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ABSTRACT

A growing focus on occupant comfort, health and wellbeing has resulted in attempts to quantify indoor environmental quality (IEQ) and to determine the relative contributions of single IEQ aspects to an overall IEQ index. The recently developed IV20 tool assesses potential IEQ to label overall IEQ, and assign separate scores for the main indoor environment (IE) areas: thermal, visual, acoustic and air quality. In the absence of objective, universally applicable IEQ weights, this paper develops and executes a methodology asking regional experts with different backgrounds to make relative comparisons between related IE aspects. The authors hypothesize that wide-ranging subjective evaluations can be combined into useful relative weights (best operational solution based on the current status of IE literature).

This paper presents results from an IE expert survey on relative IE aspect weights using simple percentile prioritization and the Analytic Hierarchy Process pairwise comparison. Results are compared to expert panel judgements to ensure validity. The advantages of this combined weight determination method are (1) that the expert survey ensures a broad spectrum of opinions and allows for input from different built environment disciplines, and (2) that the expert panel has tool-specific insight, methodology awareness and state of the art knowledge.

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Introduction

As we spent 90% of our time indoors (Klepeis et al., 2001), the indoor environment (IE) has a considerable influence on our combined comfort, health and well-being (Rohde, Larsen, Jensen, & Larsen, 2019a). An essential step towards improving indoor environmental quality (IEQ) is to quantify, prioritize and rate overall IEQ; evaluations that require IE weights in order to compare different IE aspects (such as traffic noise vs direct sunlight). A holistic IEQ assessment tool called IV20 (Larsen, Rohde, Knudsen, Jønsson, & Jensen, 2019) is being developed as part of the REBUS partnership (REBUS partnership, n.d.) to provide such IEQ assessment of indoor air quality (IAQ), thermal, visual and acoustic IE.

International standards sometimes indicate relative inter-area importance such as through PPD or PMV indexes for thermal comfort and IAQ (Fanger, 1970, 1988), but only provide recommendations for performance bandwidths or thresholds limits for single criteria. Since most IE standards are dedicated to a single IE topic, there is little information to be gained for a holistic assessment. Some third-party sustainable building certification schemes such as Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) and the WELL Building Standard do provide weights (or small point ranges) for IE categories, but the suggested weights differ widely between methods (Jensen & Birgisdóttir, 2018; Rohde, Larsen, Jensen, & Larsen, 2019b).

Some literature has been published on relative IEQ weights, but there is little consensus between findings as summarized by Zalejska-Jonsson & Wilhelmsson (2013). Also, many of the studies are concerned with ranking IE main areas (such as acoustics and IAQ) and does not address IE aspects in detail. This paper splits each main area into four categories (e.g. noise from neighbours), which are again split into one or more criteria (e.g. impact sound and airborne sound).

Some studies investigate the impact of subjectively evaluated IE aspects on perceived satisfaction/acceptability based on surveys correlating satisfaction with individual IE aspects to the overall IE satisfaction (Frontczak et al., 2012; Frontczak, Andersen, & Wargocki, 2012). Other studies do the same through a correlational method that combines occupant satisfaction questionnaires with

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field measurements data (Bluyssen, Arieas, & Van Dommelen, 2011; Humphreys, 2005; Marino, Nucara, & Pietrafesa, 2012; Ncube & Riffat, 2012; Zalejska-Jonsson & Wilhelmsson, 2013). While valuable insight can be gained from occupant satisfaction studies, they fail to represent in full the health aspect of IE assessment as 'only perceptible qualities or problems are revealed in this way, and hidden problems such as high levels of radon gas are not captured' (Malmqvist & Glaumann, 2009). Also, questions on category and criterion level require some ability to distinguish between the different concepts and indicators, which occupants rarely have.

As summarized by Malmqvist & Glaumann (2009) many approaches have been discussed regarding weight determination for building assessment tools including damage-based approaches, industry panels, and analytical hierarchy process (AHP). A few studies concerned with the development of comprehensive sustainable rating systems use an expert survey approach for criteria selection and weight determination (Ali & Al Nsairat, 2009; Alyami & Rezgui, 2012; Chandratilake & Dias, 2013; Gupta, Gregg, Manu, Vaidya, & Dixit, 2018; Markelj et al., 2014). While the results from these studies are not relevant for the topic at hand, the methodology is promising for determining relative weights in holistic assessments. The methodology is divided into an expert panel defining the assessment framework (scope, structure, content), and an expert survey ensuring agreement between a broader range of building professionals with expert knowledge on the topic.

As there is no consensus on IE weights in IE standards, assessment methods or scientific literature, the authors of this paper has developed a methodology to systematically determine building typology specific inter-area criteria weights and combine them into a set of connected weights for all hierarchical levels. As there is no agreed non-subjective methodology for deriving weights, this research seeks to increase the robustness of subjective evaluations in three ways: (1) by consulting building professionals on their topics of expertise only, (2) by assessing the inter-subjectivity of results between experts, and (3) by analysing survey results to ensure compliance with the framework and intentions set out by the expert panel.

Description of IV20

The IV20 tool was developed as part of the REBUS project (Renovating Buildings Sustainably) (REBUS partnership, n.d.), which is the result of a dedicated partnership representing all relevant stakeholders including end users, developers, manufacturers, consultants and knowledge institutions. REBUS targets deep renovations in the Danish social housing sector through strategies, methods and tool that target both building owners, developers, designers, and occupants.

The IV20 development team consists of a wide range of building professionals including IE researchers from leading Danish research institutions, IE specialists from various companies (consultant engineers, manufacturers, architects) and building professionals working with IE (professional building owners).

