool	
0	Neutral	Neutral	Neither cool nor warm	Uncertain		Comfortable	Neutral	Neither cold nor warm
1	Slightly warm	Slightly warm	Warm			Warm but fairly comfortable	Slightly warm	
2	Warm	Warm	Very hot			Uncomfortably warm	Warm	
3	Hot	Hot			Hot	Hot	Very hot	
4	Very hot	-				Very hot	Extremely hot	
5				Completely Certain Warm		Almost as hot as I can stand	Unbearably hot	The hottest I have ever been
6						So hot I am sick and nauseated	Unbearably cold	

Table A2. Scale formats used to measure occupant feedback on thermal comfort. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values. Linear transformations are applied to some original scales in the literature to fit the table.

Scales	A	B	C	D	E	F	G	H	I	J	K	L	M
Ref.	[18–23]	[24]	[9]	[25]	[26]	[27,28]	[29]	[30]	[31]	[32]	[33,34]	[35,36]	[37]
Scale type	GRS/LS	GRS	GRS	VAS	VAS	LS	GRS	GRS	GRS	GRS	GRS	GRS	LS
No. of Verbal anchor words	6-point	7-point	5-point	4-point	4-point	5-point	7-point	4-point	4-point	6-point	4-point	5-point	4-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column												
4	Very Comfortable											Extremely uncomfortable	
3		Very comfortable		Clearly comfortable			Very comfortable			Very comfortable	Very uncomfortable	Very uncomfortable	Very Uncomfortable
2	Comfortable	Comfortable				Very comfortable	Comfortable			Fairly comfortable	Uncomfortable	Uncomfortable	Uncomfortable
1		Slightly Comfortable	Comfortable		Very Comfortable	Comfortable	Slightly comfortable		Comfortable	Slightly comfortable	Slightly uncomfortable	Slightly uncomfortable	Slightly Uncomfortable
0 +	Just comfortable	Not uncomfortable	Indifference/ Not uncomfortable	Just comfortable	just comfortable	Neutral	Indifference	comfort	Slightly comfortable	Just comfortable	Comfortable	Comfortable	Not Uncom

Scales	A	B	C	D	E	F	G	H	I	J	K	L	M
0 -	Just uncomfortable			Just uncomfortable	Just uncomfortable				Slightly uncomfortable				fortable
-1		Slightly uncomfortable	Slightly uncomfortable		Very uncomfortable	Uncomfortable	Slightly uncomfortable	Rather discomfort	Uncomfortable	Slightly Uncomfortable			
-2	Uncomfortable	Uncomfortable	Uncomfortable			Very Uncomfortable	Uncomfortable	Discomfort		Fairly Uncomfortable			
-3		Very Uncomfortable	Very Uncomfortable	Clearly Uncomfortable			Very Uncomfortable	Very discomfort		Very Uncomfortable			
-4	Very uncomfortable												

Table A3. Scale formats used to measure occupant feedback on thermal acceptance. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values. Linear transformations are applied to some original scales in the literature to fit the table.

Scales	A	B	C	D	E	F	G	H	I	J
Ref.	[38]	[25]	[39]	[40]	[41]	[42]	[10]	[24]	[29,36]	[28]
Scale type	OS	VAS	GRS	VAS	VAS	GRS	NS	VAS	LS	NS
No. of Verbal anchor words	4-point	4-point	4-point	4-point	2-point	4-point	2-point	4-point	4-point	2-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column									
2						Totally acceptable				
1	Acceptable	Clearly acceptable	Acceptable	Very acceptable	Acceptable	Just acceptable	Generally acceptable	Completely acceptable	Very acceptable	Yes
0-	Slightly acceptable	Just acceptable	Just acceptable (+0.01)	Just acceptable				Just acceptable	Just acceptable	No
0+	Slightly unacceptable	Just unacceptable	Just unacceptable (-0.01)	Just unacceptable				Just unacceptable	Just unacceptable	
-1	Unacceptable	Clearly unacceptable	unacceptable	Very Unacceptable	Not acceptable	Just unacceptable	Generally Unacceptable	completely unacceptable	Very unacceptable	
-2						Totally unacceptable				

Table A4. Scale formats used to measure occupant feedback on thermal satisfaction. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values

Scales	A	B	C	D
Ref.	[38]	[30]	[43]	[44]
Scale type	LS	GRS	LS	LS
No. of Verbal anchor words	7-Point	4-Point	2-Point	5-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column			
3	Very satisfied			
2	Satisfied			Satisfied
1	Somewhat satisfied	Clearly satisfied	Satisfied	Somewhat satisfied
0+	Neutral	Just Satisfied	Not satisfied	Neutral
0 -		Just dissatisfied		

Scales	A	B	C	D
-1	Somewhat dissatisfied	Clearly dissatisfied		Somewhat dissatisfied
-2	Dissatisfied			Dissatisfied
-3	Very dissatisfied			

Table A5. Scale formats used to measure occupant feedback on thermal pleasure. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and numeric values.

