Holistic indoor environmental quality assessment

Supporting early design processes

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HOLISTIC INDOOR ENVIRONMENTAL QUALITY ASSESSMENT

SUPPORTING EARLY DESIGN PROCESSES

BY
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DENMARK

HOLISTIC
INDOOR ENVIRONMENTAL QUALITY
ASSESSMENT

SUPPORTING EARLY DESIGN PROCESSES

by

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ENGLISH SUMMARY

In many parts of the world, we spend 90% of our time indoors, most of it in our homes. Plenty of evidence exists for indoor environmental (IE) impacts on occupant health and comfort, including how the IE can be significantly improved. Despite this, little action has been taken by occupants, practitioners and legislators.

The presented research draws the contours of a coherent IEQ framework that integrate occupant comfort, health and well-being into a holistic IEQ perspective. The work presents a definition of IEQ well-being with an emphasis on positive environmental impacts, to improve occupant happiness, promote restitution, and increase acceptance with the indoor environment. This perspective has the potential to support the integration of IEQ design improvements, which are attractive to end-users and have very low investment and running costs.

This work approach IEQ assessment from a holistic perspective aiming to further large-scale IEQ improvements by supporting decision-making in early design processes. The research aids the development of a new IEQ assessment tool called **IEQ**Compass and tests the tool for its potential to be an active component in early design processes.

The built environment is faced with demands from many stakeholders, which increases expectations for low-cost and high-performance designs. As decisions are less costly and more influential in the initial stages of a project, design teams have to balance a wide range of interests already in the early design stages. To support design teams in this, IEQ assessment should be made available when there is plenty of design freedom, and while design changes are inexpensive. The research presented supports the implementation of decision support modules into IEQ assessment methods, such as for goal-setting, design proposal comparison, automated calculation, and visual result dissemination.

Contributions

The main contributions of the work are:

- A framework for holistic IEQ that combines three key components: comfort, health and well-being.
- A definition of IEQ well-being that introduces positive indoor environmental impacts on occupants.
- Recommendations for the design of future IEQ assessment methods with a focus on design decision support.
- A set of context-specific IEQ weights that enables overall IEQ labelling developed using a new methodology for relative weight determination based on domain expert surveys.
- Overall IEQ assessment can provide early-stage design decision support through design proposal comparisons and known trade-offs by using a newly developed assessment tool
- IEQ aspects can be design drivers as exemplified in experiments that demonstrate the applicability of an IEQ assessment tool in early design through the ease of use, calculation speed and result dissemination.

Implications for practice

The work presented aims to promote IEQ improvements to realise the potentials benefits for both occupants and society. The research presented supports this aim for three different stakeholders:

Occupants: Effective communication of IEQ impacts that are understandable and relevant, through IEQ labelling with visual dissemination of IEQ performance.

Practitioners: Support implementation of IEQ aspects as design drivers in the early design stages through the developed holistic IEQ assessment tool.

Legislators: Provide socio-economic incentives for law-makers to implement legislative action on IEQ improvements (e.g. through subsidies or regulation).

If implemented the work presented could improve the focus on IEQ when planning, designing, and investing in buildings, specifically dwellings. This has extensive potential benefits for improving population health and social equity, and bettering the lives of occupants, particularly vulnerable groups such as children, elderly and those with health problems. The main message is that IEQ improvements are not (always) complicated and expensive, but can be simple, low-cost design adjustments if approached holistically in the early design stages.

DANSK RESUME

I store dele af verden opholder vi os indendørs 90% af tiden, det meste af den i vores hjem. Indeklimaets indflydelse på beboeres helbred og komfort er velunderbygget, og det samme er mulighederne for at opnå betydelige forbedringer. På trods af dette, er der mangel på handling fra både beboere, udøvere og lovgivere.

Den præsenterede forskning tegner konturen af en sammenhængende struktur for indeklima-kvalitet, der integrerer beboeres komfort, helbred og velbefindende i et holistisk perspektiv. Arbejdet præsenterer en ny definition af velbefindende inden for indeklima, med vægt på positive indeklima-påvirkninger, der højner beboernes livskvalitet, restitution og tilfredshed med deres indeklima. Dette perspektiv har potentiale til at understøtte integration af indeklima-forbedringer, der er attraktive for slutbrugerne og har lave omkostninger til både investering og drift.