IV20 is an IEQ assessment tool developed to facilitate IEQ improvements in the early design stages of renovations proposals or new building designs. The tool is designed to promote a holistic IEQ focus from the very beginning of the project where the potential for influence is highest. In order to accommodate assessment in the design phases, assessments are made without physical IE measurements or occupant surveys, as they are not available until after completion. Instead, the tool assesses potential IEQ based on calculations using a wide range of available physical building characteristics such as geometry, context, components, systems and constructions. This approach to assessment and labelling of the potential IEQ of a dwelling has the advantage of being independent of uncertainties from user behaviour, user preference, and seasonal variations (in addition to being a low-cost option).

The IV20 tool makes a holistic IE assessment with separate scores for the four main IE areas: Thermal (THER), Visual (VIS), Acoustic (ACO) and Air Quality (IAQ). Each main area is divided into three traditional building-related IE aspect categories and one occupant influence category. Each of these 16 categories consists of one or more criteria (40 criteria in total). Based on the combined performance of the four main areas, an overall IE label is awarded on a scale from A–G, which is well known from the Building Energy Performance Certificates. Thus, the advantages of awarding and communicating a single index for IE is combined with the advantages of several levels of nuanced assessment (Larsen et al., 2019).

The four main IE areas are considered equally important in the IV20 assessment, based on previous investigations of IE weights that provide no reliable trends to establish differentiated IE main area weights (Heinzerling, Schiavon, Webster, & Arens, 2013; Humphreys, 2005; Ncube & Riffat, 2012). A survey of occupants in Danish dwellings showed that the four main IE areas contributed almost equally to overall satisfaction and that most respondents evaluated IE aspects to be of equal importance when making pairwise relative comparisons (Frontczak et al., 2012).

Criteria selection

The selection of criteria to include in the assessment has been conducted by an appointed panel of experts on the

REBUS platform, which according to Chang (Chang, Chiang, & Chou, 2007) has to represent a variety of disciplines. The expert panel involved in selecting criteria and deciding initial weights for IV20 consisted of 12 IE experts selected from the IV20 development team.

This criteria selection process included looking at areas of convergence and distinction of existing leading IEQ assessment methods (Cole, 2005) while taking into account the regional and building typological variations (Kohler, 1999). The final selection of criteria used a consensus-based approach within the expert panel as suggested by Chew & Das (Chew & Das, 2008), through several successive rounds of agreement similar to the DELPHI technique (Dalkey & Helmer, 1963). The selection of criteria is specific for the IV20 assessment framework; providing low-effort, early-stage assessments based on simple building data (no measurements or surveys).

Methodology

Due to the lack of objective weighting methodologies for complex groups of assessment criteria, the weight determinations are based on a multidisciplinary consensus process (Alyami & Rezgui, 2012; Chew & Das, 2008; Singh, Murty, Gupta, & Dikshit, 2012; Taylor & Ward, 2016). The research design is similar to what has been used to develop country-specific comprehensive sustainable assessment methods, that is: relying on expert opinion to rank aspects, and then allocating weights based on data analysis of survey results.

This paper seeks to develop IEQ aspect weights on several levels by conducting an IEQ expert survey. Based on the challenges identified in previous attempts at IE weight determination, this study combines a few well-known methodologies for assigning IE weights. This methodology has been used to determine IE weights for Danish multifamily dwellings, as presented in the Results section.

Perspectives on the current attempt

Previous attempts to determine relative IE weights will be discussed to provide perspective to the challenges involved and directions for how to address them in the present research. Given the theoretical complexity of the topic, this chapter is divided into three parts: (1) How to compare dissimilar aspects? (2) How to tackle 'the issue of universality'? And (3) What to include in the relative evaluation?

(1) The first and most obvious difficulty lies in comparing IE aspects with widely different indicators. This paper adopts Todd's (1996) idea of comparing dissimilar aspects through their final endpoints (their relative influence on occupants), to determine appropriate weightings.
(2) Several sources have pointed to the issue of deciding universal weights as differences between climates, countries, cultures, building typologies and occupant tasks heavily influence the priorities between IE aspects (Abdul Hamid, Farsäter, Wahlström, & Wallentén, 2018; Ding, 2008; Heinzerling et al., 2013). Instead, weights are explicitly developed for Danish multi-storey residential buildings. Although context-specific, the resulting weightings of the current investigation provide valuable insight into relative IE weights, and it is expected to be a good indication of relative priorities for closely related climates/cultures (i.e. Northern Europe) or similar project types (i.e. single family houses). The methodology presented for deriving weights is applicable regardless of the context.
(3) Inspired by Levin's criteria for environmental issue weighting (Levin, 1997), this paper acknowledges four considerations when determining relative IE weights. For the purpose at hand, weighing priorities should consider:
    (I) spatial scale (room level vs apartment level, proximity to source)
    (II) severity (degree of influence of comfort, health and wellbeing),
    (III) exposure time (occurrence frequency, duration)
    (IV) relevance (for local context, building typology, activity/use)

For instance, when evaluating the relative weights of too high temperatures, it is important to note that overheating in Danish dwellings is: (I) often not for the entire apartment, (II) primarily a comfort issue, (III) mainly a problem in summer, in the daytime, and (IV) possible for occupants to adapt activity level, clothing and place of stay.

Assuming that IE aspect weights are (1) based on the influence on occupants, (2) developed specifically for a given country and building typology, and (3) considers the four criteria listed above – how does one compare comfort aspects to health aspects?

In an attempt to quantify occupant comfort based on subjective IE evaluations by the occupants Humphreys (2005) concluded that satisfaction and dissatisfaction with the overall IE could not be determined by investigating single IE aspects as occupants balance the good features against the bad (i.e. 'subjective averaging'). Instead, each aspect should be assessed separately. This separation of aspects has many other advantages such as being able to better indicate remedial actions, compare alternatives and rate preferences which match the intentions of the IV20 assessment method (Larsen et al., 2019).