Scales	A	B
Ref.	[25,45]	[46]
Scale type	GRS/LS	GRS
No. of Verbal anchor words	7-point	3-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column	
3	Very pleasant	Pleasant
2	Pleasant	
1	Slightly pleasant	
0	Indifferent	Neutral
-1	Slightly unpleasant	
-2	Unpleasant	
-3	Very unpleasant	Unpleasant

Table A6. Scale formats used to measure occupant feedback on thermal preference. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values. Linear transformations are applied to some original scales in the literature to fit the table.

Scales	A	B	C	D
Ref.	[47]	[8,9,32,36,40,43]	[34,48]	[49,50]
Scale type	LS	LS	LS/GRS	LS/GRS
No. of Verbal anchor words	2-point	3-point	7-point	5-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column			
3			Much warmer	
2			Warmer	Much warmer
1	Want warmer	Want warmer	Slightly warmer	Warmer
0		No change	No change - Neither warmer nor cooler	No change
-1	Want cooler	Want cooler	Slightly cooler	Cooler
-2			Cooler	Much cooler
-3			Much cooler	

Table A7. Scale Formats Used to Measure Occupant Feedback on Thermal Tolerance. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Scales	A	B
Ref.	[51]	[43]
Scale type	LS	NS
No. of Verbal anchor words	5-point	2-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column	
0	Perfectly tolerable	Not tolerable
1	Slightly difficult to tolerate	Tolerable
2	Fairly difficult to tolerate	
3	Very difficult to tolerate	
4	Intolerable	

Table A8. Scale formats used to measure occupant feedback on overall IAQ sensation. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values. Linear transformations are applied to some original scales in the literature to fit the table.

<table>
<tr><th>Scales</th><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th></tr>
<tr><td>Ref.</td><td>[52]</td><td>[53]</td><td>[54]</td><td>[55]</td><td>[56]</td><td>[57]</td></tr>
<tr><td>Scale type</td><td>LS</td><td>LS</td><td>LS</td><td>LS</td><td>VAS</td><td>LS</td></tr>
<tr><td>No. of Verbal anchor words</td><td>5-point</td><td>3-point</td><td>4-point</td><td>4-point</td><td>2-point</td><td>3-point</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>Numeric value</td><td colspan="6">Verbal Anchor Words of the corresponding scales in each column</td></tr>
<tr><td>2</td><td>Very good</td><td>Excellent</td><td>Very good</td><td></td><td>Excellent</td><td></td></tr>
<tr><td>1</td><td>Good</td><td></td><td>Good</td><td>Very good</td><td></td><td>Good</td></tr>
<tr><td>0 +</td><td rowspan="2">General</td><td rowspan="2">Neutral</td><td rowspan="2">Moderate</td><td>Fairly good</td><td rowspan="2"></td><td rowspan="2">Acceptable</td></tr>
<tr><td>0 -</td><td>Fairly poor</td></tr>
<tr><td>-1</td><td>Bad</td><td></td><td>Bad</td><td>Very poor</td><td></td><td>Bad</td></tr>
<tr><td>-2</td><td>Very Bad</td><td>Terrible</td><td>Very Bad</td><td></td><td>Bad</td><td></td></tr>
</table>

Table A9. Scale formats used to measure occupant feedback on specific IAQ sensation. Scales are coded by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Scales	A	B	C	D	E
Ref.	[58]	[24,59,60]		[59–62]	[8,59,60]
Scale type	NS	LS / GRS		LS / GRS	LS / GRS
No. of Verbal anchor words	2-point	7-point	7-point	6-point	7-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column				
3		Very Dry	Very fresh		Much Too humid
2		Dry	Fresh		Very humid

Scales	A	B	C	D	E
1	Yes	Slightly Dry	Rather fresh		Slightly humid
0	No	Neutral	Neutral	No Odor	Just right
-1		Slightly humid/wet	Rather stuffy	Slightly Odor	Slightly dry
-2		humid/wet	Stuffy	Moderate Odor	Very dry
-3		Very humid/Wet	Very Stuffy	Strong Odor	Much Too dry
				Very strong Odor	
				Overpower Odor	

Table A10. Scale formats used to measure occupant feedback on IAQ satisfaction. Scales are indicated by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values.