Afhandlingen anskuer indeklima-vurderinger fra et holistisk perspektiv med henblik på at fremme omfattende forbedringer af indeklimaet ved at muliggøre beslutningsstøtte i de tidlige designstadier. Forskningen har til formål at underbygge udviklingen af et nyt værktøj til indeklima-vurdering (**IEQ**Compass), samt at teste dets potentiale for at blive en aktiv del af tidlige designprocesser.

Der stilles skrappe krav til byggebranchen fra mange forskellige interessenter, hvilket øger presset for at levere løsninger med lav pris og høj performance. Beslutninger der tages i de tidlige designstadier har større indflydelse og medfører færre omkostninger, så design teams er nødt til at balancere en bred vifte af interesser allerede fra de indledende projektfaser. For at understøtte dette, bør indeklima-vurderinger gøres tilgængelige, mens der stadig er rigelig design-frihed og inden eventuelle ændringer bliver for bekostelige. Den fremlagte forskning har medvirket til at implementere en række funktioner til beslutnings-støtte i det udviklede værktøj til indeklima-vurdering, herunder for kravspecifikation, sammenligning af designforslag, automatiserede beregninger og visuel formidling af resultater.

Forsknings-bidrag

Afhandlingens primære bidrag er:

- Et nyt perspektiv for holistisk indeklima, der er en kombination af tre områder: komfort, sundhed og velbefindende.
- En definition af indeklima-velbefindende, der introducerer indeklimaets positive påvirkninger på beboere.
- Anbefalinger til design af fremtidige værktøjer til vurdering af indeklima med fokus på beslutningsstøtte til designprocesser.
- Kontekstspecifikke indeklimavægte, der muliggør samlet indeklima-mærkning, baseret på en ny metode til at bestemme relative vægte ud fra spørgeskemaer til indeklimaeksperter

- Samlet indeklima-vurdering kan støtte beslutninger i tidlige designstadier gennem sammenligning af designforslag og synliggjorte kompromiser ved hjælp af et nyudviklet indeklima-værktøj
- Indeklima-aspekter kan fungere som design-drivere som vist i eksperimenter, der demonstrerer anvendeligheden af et værktøj til vurdering af indeklima i de tidlige designstadier som følge af brugervenlighed, høj beregningshastighed og klar formidling af resultater.

Betydning for praksis

Det fremlagte arbejde sigter mod at fremme indeklima-forbedringer til fordel for både beboere og samfund. Den forelagte forskning understøtter dette mål for tre forskellige interessenter:

Beboere: Effektiv kommunikation af indeklima-påvirkninger, der gøres forståelige og relevante gennem indeklima-mærkning med visuel formidling af performance.

Praktikere: Støtte til implementering af indeklima-aspekter som designdrivere i de tidlige designstadier gennem et nyudviklet værktøj til holistisk indeklima-vurdering.

Lovgivere: Levere socioøkonomiske incitamenter for forbedring af indeklima, så der kan indføres lovgivning på området (f.eks. gennem tilskud eller regulering).

Ved korrekt implementering kan det fremlagte arbejde øge opmærksomheden på indeklima-aspekter ved planlægning, design og investering i bygninger, i særdeleshed boliger. Dette fokus har et vidtrækkende potentiale for at forbedre befolkningens sundhed og sociale lighed, samt beboernes livskvalitet. Dette gælder især sårbare grupper som børn, ældre og personer med helbredsproblemer. Afhandlingens hovedbudskabet er, at indeklima-forbedringer ikke (nødvendigvis) er komplicerede og dyre, men kan opnås gennem simple og billige design-justeringer, hvis de anskues holistisk i de tidlige designstadier.

PREFACE

The work presented in this dissertation is part of a PhD project funded by the Department of Civil Engineering, Aalborg University and the dedicated partnership REBUS – Renovating Buildings Sustainably. The REBUS partnership is funded by Innovation Fund Denmark (5151-00002B), Realdania (PRJ-2015-00481) and The Landowners' Investment Foundation (in Danish Grundejernes Investeringsfond, 9025410). The work has been carried out by Lasse Rohde at Aalborg University in the period from August 2016 to December 2019. The author greatly appreciates the opportunity provided by the funding organisations.