In addition to handling IE comfort aspects separately, this research leans towards Chappells and Shove's (2005) understanding of comfort as a 'negotiable socio-cultural construct'. This is addressed through the inclusion of 'occupant influence' aspects that rewards the ability for occupants to affect their IE. These user criteria provide occupants with the possibility to accommodate for lacking performance(i.e. overheating) and to adapt to current conditions (occupant load, task) or personal preferences. In extension, there is a potential 'forgiveness factor' as identified by Leaman and Bordass (1999) that connects the locus of control (perceived influence) to positive IE evaluations. The inclusion of occupant influence is seen as a significant aspect in a holistic IE assessment; 'an evaluation of the whole'.

Unlike IE comfort, which is only partially constrained by physiology, IE health is concerned with both short and long-term physiological influences on occupants. As previously mentioned the IV20 assessment balances health and comfort aspects. To ensure due consideration to health aspects, the methodology includes an evaluative comparison of the survey results to literature on health effects from IE exposure.

Region and typology-specific weights

Although the specific conditions of individual projects may be unique (due to the given context, user preferences, ambitions of the building owner) project-by-project weights are not operational and ill-suited for inter-project comparisons. Realizing that both content and weights depend on the context and use of the building, criteria selection and prioritization should be developed systematically for a given region and building typology. The determination of IE weights for the IV20 tool thus acts as an exemplification of the weight determination methodology in use.

Methodology: IE weight determination

Given the lack of consensus on IE main area differentiation and the small number of studies available (particularly within the context at hand), the authors have made a strategic decision to appoint each area a 25% weight. Instead, the focus of this paper is on inter-area weights on category level (i.e. noise from neighbours) and criterion level (i.e. impact sound). Weights on category and criterion level are initially determined by the IV20 expert panel, as was done for the Swedish EcoEffect (Malmqvist & Glaumann, 2009).

Based on the arguments presented above this paper proposes the following methodology for determining IE weights (specific examples from the current research case shown in parenthesis).

- The expert panel (a team of IE experts part of the development of the IV20 tool) selects the most important IE aspects from an IE gross list (Larsen et al., 2017) for a given typology and context (Danish multi-family dwellings). Inclusion or exclusion of criteria is based on an assessment of relative influence on health and comfort, combined with practical considerations such as time, cost, equipment required, and evaluation precision (only the three most important aspects for each IE area were included).
- The expert panel suggests weights for the selected aspects based on IE standards, IE literature and health/medicinal reports. IE aspects are grouped in successive levels of hierarchy: IV20 label > main area > category > criterion. This structure ensures a better overview of the overall assessment and allows for easy adaption of weights with changing conditions such as building practice, building regulations or new insights.
- A survey is conducted asking regional IE experts with building industry knowledge to prioritize IE aspects by performing a series of simple relative comparisons. It is crucial that the survey carefully explains the conditions for the comparisons such as the specifics of the context, and the considerations to be included in the evaluation.
- Survey results undergo an evaluative comparison with the expert panel weights. This comparison is performed by a core group within the expert panel. This core group must contain the following competences:
  - (I) holistic IE expert knowledge (all four main areas)
  - (II) specific tool insight (assessment scope/methodology/precision)
  - (III) specific survey insight (structure, instructions, wording)
  - (IV) knowledge of current building mass + current/near future trends

The core group makes adjustments to the survey weights in cases where the expert panel identifies one or more of the following criteria; lack of conformity with the assessment typology (glare is less of an issue in dwellings), too high/low impact compared to the current building tradition (mechanical cooling remains very rare in Danish dwellings); limited assessment precision (data uncertainty for the outdoor air quality evaluation method); unbalanced representation of priority conditions (underrepresented health dimension according to literature); and clear indications of misinterpretation due to survey ambiguity.

- The different levels of hierarchy are combined into a final overall set of weights for the given assessment.

The suggested method for relative IE weights thus builds on a series of integrated methodologies including Expert panel, Endpoint method, and AHP Expert survey.

Survey

An online survey was performed from December 2018 to January 2019 with the purpose to provide topic-specific expert opinions on (1) criterion level, using a simple %-allocation method, and (2) category level, using the AHP pairwise comparison method.

Unlike many IE questionnaires directed at occupants, the survey was aimed directly at building professionals, and responses were collected only from those with adequate IE knowledge within the specific areas (see Participants section below for more information). This strategy served two purposes: (1) ensuring a sufficient level of knowledge required to answer questions on specific IE topics (criterion level), and (2) avoiding some of the subjectivity bias when asking occupants, who are likely to be more influenced by their current living condition and their present context when answering the questionnaire. Building professionals are better equipped to give generalized answers based on their knowledge and experiences and are more likely to provide consistent answers compared to occupants (Humphreys, 2005). Building professionals surveyed include both academics and practitioners to combine new research knowledge with insight into current conditions in the Danish built environment.

Participants

The survey was distributed via email to 94 potential participants in the Danish building sector through their work emails. As the survey was only interested in responses from experts within one or more IE topics, only building professionals or researchers currently working with the built environment in a Danish context were considered. Potential participants were identified using extended professional networks of the REBUS project, either directly through personal email-addresses or by asking specific departments or companies to provide email addresses for participants to invite. The aim was to gather responses from a wide range of experts covering all four main IE areas (thermal, visual, acoustic and air quality), with representatives from both academia (researchers) and practice. Practitioners invited include both construction professionals, and various industry professionals such as architects, engineers, manufacturers, and IE consultants. Participant profiles were scanned for 'relevance' by looking at their educational background, as well as their (current and previous) workplace and work tasks.