Scales	A	B	C	D	E	F
Ref.	[63]	[64]	[65]	[61,66–72]	[73,74]	[75]
Scale type	LS	LS	LS	LS	VAS	GRS
No. of Verbal anchor words	5-point	4-point	5-point	7 -Point	4-point	6-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column					
3				Very satisfied		Strongly satisfied
2	Very satisfied		Very satisfied	Satisfied		
1	Slightly satisfied	Satisfied	Satisfied	Slightly satisfied	Strongly satisfied	Satisfied
+ 0	Satisfied	Slightly unsatisfied	Neutral	Neither satisfied Nor dissatisfied	(0.05) Just satisfied	Just-Satisfied Just - Dissatisfied
- 0					(-0.05) just dissatisfied	
-1	Slightly unsatisfied	Unsatisfied	Dissatisfied	Slightly dissatisfied	Strongly dissatisfied	Dissatisfied
-2	Very Unsatisfied		Very dissatisfied	Dissatisfied		
-3				Very dissatisfied		Strongly dissatisfied

Table A11. Scale formats used to measure occupant feedback on IAQ acceptance. Scales are indicated by letters, with corresponding references, scale type, verbal anchor words, and associated numeric values. Linear transformations are applied to some original scales in the literature to fit the table.

Scales	A	B	C
Ref.	[20,59,76]	[24]	[60]
Scale type	VAS	GRS	VAS
No. of Verbal anchor words	4-point	4-point	2-point
Numeric value	Verbal Anchor Words of the corresponding scales in each column		
1	Clearly acceptable	Completely acceptable	Acceptable
0+	Just acceptable	Just acceptable	
0-	Just not acceptable	Just unacceptable	
-1	Clearly not acceptable	Completely unacceptable	Not acceptable

Table A12. Categories of symptoms and their corresponding examples, [59,77–82]

Category	Symptoms
Respiratory	Cough, Sneezing, Shortness of breath, Wheezing, Chest tightness, Nasal symptoms (irritation, itching, stuffy or runny nose, burning)
Dermal	Dry skin, Rash, Irritated and flushed facial skin, Scaling or itching scalp, Hands dry, itching, red skin
General	Fatigue, feeling heavy-headed, Headache, Nausea/dizziness, Difficulty concentrating, Fever or chills, Joint pain, Muscle pain, Malaise, Irritability, Lack of concentration, upset stomach, Difficulty remembering things, Depression, Heartburn, Hyperventilation
Eye	Eye irritation, Dry, itching, or irritated eyes, Tired or strained eyes, Redness of the eyes
Throat	Sore throat, Hoarse or dry throat, Smarting of the throat, Throat irritation

REFERENCES

[1] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Build Environ 45 (2010) 29–39. https://doi.org/10.1016/j.buildenv.2009.02.016.

[2] D.I. Bogatu, J. Shinoda, J.J. Aguilera, B.W. Olesen, F. Watanabe, Y. Kaneko, O.B. Kazanci, Human physiology for personal thermal comfort-based HVAC control – A review, Build Environ 240 (2023) 110418. https://doi.org/10.1016/J.BUILDENV.2023.110418.

[3] Y. Xie, J. Niu, H. Zhang, S. Liu, J. Liu, T. Huang, J. Li, C.M. Mak, Development of a multi-nodal thermal regulation and comfort model for the outdoor environment assessment, Build Environ 176 (2020) 106809. https://doi.org/10.1016/J.BUILDENV.2020.106809.

[4] W. Liu, Y. Zhang, Q. Deng, The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate, Energy Build 128 (2016) 190–197. https://doi.org/10.1016/J.ENBUILD.2016.06.086.

[5] Z. Fang, Z. Lin, C.M. Mak, J. Niu, K.T. Tse, Investigation into sensitivities of factors in outdoor thermal comfort indices, Build Environ 128 (2018) 129–142. https://doi.org/10.1016/J.BUILDENV.2017.11.028.