This dissertation is paper-based, and the papers A-D have been integrated directly into the main body of text to give the reader a more continuous reading experience. Paper E and F are located in the appendix with references in the main text. Note that Paper F is authored by Associate Professor Tine Steen Larsen, with the author of this dissertation as a co-author. Paper F is included in the dissertation to provide essential context for paper C and D by presenting an IEQ assessment tool developed as part of the REBUS project (REBUS, 2016). The tool is referred to using both the Danish prototype working title IV20 (Paper B, C and E), and its proper name **IEQ**Compass (Paper D, F and the dissertation). Unless otherwise stated, all illustrations are the author's own work.

PAPER OVERVIEW

The core of this dissertation is the following collection of papers:

Paper A — *"Framing holistic indoor environment: Definitions of comfort, health and well-being"*
Rohde, L., Larsen, T. S., Jensen, R. L., and Larsen, O. K.
Indoor and Built Environment 2019

Paper B — *"How should assessment methods for Indoor Environment be designed to facilitate decision support?"*
Rohde, L., Larsen, T. S., Jensen, R. L., and Larsen, O. K.
Submitted November 2019 (Architectural Engineering and Design Management)

Paper C — *"Determining indoor environmental criteria weights through expert panels and surveys"*
Rohde, L., Larsen, T. S., Jensen, R. L., Larsen, O. K., Jønsson, K. T., and Loukou, E.
Building Research and Information 2019

Paper D — *"Holistic Indoor Environmental Quality assessment as a driver in early building design"*
Rohde, L., Jensen, R. L., Larsen, O. K., Rohde, L., and Larsen, T. S.
Submitted October 2019 (Building Research & Information)

Paper E — *"Historical development of IEQ in Danish dwellings - has energy efficiency requirements inhibited positive IEQ developments?"*
Rohde, L., Larsen, T. S., Jensen, R. L., Larsen, O. K., Jønsson, K. T., and Loukou, E.
Proceedings of Building Simulation 2019

Paper F *"**IEQ**Compass – A Tool for Holistic Evaluation of Potential Indoor Environmental Quality"*
Larsen, T. S., Rohde, L., Jønsson, K. T., Rasmussen, B., Jensen, R. L., Knudsen, H. N., Witterseh, T., Bekö, G.
Submitted November 2019 (Building and Environment)

RELATED RESEARCH

In addition to paper A-F, the author of this dissertation has published a conference proceeding and a technical report during the PhD study. These papers are not part of the dissertation but are included to show additional research activities related to the research presented in the dissertation. The technical report (Paper G) includes the analysis that is summarised in paper B of the dissertation. The conference paper presents a brief overview of an IEQ assessment tool, which is presented in detail in Paper F.

Paper G *"Comparison of Five Leading Sustainable Building Certifications Concerning Indoor Environmental Assessment Content"*
Rohde, L., Larsen, T. S., Jensen, R. L., and Larsen, O. K. Technical report, Aalborg University

Paper H *"Evaluation of Improved Indoor Environmental Quality during Renovation using the new IV20 Tool"*
Larsen, T. S., Rohde, L., Knudsen, H. N., Jønsson, K. T., and Jensen, R. L.
Proceedings of Building Simulation 2019

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A warm thanks to my colleagues at Aalborg University who collaborated with me on my papers, and to fellow researchers on the REBUS project who I have been working with throughout the PhD. I would also like to thank the funders of the REBUS-partnership - Innovationsfonden, Realdania and Grundejernes Investeringsfond - who helped made this PhD possible. Also, thank you to all survey respondents, and to workshop and design experiment participants, who generously shared their insights and opinions with me.

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Finally, I extend my deepest gratitude to my family for their continued encouragement, and for asking into my work with genuine interest. A special mention to my parents and my mother-in-law, who helped with both children and logistics, particularly during conference participations and in the final phase of the dissertation writing. And to my wife and two sons, thank you for your support, your unconditional love, and for making me maintain the right work-life balance!