The invitation email contained a half-page description of the research project and a request to participate in the online survey through an embedded link. Reminders to participate were sent out twice, also through email. In total, 94 personal emails were sent out of which eight did not reach their respondent (not delivered) or came back with 'out of office' auto-replies (vacation, maternity leave).

Also, a non-personal invite link was shared through the REBUS network. Respondents from the open link were checked for duplicates, as well as screened to ensure that they were qualified for participation using the same requirements as for the direct invitations.

Questionnaire

The questionnaire opened with a short description of the survey purpose, a graphical overview of the questionnaire structure, and a brief description of how to fill out the different parts of the survey. It was emphasized that the survey context was the indoor environment in Danish multi-storey residential buildings. Thus, each IE topic question was to be answered as to its relevance for Danish multi-storey residential buildings based on their relative potential influence on occupant health, comfort and well-being.

The questionnaire was designed to provide evaluations from a wide range of experts on the topics shortlisted through the REBUS IV20 project work. The questionnaire consisted of three parts:

(1) Background information and expertise level identification (Q.1)
(2) IE priorities on criterion level using relative % distribution (Q.2)
(3) IE priorities on category level using AHP (Q.3)

Each part opened with a brief repetition of the survey context and an elaborated explanation of how to fill out the following part of the questionnaire. Relative comparisons were always made between parameters on the same hierarchy level.

The first part of the questionnaire (Q.1) was split into two sections. The first section asked employment-related demographic questions (name, employer name, employee title, job discipline and work tasks), some of which was used to filter responses to check for tendencies within specific work-related groups. The second section collected self-reported expertise level by IE topic, by asking respondents to indicate their knowledge level by IE main category (thermal, visual, acoustic and air quality) from the options ‘Expert knowledge’, ‘Comprehensive knowledge’, ‘Limited knowledge’, and ‘No knowledge’. Participants were only presented with questions from the second and third part of the questionnaire for the areas for which they had expressed a knowledge level of ‘Expert’ or ‘Comprehensive’.

The second part (Q.2) contained a series of relative IE criteria priority questions where the respondent had to distribute 100% points between 2–4 related IE criteria (plus a single instance of 6 criteria) by typing numbers in editable fields. The sum of the answers was checked to match 100% (allowing +/− 1% for rounding off) for the participant to continue to the next page. Questions were structured to move systematically through each IE category (three or four sets of answers for each category) that the respondent had expressed a sufficient level of expertise within. Responses were averaged across all participants who completed all answers in a given IE main area.

The third part (Q.3) consisted of pairwise comparisons between IE categories using the AHP method. Participants were asked indicate their preference on a scale of 17 options for each IE category pair, reflecting the relative pairwise importance of option A to option B. The 17 boxes consisted of 1 neutral box (options are equally important, coded ‘0’), and 8 steps of gradually greater relative importance on each side of the scales, moving from option A being slightly more important to extremely more important than option B (coded ‘+1’to ‘+8’), or vice versa (coded ‘−1’to ‘−8’). One comparison pair was presented at a time, with six pairs for each IE category. Questions were structured to move systematically through each IE category that the respondent had expressed a sufficient level of expertise within. The order of the pairwise comparisons was randomized both within individual categories and between IE categories. Responses were analysed to calculate combined weights using AHP analysis as elaborated below.

The results section will report briefly on the first part of the survey, and present an analysis on the second and third part of the survey in the Results section.

Data treatment

The analytic hierarchy process is a popular method for multi-criteria decision making developed by Saaty (1977) that relies on expert judgements to derive priority scales. The method has been used extensively for ranking building environmental aspects, particularly because it accommodates the evaluation of qualitative and quantitative aspects on the same scale of preference. AHP builds on pairwise comparisons that allows for a simpler and more accurate ranking of aspects compared to evaluating all aspect at once (Ishizaka & Labib, 2011) by modelling the problem as a hierarchy.

This survey used four separate AHP’s, one for each main IE area, to ensure that aspects were easier to compare. Each AHP resulted in a set of four category weights that can be combined with the results from the relative criteria weights on the first part of the survey. AHP was not used for the criteria weights (Q.2) as the number of aspects to compare were often too few to be relevant (3 cases with a single criterion and 8 cases with two criteria). Also, a single occurrence of 6 criteria would result in 15 pairs alone, which would not be operational.

AHP uses a relative value scale based on verbal judgements, combined with an AHP scale (the fundamental AHP scale) that translate these judgements into ratios. This study uses a balanced-N scale proposed by Goepel (2019) based on the original balanced scale (Salo & Hämäläinen, 1997), which improves sensitivity when aspects are relatively evenly judged, as the local weights are evenly dispersed over the weight range. The balanced n-scale takes the number of criteria of the AHP into account, ensuring no weight dispersion and a lower weight uncertainty than the original balanced scale (Goepel, 2019).

AHP allows for consistency checks between the pairwise comparisons. Many AHP tools display response consistency and even indicate which judgements need to be changed to improve consistency. For this study, it was decided not to show consistency to participants, to avoid influencing their responses. Instead, responses underwent a subsequent consistency test.

Results

This section presents the expert survey results and the evaluative comparison with the expert panel weights. Combined weights are proposed for all four levels of aggregation in the IV20 assessment method.

Respondents (Q.1)

Of the 86 received emails, 59 respondents activated the link resulting in a response rate of 68.6%. However, nine responses were discarded for being only partially completed; in some cases, the questionnaire was merely opened (response rate for completed responses: 58.1%).

The non-personal invite resulted in an additional 17 completed answers, increasing the total pool of completed answers to 67.