[6] Y. He, H. Zhang, E. Arens, A. Merritt, C. Huizenga, R. Levinson, A. Wang, A. Ghahramani, A. Alvarez-Suarez, Smart detection of indoor occupant thermal state via infrared thermography, computer vision, and machine learning, Build Environ 228 (2023) 109811. https://doi.org/10.1016/J.BUILDENV.2022.109811.

[7] W. Luo, R. Kramer, M. Kompier, K. Smolders, Y. de Kort, W. van Marken Lichtenbelt, Effects of correlated color temperature of light on thermal comfort, thermophysiology and cognitive performance, Build Environ 231 (2023) 109944. https://doi.org/10.1016/J.BUILDENV.2022.109944.

[8] T. Chaudhuri, D. Zhai, Y.C. Soh, H. Li, L. Xie, Random forest based thermal comfort prediction from gender-specific physiological parameters using wearable sensing technology, Energy Build 166 (2018) 391–406. https://doi.org/10.1016/J.ENBUILD.2018.02.035.

[9] X. Jia, S. Li, Y. Zhu, W. Ji, B. Cao, Transient thermal comfort and physiological responses following a step change in activity status under summer indoor environments, Energy Build 285 (2023). https://doi.org/10.1016/j.enbuild.2023.112918.

[10] T. Xu, R. Yao, C. Du, B. Li, Outdoor thermal perception and heatwave adaptation effects in summer – A case study of a humid subtropical city in China, Urban Clim 52 (2023) 101724. https://doi.org/10.1016/J.UCLIM.2023.101724.

[11] Nikolopoulou, RUROS: Rediscovering the Urban Realm and Open Spaces. Final Project Report for EU, Section 6, (2011).

[12] Pantavou K., Lykoudis S., Delibasis K. K., Tseliou A., Koletsis I., Nikolopoulou M., Tsiros I.X.1, The integration of three field survey datasets in Athens, Greece: transformation of five-point to seven-point thermal sensation scale, 2019. http://alpha.cres.gr/ruros/.

[13] G. Winakor, A questionnaire to measure environmental and sensory factors associated with personal comfort and acceptability of indoor environments., ASHRAE Trans. 88 (2), 470–491. (1982).

[14] A.T.M.H.Y.T. K. Nagano, Effects of ambient temperature steps on thermal comfort requirements., Int. J. Biometeorol, 50 (2005) 33–39.

[15] R.F.G. N.R.S. Hollies, Psychological scaling in comfort assessment (Ch. 8), Ann Arbor Science Publishers Inc., (1972) 107–120.

[16] A.P. Gagge, J.A.J. Stolwijk, J.D. Hardy, Comfort and thermal sensations and associated physiological responses at various ambient temperatures, Environ Res 1 (1967) 1–20. https://doi.org/10.1016/0013-9351(67)90002-3.

[17] S.M. Frank, S.N. Raja, C. Bulcao, D.S. Goldstein, Age-related thermoregulatory differences during core cooling in humans, American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 279 (2000) R349–R354. https://doi.org/10.1152/ajpregu.2000.279.1.R349.

[18] R. Rawal, M. Schweiker, O.B. Kazanci, V. Vardhan, Q. Jin, L. Duanmu, Personal comfort systems: A review on comfort, energy, and economics, Energy Build 214 (2020). https://doi.org/10.1016/j.enbuild.2020.109858.

[19] E. Arens, H. Zhang, C. Huizenga, Partial- and whole-body thermal sensation and comfort - Part I: Uniform environmental conditions, in: J Therm Biol, 2006: pp. 53–59. https://doi.org/10.1016/j.jtherbio.2005.11.028.

[20] H. Zhang, E. Arens, D. Kim, E. Buchberger, F. Bauman, C. Huizenga, Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system, Build Environ 45 (2010) 29–39. https://doi.org/10.1016/j.buildenv.2009.02.016.

[21] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, Q. Meng, Human comfort and perceived air quality in warm and humid environments with ceiling fans, Build Environ 90 (2015) 178–185. https://doi.org/10.1016/j.buildenv.2015.04.003.

[22] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, Indoor Air 20 (2010) 273–283. https://doi.org/10.1111/j.1600-0668.2010.00657.x.

[23] S.G. Hodder, K. Parsons, The effects of solar radiation on thermal comfort, Int J Biometeorol 51 (2007) 233–250. https://doi.org/10.1007/s00484-006-0050-y.

[24] H. Jiang, B. Cao, Y. Zhu, Thermal comfort of personal protective equipment (PPE) wearers in different temperatures and activity conditions, Journal of Building Engineering 78 (2023). https://doi.org/10.1016/j.jobe.2023.107609.