To my beloved wife, Freya

who partly advised against it, but supported me through it nevertheless,

and to my sons Sigurd and Osvald,

may you stay as curious and passionate about life as you are now

CONTENTS

GLOSSARY

BPS	Building Performance Simulation(s).
DALY	Disability-Adjusted Life Year. In simple terms, one DALY is the equivalent of one lost year of ‘healthy’ life. DALY is the sum of two indicators: premature mortality (Years of Life Lost) and health impairment (Years Lost due to Disability). DALY summed across a population (also known as the burden of disease) indicates the gap between current health and the ideal health of a population.
DSS	Design Decision Support.
early design (stages)	Design stages for buildings ranging from the initial drafts until the transition to Detailed Design (or Technical Design). Design stages have different names and definitions depending on the source but for this work ‘early design stages’ cover all of the following terms: Design Strategy/Conceptual Design, Predesign/Schematic Design/Preliminary Design, and Design/Design Development.
holistic	Being concerned with ‘wholes’ rather than ‘parts’. The definition of a holistic perspective is context-specific, but for this dissertation, the following apply: *Holistic design* treats design aspects such as aesthetics, functionality and sustainability as an interconnected whole. *Holistic medicine/health* considers both the body and the mind. *Holistic indoor environmental quality* is concerned with; all major indoor environmental disciplines including indoor air quality, thermal, visual and acoustic performance; all potential impacts on occupants including health, comfort and well-being; overall performance of indoor environment from all relevant aspects (both qualitative and quantitative)
IE	Indoor Environment(al).
IEQ	Indoor Environmental Quality.
performance gap	Discrepancy between calculated and as-built performance, such as indoor environmental performance and energy performance.

CHAPTER 1. INTRODUCTION

This dissertation presents research on definition, assessment and design of holistic indoor environment (IE) in buildings. In addition to contributing to the field of IE research, the work presented aims to provide support for built environment practitioners on indoor environmental quality (IEQ) topics. Motivational drivers for this dissertation have both an occupant's and a practitioner's perspective. IEQ has significant physical and psychological consequences for occupants which should be researched, mapped and communicated to both building professionals and building occupants (Chapter 1 and 2). Practitioners are faced with challenges of growing technical complexity, due to increasingly demanding legislation on sustainability topics, particularly energy efficiency. The work presented provides practitioners with an overview of critical IE topics, suggest context-specific relative IE priorities, and develop tools and methods for early-stage IE decision support (Chapter 3 and 4). The research performed aims to improve conditions for the design of good indoor environment as well as providing all stakeholders with fuller and more easily accessible dissemination of IEQ (Chapter 4 and 5).

The research is performed with a holistic perspective on indoor environment and integrated design processes. Building design is a complicated process, with a variety of stakeholders with different interests and focuses, which sometimes result in good intentions turning into bad solutions. From 2009 to 2014 Danish schools were renovated for DKK 18 billion, aiming to improve energy efficiency and indoor environment. The large-scale investment was partly driven by research demonstrating that IE aspects had a significant influence on children's learning environments. Light intensity and light colour affect mood and test performance (Barkmann, Wessolowski, & Schulte-Markwort, 2012; Sleegers et al., 2013), while classroom acoustics affect both reflection and detailing abilities (Crukley & Scollie, 2012; Sullivan, Osman, & Schafer, 2015), national test results (Toftum et al., 2015), and absence due to illness (Gaihre, Semple, Miller, Fielding, & Turner, 2014; Mendell et al., 2013). Renovation proposals were ambitious on both energy and IE performance, but budget cuts made some schools discard plans to install mechanical ventilation. With a new highly airtight envelope the outdoor air supply was lowered, and the resulting air quality was in some cases worse than before the renovation (Clausen, Toftum, & Birgitte Andersen, 2014; Ingeniøren, 2014).

A similar issue with an unbalanced focus on the demands for high energy efficiency and good IEQ is seen in several Danish housing projects. Danish houses that were energy-renovated with highly airtight envelopes and no mechanical ventilation found to have outdoor air supply lower than required by the regulations, causing poor IAQ and moisture problems (Jensen, Jensen, Nørgaard, Justesen, & Bergsøe, 2011). Even buildings with a focus on IEQ can have balancing issues, as exemplified in the monitoring of eight passive houses (Comfort Houses) that showed insufficient heating capacity in the winter, and issues with overheating in the summer (Camilla Brunsgaard, Heiselberg, Knudstrup, & Larsen, 2012).