Based on the self-reported knowledge level, each category received between 25 and 55 responses. Table 1 shows the distribution of the 67 responses by knowledge level for each IE main category. Thermal has the highest amount of answers, followed by IAQ. Acoustics have the fewest responses, and appears to be a very specialized area, where the majority of respondents (0.55) indicate 'limited knowledge'.

The distinction between 'Expert' and 'Comprehensive' knowledge level was used to screen for potential differences between answers in the data analysis, to argue whether both can safely be included. As differences were minimal, both groups of responses were included equally in the calculated weighting.

Since invitations were sent to specific individuals, organizations, and companies, the responses cannot be considered as representative of the population of IE informed building professional experts, due to potential selection bias. The response rate is very high, however, and the total number of responses is high, considering the very specific requirements for participation (Danish building professionals with considerable knowledge on IE topics).

Responses are considered to have a wide coverage as experts within five different disciplines are represented; Consultant Engineer, Researcher, Architect, Manufacturer, and Entrepreneur (with the first two being overrepresented, as expected due to the self-reported IE knowledge requirements).

The self-reported knowledge levels indicate certain discipline tendencies including that acoustic expert respondents were dominated by Consultant Engineers (8 out of 10), while Visual experts in the survey are split evenly across four out of the five disciplines. This means that a low rate of Consultant Engineers (0.09) and Researchers (0.13) consider themselves as Visual experts, compared to Architects (0.75) and Manufacturers (0.50). This knowledge could be used to increase the number of respondents within specific IE topics in future surveys.

Table 1. Distribution of self-reported knowledge level by IE main category for all 67 responses of the expert survey.

Area-specific level of knowledge	ACO	IAQ	THER	VIS
Expert	10	20	27	11
Comprehensive	15	27	28	26
Limited	37	13	6	23
None	5	7	6	7
Responses used: (expert+comprehensive)	25	47	55	37

A satisfactory balance was obtained between practice and academia (43/24) when sorting respondents based on their current workplace. Respondents indicated a wide range of work tasks Consulting (43), Research/R&D (40), Teaching (27), Politics/Legislation (8), Building site/Execution (8), and Operation/Maintenance (3), as well as a few 'other' categories. Results will be presented for all groups combined, as no significant differences were found when comparing results from male vs female respondents (19/48), or results from practice vs academia (43/24).

Criterion level (Q.2)

Table 2 shows the survey results on criterion level by IE criteria included in the IV20 assessment. Each IE main area consists of four categories of which the fourth is always concerned with the potential for users to influence their IE. The sum of criteria within each category adds up to 100%. The three categories with only a single criterion were automatically set to 100% and not included in this part of the survey. The table includes a brief description of each criterion.

Responses have been averaged for each category, as listed in Table 2 (rounded numbers) alongside weights chosen by the IV20 expert panel for the beta version of IV20. The combined weights listed in Table 2 are, for the most part, rounded versions of the survey results (white cells, marked [a]), and they will not be commented further. A few categories have had small adjustments (light grey cells, marked [b] and [c]), to adjust for current conditions in Danish multifamily dwellings. Reverberation time (ACO3.2) is increased slightly as this is an increasing problem because of larger glazed areas, larger room sizes, the introduction of hard and smooth surfaces, as well as a tendency towards minimalistic furnishing by the occupants. Thermostat controls on room level are lowered slightly; as it is already the norm in Danish dwellings (a few exceptions do occur).

Determining combined criteria weights

For three of the 16 categories, the IV20 expert panel weights have either influenced or entirely replaced the Survey weights (dark grey cells, marked [d] and [e]). Arguments for leaning more towards the IV20 expert panel weights will be presented for each of the three affected categories below.

ACO1: traffic noise

The first category of the acoustics assessment is concerned with noise from outside the building. The category consists of two criteria: ACO1.1 – noise from traffic and industry (noise level inside the apartment),

Table 2. Criteria weights from the expert panel, the expert survey and combined.

	IE Criterion Description	Expert panel [%]	Expert survey [%]	Combined weights [%]
ACO1.1	Traffic noise (and industrial noise)	90	65	80[d]
ACO1.2	Openable window towards quiet side	10	35	20[d]
ACO2.1	Airborne sound, neighbours	40	50	50[a]
ACO2.2	Impact sound, neighbours	60	50	50[a]
ACO3.1	Noise from technical installations	60	64	60[b]
ACO3.2	Reverberation time	40	36	40[b]
ACO4.1	Openable windows in multiple directions	100	N/A	N/A
IAQ1.1	Outdoor air quality (and filtration)	100	N/A	N/A
IAQ2.1a	Mechanical ventilation (and commisioning)	80	72	70[a]
IAQ2.3a	Low-emission materials	20	28	30[a]
IAQ2.1b	Natural ventilation potential	50	35	35[a]
IAQ2.2b	Bathroom exhaust fan	30	36	35[a]
IAQ2.3b	Low-emission materials	20	29	30[a]
IAQ3.1	Options for drying clothes	30	32	30[a]
IAQ3.2	Stove exhaust hood	35	46	50[a]
IAQ3.3	Stove type (electricity or gas)	35	22	20[a]
IAQ4.1	Window opening, ventilation type	30	41	30[c]
IAQ4.2	Window opening, window position	40	31	40[c]
IAQ4.3	Ventilation boost, mechanical ventilation	30	28	30[a]
THER1.1	Hours of overheating in critical room	90	59	90[e]
THER1.2	Cold surface discomfort from cooling	10	41	10[e]
THER2.1	Heat source and control options	50	57	50[b]
THER2.2	Low surface temperatures	50	43	50[b]
THER3.1	Drafts from leaky openings	33	39	40[a]
THER3.2	Down draft from surfaces	33	26	25[a]
THER3.3	Drafts from air movements	33	35	35[a]
THER4.1	Window opening (occupant present)	15	26	25[a]
THER4.2	Window opening (occupant not present)	10	13	15[a]
THER4.3	Ventilation boost with mechanical ventilation	15	11	10[a]
THER4.4	External shading and control options	20	18	20[a]
THER4.5	Cooling system and control options	20	7	5[a]
THER4.6	Temperature regulation on room level	20	25	25[a]
VIS1.1	Daylight	80	63	80[d]
VIS1.2	Colour rendering of windows	20	37	20[d]
VIS2.1	Sunlight exposure (hours/day)	100	N/A	N/A
VIS3.1	View out (access and quality)	40	39	40[a]
VIS3.2	View in exposure (reduced privacy)	45	33	35[a]
VIS3.3	External shading influence (view out, view in)	15	28	25[a]
VIS4.1	External solar shading, regulation	50	51	50[a]
VIS4.2	External solar shading, activation	50	49	50[a]