[25] W.H. Ko, S. Schiavon, H. Zhang, L.T. Graham, G. Brager, I. Mauss, Y.W. Lin, The impact of a view from a window on thermal comfort, emotion, and cognitive performance, Build Environ 175 (2020). https://doi.org/10.1016/j.buildenv.2020.106779.

[26] D. Mou, B. Cao, Y. xin Zhu, Field study on thermal comfort of naturally ventilated residences in southwest China, J Cent South Univ 29 (2022) 2377–2387. https://doi.org/10.1007/s11771-022-5109-3.

[27] Z. Xie, B. Cao, Y. Zhu, A novel wind comfort evaluation method for different airflows by considering dynamic characteristics of wind direction and velocity, Build Environ 246 (2023). https://doi.org/10.1016/j.buildenv.2023.110976.

[28] S. Liu, B. Cao, Y. Zhu, Experimental study on comparison of indoor and multiple outdoor thermal environments excluding visual and acoustic interference, Sustain Cities Soc 94 (2023). https://doi.org/10.1016/j.scs.2023.104564.

[29] S. Li, X. Jia, B. Cao, Y. Zhu, Improvement of thermal perceptions and physiological responses using torso heating under short-term cold exposure, Science of the Total Environment 892 (2023). https://doi.org/10.1016/j.scitotenv.2023.164491.