The two examples illustrate the need for increased focus on IE topics and improved decision support for practitioners, to avoid ill-informed compromises. They also exemplify that a holistic perspective is a precondition for well-executed buildings in a dynamic and increasingly strict built environment context.

1.1. WHAT IS INDOOR ENVIRONMENT?

Since the earliest examples of improvised shelters, erecting buildings has been about improving comfort and being safe. Although modern buildings serve a range of purposes, the primary purpose is to create an indoor environment, which is different from the outdoor environment. As we spend up to 90% of our time indoors (Klepeis et al., 2001), the IE has an significant influence on many aspects of the combined comfort, health and well-being of occupants.

1.1.1. INDOOR ENVIRONMENTAL TERMS

Indoor environment in buildings is a well-established multidisciplinary research field, with a range of different terms and metrics that address the influence on occupants. Research on IE comfort investigate occupant's perception of their indoor environment and has helped set performance thresholds for a range of comfort criteria. Productivity studies have shown how IEQ influence occupant performance in various ways, including improved concentration and task solving. IE health research has mapped negative health impacts on occupant health, resulting in restricting or banning toxic substances in buildings. The value of adverse health impacts has been quantified in research using metrics such as 'years of potential life lost' and Disability-Adjusted Life Years (DALY). Other more qualitative concepts such as well-being and the influence of sociological and psychological characteristics are less defined, but receive increased attention. The main IEQ terms and their definitions will be elaborated in Chapter 2.3, Paper A – *Framing holistic indoor environment: definitions of comfort, health and well-being*.

1.2. IEQ IN HOMES

Indoor Environment in dwellings has a worryingly low focus considering that people in industrialised countries spend more than 90% of their time indoors (Klepeis et al., 2001). Research into improving the indoor environment in offices has been performed from a productivity perspective where increased efficiency and reduced sick leave lead to return on investment. Nevertheless, we spend close to 16 hours daily at home (Baker, Keall, Au, & Howden-Chapman, 2007; Leech, Nelson, Burnett, Aaron, & Raizenne, 2002), which beats the time spent at work by more than a factor three for a full-time employee. Furthermore, one out of six Europeans reports living in unhealthy buildings, and they are more than 1½ times as likely to suffer from poor health (VELUX, 2017).

Unlike office productivity gains, there are no immediate economic incentives for homeowners to invest in a better indoor environment. As a result, the private building sector does not automatically generate a demand for a good indoor environment. Also, most occupants are not aware of the implications of a poor IE, because the topic is complicated, and there is a lack of information available for end-users. If the building industry would address the most relevant parameters of IE in dwellings in a holistic and comprehensible fashion, it would be better equipped to suggest IEQ improvements and to communicate the combined benefits to occupants. Also, increased political awareness on the potential societal benefits of improved IEQ could spur political support of large-scale IE investments.

1.2.1. IEQ IN HOMES IS A GREAT PUBLIC INVESTMENT

Indoor environmental improvements are a good investment from a socio-economic perspective, as high-quality IE promote healthy citizens, which reduce both health care costs and health inequities between citizens. Additional financial benefits typically mentioned for large-scale investments in energy renovations might also apply here, such as increased employment, development of national know-how and new technological developments.

An investment in reduced health care

IEQ improvements have wide-ranging socio-economic benefits from a healthier population resulting in significant reductions in health care expenses, as well as lowered social benefit expenses and lost potential tax revenue from sick leave, early retirement and early deaths. The potential economic benefits for improving a given IEQ aspect can be estimated by calculating the health consequences for conditions depending on that aspect, also known as the burden of disease. This is typically done by calculating the total Disability-Adjusted Life Years (DALY) across a population. Two European projects, EnVIE (De Oliveira Fernandes, E.; Jantunen, M.; Carrer, P.; Seppänen, O.; Harrison, P.; Kephalopoulos, 2009) and IAIAQ (Jantunen, Oliveira, Carrer, & Kephalopoulos, 2011) estimated that approximately 2 million DALY are lost annually across 26 European countries based on exposure to indoor pollutants. This means that inadequate IAQ in Europe results in societal costs around €230 billion per year assuming one DALY to be worth €115,000 (Quinet, E.; Baumstark, L.; Bonnet, J.; Croq, A.; Ducos, G.; Meunier, D.; Rigard-Cerison, A.; Roquigny, 2013).