[e] significant deviation (>15% step from rounding off)
[d] considerable deviation (15% step from rounding off)
[c] modest deviation (10% step from rounding off)
[b] slight deviation (5% step from rounding off)
[a] no deviation (just rounding off)

and ACO1.2 – openings towards the quiet side of the building (presence or absence of this option on apartment level). The survey weights put a much higher emphasis on the 'quiet side opening' than what was intended when developing the tool (survey: 35% vs expert panel: 10%). After re-examining the wording of the question, it may have been misunderstood as 'whether the apartment has openable windows in general', instead of 'whether it is a benefit for the acoustic IE that it has one or more openable windows towards a quiet side'. The potential to open a window towards the quiet side of a building from one or more rooms must have a significantly lower weight than the overall noise level from the outside, which applies to all rooms, and also for situations with closed windows. In addition, traffic noise has a well-documented health dimension to consider (Sørensen et al., 2012). As a result, the final ACO1 weights listed in Table 2 (80%/20%), is an average weight between the expert panel weights and the survey weights.

THER1: summer comfort

The first category of the thermal assessment is concerned with thermal comfort outside the heating season. The category consists of two criteria: THER1.1 – overheated rooms (calculation of hours over a set temperature), and THER1.2 – cold surfaces from cooling (a cooling system designed to prevent local discomfort). Mechanical cooling is very rare in Danish dwellings, but has been included in the IV20 assessment (with low weight: 10%) as issues with too high temperatures is an increasing challenge in new or newly renovated projects. Recent developments point to an increase in cooling systems in the near future. The survey results clearly show that comfort issues from cooling are recognized by the survey experts (41% weight), confirming its presence in the assessment. However, as the occurrence of mechanical cooling is infrequent in multifamily dwellings, assigning a too high weight to this criterion would devaluate THER1.1. The weights proposed by the IV20 expert panel has been adopted instead of the survey weights, to accommodate for the current low occurrence of mechanical cooling in multifamily dwellings, something that may well be adjusted in later versions of the tool.

VIS1: daylight

The first category of the visual assessment is concerned with daylight amount, distribution and colour rendering. The category consists of two criteria: VIS1.1 – daylight amount and distribution (glazed area vs floor area plus correction factors), and VIS1.2 – colour rendering (window Ra value). Survey weights put more emphasis on the colour rendering aspect than the expert panel (survey: 37% vs expert panel: 20%). The survey weights confirm that colour rendering is an important aspect and that it should be part of the daylight assessment. Despite the three-layered glazing of many new buildings, the colour rendering of Danish dwellings is adequate, which means that this criterion will rarely be activated (exceptions include tinted windows or coloured glass). Assigning a too high weight to these criteria would devaluate the daylight criterion, which is why the final weights are based on the expert panel weights.

Category level (Q.3)

Table 3 shows the survey results on category level, by IE main area included in the IV20 assessment. Each main area consists of four categories of which the fourth is always concerned with the potential for the user to influence their own IE. The table includes a brief description of each category.

Pairwise comparison matrixes were compiled for each category, and criteria weight vectors were built using normalized pairwise comparison matrixes. Consistency checks for the four AHP's ranged from 0.51% to 5.0%, which is well below the recommended 10% threshold for consistent answers. Table 3 lists the resulting category weights (rounded numbers) alongside weights chosen by the expert panel for the beta version of IV20. The colours of the combined weights column indicate the relative agreement between survey and panel weights. The results show considerable agreement between the survey and the experts, except for ACO4 (as discussed below).

Determining combined category weights

Results from the expert survey showed categories that were more even than initially suggested by the expert panel, resulting in slightly less inter-category distinction in the combined weights. The survey experts prioritized user categories as high as the other categories (range: 20.2–30.4%), indicating strong support for the inclusion of user categories in IE assessment for multifamily dwellings. The IV20 expert panel prefers a slightly more conservative approach for the user category weights, to preserve IE performance robustness. Robustness arguments span across three aspects.

(1) The user categories often indicate the potential for users to improve IE performance when it is lacking. The ability to control solar shading or increase ventilation rates can be an effective way to combat too high indoor temperatures, but a well-balanced design that prevents too high temperatures of occurring must be more important. In other words, the weights of the *condition* should be higher than the weights of the *symptom treatment*.
(2) In extension of argument one, a design with a high potential for good performance should be valued higher than the possibility to compensate for lack of performance, as there is no guarantee that the users will take advantage of that possibility. Research indicates that occupants fail to influence their IE for a range of reasons (Andersen, Toftum, Andersen, &

Table 3. Sub-category weights from the expert panel, the expert survey and combined.