[30] M. Haneda, N. Nishihara, S.I. Tanabe, Subjective experiment for the effect of thermal environment and ventilation rate on productivity, Journal of Environmental Engineering 74 (2009) 507–515. https://doi.org/10.3130/aije.74.507.
[31] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, Indoor Air 20 (2010) 273–283. https://doi.org/10.1111/j.1600-0668.2010.00657.x.
[32] Z. Li, Q. Zhang, O.B. Kazanci, F. Fan, B.W. Olesen, Investigation of group differences in human perceptions of indoor environment in open-plan offices in a severe cold region, Build Environ 213 (2022) 108855. https://doi.org/10.1016/J.BUILDENV.2022.108855.
[33] C. Zhong, J.H. Choi, Development of a Data-Driven Approach for Human-Based Environmental Control, Procedia Eng 205 (2017) 1665–1671. https://doi.org/10.1016/J.PROENG.2017.10.341.
[34] S.Q. da S. Hirashima, E.S. de Assis, M. Nikolopoulou, Daytime thermal comfort in urban spaces: A field study in Brazil, Build Environ 107 (2016) 245–253. https://doi.org/10.1016/J.BUILDENV.2016.08.006.
[35] M. Schweiker, M. André, F. Al-Atrash, H. Al-Khatri, R.R. Alprianti, H. Alsaad, R. Amin, E. Ampatzi, A.Y. Arsano, E. Azar, B. Bannazadeh, A. Batagarawa, S. Becker, C. Buonocore, B. Cao, J.H. Choi, C. Chun, H. Daanen, S.A. Damiati, L. Daniel, R. De Vecchi, S. Dhaka, S. Domínguez-Amarillo, E. Dudkiewicz, L.P. Edappilly, J. Fernández-Agüera, M. Folkerts, A. Frijns, G. Gaona, V. Garg, S. Gauthier, S.G. Jabbari, D. Harimi, R.T. Hellwig, G.M. Huebner, Q. Jin, M. Jowkar, J. Kim, N. King, B. Kingma, M.D. Koerniawan, J. Kolarik, S. Kumar, A. Kwok, R. Lamberts, M. Laska, M.C.J. Lee, Y. Lee, V. Lindermayr, M. Mahaki, U. Marcel-Okafor, L. Marín-Restrepo, A. Marquardsen, F. Martellotta, J. Mathur, I. Mino-Rodriguez, A. Montazami, D. Mou, B. Moujalled, M. Nakajima, E. Ng, M. Okafor, M. Olweny, W. Ouyang, A.L. Papst de Abreu, A. Pérez-Fargallo, I. Rajapaksha, G. Ramos, S. Rashid, C.F. Reinhart, M.I. Rivera, M. Salmanzadeh, K. Schakib-Ekbatan, S. Schiavon, S. Shooshtarian, M. Shukuya, V. Soebarto, S. Suhendri, M. Tahsildoost, F. Tartarini, D. Teli, P. Tewari, S. Thapa, M. Trebilcock, J. Trojan, R.B. Tukur, C. Voelker, Y. Yam, L. Yang, G. Zapata-Lancaster, Y. Zhai, Y. Zhu, Z.S. Zomorodian, Evaluating assumptions of scales for subjective assessment of thermal environments – Do laypersons perceive them the way, we researchers believe?, Energy Build 211 (2020). https://doi.org/10.1016/j.enbuild.2020.109761.
[36] X. Jia, B. Cao, Y. Zhu, A climate chamber study on subjective and physiological responses of airport passengers from walking to a sedentary status in summer, Build Environ 207 (2022) 108547. https://doi.org/10.1016/j.buildenv.2021.108547.
[37] S.G. Hodder, K. Parsons, The effects of solar radiation on thermal comfort, Int J Biometeorol 51 (2007) 233–250. https://doi.org/10.1007/s00484-006-0050-y.
[38] J. Kim, F. Bauman, P. Raftery, E. Arens, H. Zhang, G. Fierro, M. Andersen, D. Culler, Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers, Build Environ 148 (2019) 348–360. https://doi.org/10.1016/J.BUILDENV.2018.11.012.
[39] L. Yang, S. Zhao, Y. Zhai, S. Gao, F. Wang, Z. Lian, L. Duanmu, Y. Zhang, X. Zhou, B. Cao, Z. Wang, H. Yan, H. Zhang, E. Arens, R. de Dear, The Chinese thermal comfort dataset, Sci Data 10 (2023) 662. https://doi.org/10.1038/s41597-023-02568-3.
[40] H. Zhang, E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y. Zhai, M. Pigman, Using footwarmers in offices for thermal comfort and energy savings, Energy Build 104 (2015) 233–243. https://doi.org/10.1016/J.ENBUILD.2015.06.086.
[41] F. Zhang, S. Haddad, B. Nakisa, M.N. Rastgoo, C. Candido, D. Tjondronegoro, R. de Dear, The effects of higher temperature setpoints during summer on office workers' cognitive load and thermal comfort, Build Environ 123 (2017) 176–188. https://doi.org/10.1016/J.BUILDENV.2017.06.048.
[42] Shan Zhou, Baizhan Li, Runming Yao, Wei Yu, Chenqiu Du, Zhanli Xi, SSRN-id4637321 (8), (2023).
[43] Z. Li, D. Loveday, P. Demian, Nudging and usage of thermal comfort-related systems, Energy Build 252 (2021) 111480. https://doi.org/10.1016/J.ENBUILD.2021.111480.
[44] D.A. Winkler, A. Beltran, N.P. Esfahani, P.P. Maglio, A.E. Cerpa, FORCES: Feedback and control for occupants to refine comfort and energy savings, in: UbiComp 2016 - Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Association for Computing Machinery, Inc, 2016: pp. 1188–1199. https://doi.org/10.1145/2971648.2971700.
[45] T. Parkinson, R. De Dear, C. Candido, Thermal pleasure in built environments: Alliesthesia in different thermoregulatory zones, Building Research and Information 44 (2016) 20–33. https://doi.org/10.1080/09613218.2015.1059653.
[46] S. Liu, N. Nazarian, M.A. Hart, J. Niu, Y. Xie, R. de Dear, Dynamic thermal pleasure in outdoor environments - temporal alliesthesia, Science of The Total Environment 771 (2021) 144910. https://doi.org/10.1016/J.SCITOTENV.2020.144910.
[47] Y. Murakami, M. Terano, K. Mizutani, M. Harada, S. Kuno, Field experiments on energy consumption and thermal comfort in the office environment controlled by occupants' requirements from PC terminal, Build Environ 42 (2007) 4022–4027. https://doi.org/10.1016/J.BUILDENV.2006.05.012.
[48] W. Luo, R. Kramer, Y. de Kort, P. Rense, W. van Marken Lichtenbelt, The effects of a novel personal comfort system on thermal comfort, physiology and perceived indoor environmental quality, and its health implications - Stimulating human thermoregulation without compromising thermal comfort, Indoor Air 32 (2022). https://doi.org/10.1111/ina.12951.
[49] T.O. Adekunle, M. Nikolopoulou, Winter performance, occupants' comfort and cold stress in prefabricated timber buildings, Build Environ 149 (2019) 220–240. https://doi.org/10.1016/J.BUILDENV.2018.12.019.
[50] T.O. Adekunle, M. Nikolopoulou, Thermal comfort, summertime temperatures and overheating in prefabricated timber housing, Build Environ 103 (2016) 21–35. https://doi.org/10.1016/J.BUILDENV.2016.04.001.
[51] ISO 10551:2019, Ergonomics of the physical environment — Subjective judgement scales for assessing physical environments, 2019. https://www.iso.org/standard/67186.html.
[52] R. Tang, Z. Wang, Field study on indoor air quality of urban apartments in severe cold region in China, Atmos Pollut Res 9 (2018) 552–560. https://doi.org/10.1016/J.APR.2017.12.004.
[53] G. Torriani, G. Lamberti, F. Fantozzi, F. Babich, Exploring the impact of perceived control on thermal comfort and indoor air quality perception in schools, Journal of Building Engineering 63 (2023). https://doi.org/10.1016/j.jobe.2022.105419.
[54] Z. Cheng, N. Lei, Z. Bu, H. Sun, B. Li, B. Lin, Investigations of indoor air quality for office buildings in different climate zones of China by subjective survey and field measurement, Build Environ 214 (2022). https://doi.org/10.1016/j.buildenv.2022.108899.