A large part of the potential societal health savings from improving IEQ comes from housing improvements. A European analysis of the combined costs and consequences of inadequate housing report combined annual costs of €194 billion from healthcare, medical and social services, and lost productivity and opportunities (Eurofound, 2016). The report estimate that adequate housing across Europe would require a €295 billion investment, resulting in a payback time of just 1.5 years if we consider the combined socio-economic savings.

Health problems from inadequate housing have been discussed previously (Beranova et al., 2017; Bonnefoy, 2007; Braubach, Jacobs, & Ormandy, 2011; Ortiz, Casquero-Modrego, & Salom, 2019). Ortiz et al. presents potential health benefits and derived economic healthcare savings as an argument to renovate dwellings (Ortiz et al., 2019). The paper list examples of health consequences including impacts from Indoor air quality (respiratory diseases; cardiovascular diseases; lung cancer), Lighting conditions (desynchronization; psychological aspects), High temperatures (excess summer deaths; circulatory diseases; respiratory diseases), Low temperatures (excess winter deaths; hypertension and other cardiovascular diseases; respiratory diseases e.g. asthma, chronic bronchitis and obstructive pulmonary diseases), Noise (cardiovascular disease; mild cognitive impairment; sleep disturbance; tinnitus; mortality increase), and Moisture and mold (respiratory diseases e.g. irritation, allergies, infections and asthma).

IEQ can help reduce social inequity

In addition to reducing health care expenses, investing in good living conditions is the best way to reduce health inequity according to a new WHO report (WHO Europe, 2019). The report shows that a public investment increase of 1% reduces health inequity by almost 2%, which is more efficient than direct health service investments.

Studies show correlations between low income and health risk factors, such as unhealthy lifestyles and house deficiencies leading to bad IE (VELUX, 2018). In addition, people with low income are more likely to be exposed to unhealthy work environments, and have lower chance of individually signed health insurances and access to private hospitals. IEQ improvements in homes can, unlike work environments and schools, target vulnerable user groups, which are not part of the workforce. People that spend most of their time at home, such as elderly, infants and adults on parental leave. The same is true for already exposed people such as those on medical or stress leave, and people who are disabled or disability retired. Low-income families are both more likely to suffer from home deficiencies, and more likely to be social housing or affordable housing tenants, which places responsibility for action and investment in IEQ on the building owners (VELUX, 2018). In Denmark, non-profit housing organisations own and operate extensive (state-owned) social housing portfolios, which represent a significant potential for improved living conditions. Investments in high-quality IE can have economic co-benefits for the building owner such as improved occupation from fewer move-outs and more attractive dwellings.

1.2.2. HOME IS WHERE THE OCCUPANT IS

A much-cited argument for the importance of improving IEQ conditions is that people spend 90% of their time indoors. The actual distribution of the time spent indoors receives far less attention, however, but serves as a perfect argument for a greater focus on IEQ in dwellings. Studies of citizens in the U.S and Canada, show that people spend close to 16h in their homes every day (Leech et al., 2002). The 8 hours daily spent outside the home, is divided into a range of much smaller exposures including office/factory (1.4h), school/public building (0.9h), bar/restaurant/mall/store (1.0h), other indoor locations (2.0h), in vehicles (1.3h), and outdoors (1.6h) (Leech et al., 2002). If we compare the time spent in dwellings (16h) with the total time spent in all other building types (5.3h), the average potential exposure is three times as high in dwellings, as in all other building types combined. The exposure time alone makes IEQ in homes critical – perhaps even essential – to improving public health.