	IE Category Description	Expert panel [%]	Expert survey [%]	Combined weights [%]
ACO1	Noise from the surroundings	20.0	27.6	35[b]
ACO2	Noise from the building	50.0	27.4	35[c]
ACO3	Noise from the apartment	25.0	23.2	25[a]
ACO4	Occupant influence potential	5.0	21.8	5[d]
IAQ1	Influence from the outdoor air	15.0	22.6	15[c]
IAQ2	Influence from building and materials	35.0	26.9	35[c]
IAQ3	Influence from activities in the apartment	30.0	25.8	30[b]
IAQ4	Occupant influence potential	20.0	24.7	20[b]
THER1	Temperature outside the heating season	30.0	20.7	30[c]
THER2	Temperatures in the heating season	25.0	27.0	25[a]
THER3	Discomfort from drafts	25.0	21.9	20[a]
THER4	Occupant influence potential	20.0	30.4	25[b]
VIS1	Daylight	40.0	24.1	35[c]
VIS2	Sunlight exposure	20.0	25.2	25[a]
VIS3	View out, View in and External shading	30.0	30.5	30[a]
VIS4	Occupant influence potential	10.0	20.2	10[c]

[e] significant deviation (>15% step from rounding off)
[d] considerable deviation (15% step from rounding off)
[c] modest deviation (10% step from rounding off)
[b] slight deviation (5% step from rounding off)
[a] no deviation (just rounding off)

Olesen, 2009; Frontczak et al., 2012). Occupants may not notice bad performance by not paying much attention to it, by lowering their expectations, or by having a delayed reaction. Also, occupants may not fully understand their options as systems may be challenging to operate, and they may be in doubt how to influence what. Finally, users may forget to utilize their options, as they do not have the full overview of options, or they forget to re/deactivate measures when conditions have changed.

(3) Since user influence is usually initiated by occupants experiencing bad IE performance, they are mainly activated to improve occupant comfort and well-being. If the air in a room is experienced as humid, malodorous or too warm occupants are likely to increase natural ventilation rates to improve comfort. However, the same air may just as well need changing because of chemical substances, emissions or particles that go unnoticed, meaning that the health aspect of IE risks being underrepresented with too high user category weights.

As a result, the combined weights for user categories are lowered compared to the survey weights to improve robustness. IAQ4 and THER4 are reduced by a single 5% step, while VIS4 is reduced by two 5% steps, and ACO4 is reduced by three 5% steps. Specific arguments for leaning more towards the expert panel weights will be presented for each category below.

ACO

ACO4 is kept as low as a 5% weight as suggested by the expert panel, as it only includes a single criterion concerning 'openable windows to the silent side'. As the Danish building regulation requires openable windows, no dwellings should score no pts in the category, and most would score max pts since all available facades often will have openable windows. Note, that these 5% only reflect the relative influence on the acoustic IE (thermal and IAQ-related benefits of having openable windows are scored elsewhere). If legislation changes to allow for new buildings without openable windows, this category weight should be increased. The 15.8% relative influence cut from ACO4 is distributed relatively over the other ACO categories, resulting in the following weights ACO1-33.5%, ACO2-33.3%, and ACO3-28.2% (see Table 3 for rounded values).

IAQ

Survey weights put IAQ4 at 24.7%, but it was decided to keep the 20% suggested by the expert panel. Particularly because IAQ holds several health dimensions that users cannot register and thus, they are less likely to react to lacking air quality performance. Also, IAQ1 is kept at the 15% suggested by the expert panel, as Danish pollution maps show pollution levels well below the thresholds set by the World Health Organization (WHO, 2018) and the WELL building standard (IWBI, 2019) known for its rigorous IAQ requirements. The relatively low IAQ1 weight is consistent with the survey results, who prioritized it as the lowest category. A further argument for a more conservative IAQ1 weight is the data uncertainty of the available Danish pollution maps. The 7.6% and 4.7% capped from IAQ1 and IAQ4 are distributed relatively across IAQ 2-33.2% and IAQ3-31.8% (see Table 3 for rounded values).

THER

The expert survey showed a preference for the thermal IE user category boasting an impressive 30.4%. Thermal IE is very comfort-centred, and as such, there is little risk that a high user weight will skewer the health vs comfort balance, and users are more likely to react to thermal discomfort (compared to IAQ). Also, THER4 includes six criteria, so it is only natural that it is the user category with the highest weight. The final weight has been set to a compromise between the expert panel weights and the survey weights, with the argument that reducing the number of hours with too high temperatures should be weighted higher than the possibility to compensate for it. Thus, 5% of the THER4 weights are moved to the THER1 weights.

VIS

The combined weights for VIS4 are based on the original expert panel weights of 10%, rather than the survey weights at 20%. VIS4 is only related to external solar shading, something uncommon in multifamily dwellings. The 10% cut from VIS4 is moved to VIS1 – daylight, as this has a solid foundation (well-document in academic literature, strong tradition in standards, long experience in practice, reliable assessment methodology) compared to less established aspects of VIS2 – sun hours and VIS3 – view in and view out (which remain at 25% and 30% as per the survey results).

Final combined weights

By combining the final weights presented above on category and criterion level with the overall label and category weights decided by the expert panel, the final combined weights of the IV20 framework can be determined.

Discussion

This study contributes to the complex discussion of how IEQ aspects contribute to overall IEQ. The findings differ from the existing research in both the detail level of the IEQ aspects weighted, and the resolution of the relative comparisons, as well as the methodology, used to rank them.

Previous post occupant evaluation (POE) studies have investigated the relative importance of IEQ aspects, but literature reviews summarize that the combined findings of weights are inconclusive (Humphreys, 2005; Zalejska-Jonsson & Wilhelmsson, 2013). Also, most POE studies only tackle IE parameters on an overall level, i.e. thermal, visual, acoustic and air quality.