[55] J. Wang, G. Smedje, T. Nordquist, D. Norbäck, Personal and demographic factors and change of subjective indoor air quality reported by school children in relation to exposure at Swedish schools: A 2-year longitudinal study, Science of The Total Environment 508 (2015) 288–296. https://doi.org/10.1016/J.SCITOTENV.2014.12.001.

[56] G. McGill, M. Qin, L. Oyedele, A Case Study Investigation of Indoor Air Quality in UK Passivhaus Dwellings, Energy Procedia 62 (2014) 190–199. https://doi.org/10.1016/J.EGYPRO.2014.12.380.

[57] S.S. Korsavi, A. Montazami, D. Mumovic, Perceived indoor air quality in naturally ventilated primary schools in the UK: Impact of environmental variables and thermal sensation, Indoor Air 31 (2021) 480–501. https://doi.org/10.1111/ina.12740.

[58] J. Wang, D. Norbäck, Subjective indoor air quality and thermal comfort among adults in relation to inspected and measured indoor environment factors in single-family houses in Sweden-the BETSI study, Science of The Total Environment 802 (2022) 149804. https://doi.org/10.1016/J.SCITOTENV.2021.149804.

[59] P. Wargocki, The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity, Indoor Air 10 (2000) 222–236. https://doi.org/10.1034/j.1600-0668.2000.010004222.x.

[60] P.M. Bluyssen, European indoor air quality audit project in 56 office buildings, Indoor Air 6 (1996) 221–238. https://doi.org/10.1111/j.1600-0668.1996.00002.x.

[61] S. Altomonte, S. Schiavon, Occupant satisfaction in LEED and non-LEED certified buildings, Build Environ 68 (2013) 66–76. https://doi.org/10.1016/J.BUILDENV.2013.06.008.

[62] A.K. Kaushik, M. Arif, M.M.G. Syal, M.Q. Rana, O.T. Oladinrin, A.A. Sharif, A.S. Alshdiefat, Effect of Indoor Environment on Occupant Air Comfort and Productivity in Office Buildings: A Response Surface Analysis Approach, Sustainability (Switzerland) 14 (2022). https://doi.org/10.3390/su142315719.

[63] H. Tang, Y. Ding, B.C. Singer, Post-occupancy evaluation of indoor environmental quality in ten nonresidential buildings in Chongqing, China, Journal of Building Engineering 32 (2020) 101649. https://doi.org/10.1016/J.JOBE.2020.101649.

[64] Q.J. Kwong, J. Abdullah, S.C. Tan, T.H.G. Thio, W.S. Yeaw, A field study of indoor air quality and occupant perception in experimental laboratories and workshops, Management of Environmental Quality: An International Journal 30 (2019) 467–482. https://doi.org/10.1108/MEQ-04-2018-0074.

[65] F. Ma, C. Zhan, X. Xu, Investigation and evaluation ofwinter indoor air quality of primary schools in severe cold weather areas of China, Energies (Basel) 12 (2019). https://doi.org/10.3390/en12091602.

[66] C. Huizenga, L. Zagreus, E. Arens, D. Lehrer, UC Berkeley Indoor Environmental Quality (IEQ) Title Measuring indoor environmental quality: a web-based occupant satisfaction survey Publication Date Measuring Indoor Environmental Quality: A Web-based Occupant Satisfaction Survey, 2003.