As the established IE weights of the current study contain detailed relative priorities on both category and criteria level, the resolution is much higher than in most leading assessment methods such as BREEAM, LEED and WELL that merely assign a few points or credits to each criterion. BREEAM has published a methodology for generating BREEAM category weightings (such as 'Health and Wellbeing' or 'Water'), but no strategy for prioritizing anything below that level (Taylor & Ward, 2016). The DGNB assessment method has detailed criteria weights, but there is no underlying methodology for deriving the weights.

There are many approaches to establishing relative IE rankings, each with their limitations. The methodology used in this study seeks to increase the robustness of subjective IE priorities in several ways while acknowledging the influence of variations in culture, climate and building typology.

One of the limitations of POE studies is that responses are highly influenced by the conditions of the occupant's dwelling and its current performance at the time of the response. Thus, there is a risk that the resulting weightings will be both building-specific and season-specific. This bias can be tackled somewhat through a high sample size and intelligent sampling of buildings. Still, it is difficult to avoid that the weights (also applicable for new built) are skewed towards a particular aspect, i.e. if the occupants surveyed live in buildings with draft issues. Experts were explicitly instructed at the beginning of the survey not to let themselves be biased by their personal preferences for IE, their own private experiences with IE, or by the conditions of the buildings they currently live/work in, including the building that they occupy at the time of answering the survey. Instead, IE experts were asked to determine relative weights based on the potential consequences in the context of the current building mass and building tradition in the Danish building industry, through a combination of experience and research knowledge.

Another advantage of asking experts is that IE aspects can be evaluated on a much more detailed level that if asking occupants. While IE topics can be communicated in simple terms (i.e. 'sound' instead of 'acoustic') it is challenging to balance giving respondents a detailed understanding of each criterion (i.e. 'surface material emissions') while keeping very brief and operational explanations. The difficulty lies not only in finding a common language but also in explaining to occupants the nuances between the criteria.

Since IV20 considers both the comfort and health dimensions of IEQ, it is imperative that the survey results reflect this dimension. Unlike POE studies that survey occupant satisfaction, the IE experts were asked to consider the evidence for health effects. The authors are convinced that IE expert based weights (compared to POE or other occupant-based weights) are less prone to an underrepresentation of health dimensions as a result of not understanding the 'unfelt' dimensions of IE.

Deriving weights from expert surveys potentially introduce a range of other bias, which the authors have sought to avoid or limit.

Experts are prone to IE aspect preference based on their professional expertise and focus. On the main area level, this bias is tackled through the required area of expertise indication, meaning that thermal experts could prioritize category and criteria weights within thermal IE, but not thermal over visual. The potential bias from the preference for more specific criteria, such as a research interest in drafts, decreases with the number of experts asked. Compared to expert panel weights, the expert survey thus significantly decreases this concern of specific preferences, due to a much more comprehensive representation of experts.

There is an overlap between the expert panel and the expert survey, as nine of the 67 responses of the survey came from expert panel members (ratio: 0.134). As the expert panel included several leading national IE experts, this overlap was tolerated in order to ensure a broad representation of experts in each of the four IE domains. The domains with the fewest survey responses (acoustic 25, visual 37) saw very modest contributions from the overlapping responses (acoustic 3, visual 3), which limits the impact of the overlap.

Expert panel ratings were performed early 2019, up to one year before the expert survey. There were no considerable IE-relevant changes in building practice or buildings regulations in this period. The period between the two ratings is mainly due to the processes ongoing during the development of IV20 tool. The gap could be decreased considerably when the weights are reevaluated.

The sample size is considered a good representation of Danish IE experts, considering the strict inclusion requirements of potential respondents: IEQ experts in a Danish context (and Danish speaking, as the survey was in Danish), who has experience with multi-story residential buildings. Given the limited response time and the fact that web surveys usually have low response rates, the response rate for this study was very high. Higher sample size could be achieved through a systematic collection of potential respondents into an expert catalogue for the next iteration of the weights. As indicated above, relative weights are dynamic, and the frequency of required iterations depends on the developments of the built environment within the given context. In the Danish context, energy efficiency requirements have been the driver for significant developments in Danish building tradition in the last few decades. Considering the frequency of recent building regulation changes, the weights could be revised every five years.

Conclusion

Region-specific IE weights have been established based on a relative priority survey by asking Danish buildings professionals with IE expert knowledge. Three measures were taken to increase the robustness of the subjective evaluations. (1) A wide range of IE experts was consulted on topics within their area of expertise only, resulting in between 25 and 55 respondents for each IE main area. (2) AHP consistency checks showed that the pairwise comparison responses on category level were consistent for individual responses and that there was considerable consistency between experts within each main area. (3) Survey results were evaluated by a multi-disciplinary expert panel to ensure compliance with the four weighting criteria, particularly concerning typological/building tradition relevance and scientific evidence for weight differentiation.

There was a considerable agreement between weights derived from the survey results and the weights suggested by the expert panel. Category and criterion level weights have been combined and added to the overall aggregation of relative IE weights for the IV20 assessment methodology.

The findings are relevant for a wide range of stakeholders, including researchers, consultants, designers and end users. Relative weights were explicitly established for the IV20 assessment method but are equally relevant for the design of other IE assessment tools or as input for comprehensive assessment methods such as DGNB. The established IE priority hierarchy is also relevant in the light of the Energy Performance Buildings Directive's recent focus on not compromising the health, comfort and well-being of residents (The European Parliament and The Council of the European Union, 2018). IE priorities could also be used by professional building owners to set client demands or to guide private buildings owners when buying or renovating their homes. Finally, the findings provide interesting insights for legislation work and could help shape commercial interest in the near future.

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