[67] Y.S. Lee, S. Kim, Indoor environmental quality in LEED-certified buildings in the U.S., Journal of Asian Architecture and Building Engineering 7 (2008) 293–300. https://doi.org/10.3130/jaabe.7.293.

[68] T. Cheung, S. Schiavon, L.T. Graham, K.W. Tham, Occupant satisfaction with the indoor environment in seven commercial buildings in Singapore, Build Environ 188 (2021) 107443. https://doi.org/10.1016/J.BUILDENV.2020.107443.

[69] L. Wang, D. Zheng, Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation, Build Environ 182 (2020) 107014. https://doi.org/10.1016/J.BUILDENV.2020.107014.

[70] L. Wang, D. Zheng, Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation, Build Environ 182 (2020) 107014. https://doi.org/10.1016/J.BUILDENV.2020.107014.

[71] H.H. Liang, C.P. Chen, R.L. Hwang, W.M. Shih, S.C. Lo, H.Y. Liao, Satisfaction of occupants toward indoor environment quality of certified green office buildings in Taiwan, Build Environ 72 (2014) 232–242. https://doi.org/10.1016/J.BUILDENV.2013.11.007.

[72] J. Kim, R. de Dear, C. Cândido, H. Zhang, E. Arens, Gender differences in office occupant perception of indoor environmental quality (IEQ), Build Environ 70 (2013) 245–256. https://doi.org/10.1016/J.BUILDENV.2013.08.022.

[73] Z. Pei, B. Lin, Y. Liu, Y. Zhu, Comparative study on the indoor environment quality of green office buildings in China with a long-term field measurement and investigation, Build Environ 84 (2015) 80–88. https://doi.org/10.1016/J.BUILDENV.2014.10.015.

[74] M. Frontczak, R.V. Andersen, P. Wargocki, Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing, Build Environ 50 (2012) 56–64. https://doi.org/10.1016/J.BUILDENV.2011.10.012.

[75] Z. Wang, H. Zhao, B. Lin, Y. Zhu, Q. Ouyang, J. Yu, Investigation of indoor environment quality of Chinese large-hub airport terminal buildings through longitudinal field measurement and subjective survey, Build Environ 94 (2015) 593–605. https://doi.org/10.1016/J.BUILDENV.2015.10.014.

[76] V. V. Agafonova, Study of Air Quality in the Office Building, in: IOP Conf Ser Mater Sci Eng, Institute of Physics Publishing, 2020. https://doi.org/10.1088/1757-899X/753/4/042004.

[77] A.H. Abdullah, Y.Y. Lee, E. Aminudin, Y.H. Lee, INDOOR AIR QUALITY ASSESSMENT FOR A MULTI-STOREY UNIVERSITY OFFICE BUILDING IN MALAYSIA, n.d. http://meridian.allenpress.com/jgb/article-pdf/14/4/93/2403383/i1943-4618-14-4-93.pdf.

[78] D. Jung, Y. Choe, J. Shin, E. Kim, G. Min, D. Kim, M. Cho, C. Lee, K. Choi, B.L. Woo, W. Yang, Risk Assessment of Indoor Air Quality and Its Association with Subjective Symptoms among Office Workers in Korea, Int J Environ Res Public Health 19 (2022). https://doi.org/10.3390/ijerph19042446.

[79] Y. Wu, Y. Lu, D.C. Chou, Indoor air quality investigation of a university library based on field measurement and questionnaire survey, International Journal of Low-Carbon Technologies 13 (2018) 148–160. https://doi.org/10.1093/ijlct/cty007.

[80] I. Mujan, D. Licina, M. Kljajić, A. Čulić, A.S. Anđelković, Development of indoor environmental quality index using a low-cost monitoring platform, J Clean Prod 312 (2021) 127846. https://doi.org/10.1016/J.JCLEPRO.2021.127846.

[81] P.M. Bluyssen, EPIQR and IEQ: indoor environment quality in European apartment buildings, Energy Build 31 (2000) 103–110. https://doi.org/10.1016/S0378-7788(99)00024-9.

[82] S.N. Nazli, A.Z. Ul-Saufie, A. Abd Razak, M. Elbayoumi, Assessment of Indoor Air Quality in Small and Medium Food Industries and Effects towards Perceived IAQ Symptoms, Sustainability (Switzerland) 15 (2023). https://doi.org/10.3390/su15054065.