Also, the indoor environment in homes is potentially worse than in work environments, as there is a less developed system to evaluate IEQ in dwellings. For instance, national regulations do not exist for many IE criteria, although international standards specify IEQ recommendations in four different categories (DS/EN 16798-1, 2019). This lack of regulation is mainly due to an assumed degree of freedom to make behavioural adjustments (activity level, clothing level, choice of room) and environmental modifications (opening/closing windows, operating thermostats and lights). However, in less robust indoor environments it can be challenging to achieve the right balance between closely intertwined aspects such as CO_2-levels, relative humidity, thermal comfort, protection from noise, and access to light and views. This difficulty can lead to vicious circles of attempted environmental modifications such as opening a window to improve air quality, only to be exposed to noise and draft, making one close the window again. Also, behavioural adjustments are not necessarily preferable or possible, as they are limited by both social and physical constraints (elaborated in Chapter 2.3, Paper A).

Another issue of assuming that the behavioural freedom of occupants can replace IEQ regulation is that occupants can only be expected to modify their environment or behaviour for the perceived IE (comfort-related influences). Many health-related aspects do not affect the sensory systems and occupants will not have a chance to apply adaptive responses to 'invisible' harmful exposures, such toxic emissions and exposure to low-frequency noise, which have long-term health consequences.

An additional argument for directing focus to IEQ in dwellings is that it allows us to target aspects of occupant health that would otherwise be difficult to influence, such as physical and mental restitution, and sleep quality.

1.2.3. BARRIERS ON MOTIVATION AND WILLINGNESS

Indoor environmental improvements are great investments in office environments for a range of reasons (Clements-Croome, 2018). For employers, this is mainly due to increased productivity and reduced sick leave (Wargocki et al., 2006). As personnel costs, such as salaries and benefits, account for up to 90% of business operating costs, even modest productivity boosts are worth the investment (WGBC, 2014). Other benefits include lower turnover rates, increased ability to attract workforce and improved branding value (Wargocki et al., 2006; WGBC, 2014).

Although increased productivity and reduced sick leave could also be arguments raised for improved IEQ in dwellings, there is no immediate monetary payback perspective for homeowners to invest in IEQ. Instead, homeowners should be motivated to invest in a more comfortable, healthy and happier life. In a Danish private homeowner survey, respondents rated the indoor environment as the most important of five housing factors, with low energy consumption and architecture rated as the least important (A. Mortensen, Heiselberg, & Knudstrup, 2016). Yet, when asked about their reasons for renovating 'lower energy consumption' was the most chosen statement (56%), with indoor environment in fourth place (28%), and financial arguments about savings, rent and resale value in second, third and fifth place (A Mortensen, Heiselberg, & Knudstrup, 2014). In addition to the obvious financial reasons, the low priority of IEQ improvements is hypothesised to be due to the limited available knowledge of IEQ improvement potential, and that IEQ is communicated in a way that does not appeal to occupants.

1.2.4. COMMUNICATING GOOD IEQ

IEQ-related topics are sometimes presented negatively by both researchers, practitioners and the press. Scare campaigns on radon exposure levels or the invasion of toxic gases, attract (negative) attention to IEQ issues while addressing aspects that occupants often cannot see, feel or comprehend. In contrast, architects, designers and sales personnel advertise positive investment options that are functional, fashionable and sustainable, often accompanied by showrooms or 3D visualisations of their products. As IEQ home investments have to compete with other investment options, they need to be made more attractive and comprehensible.

For homeowners, the cost of investing in a better indoor environment has to be balanced solely by the improved living conditions of the occupants. This requires a new way of communicating the value of positive IE impacts to make homeowners aware of the many potential health benefits. There is a huge demand for healthy and responsible/sustainable products within the food industry (organic, low-fat, whole-grain, superfoods, no additives etc.) and personal care (no parabens, no phthalates, no added perfumes and colours). Also there is a growing market for healthy lifestyle products and services such as fitness and exercise, coaching and meditation, diets and food supplements. This interest and willingness to pay extra for healthy products for themselves and their family must be translatable to indoor environments if we communicate that the air they breathe affects their health just as the food they eat. A survey of 14,000 Europeans revealed that improving overall well-being was an equally important motivator for renovating their home as reducing energy costs - and more important than the other five options in the survey (VELUX, 2016). Other studies show that the ability to open windows is very important to Danish homeowners, and indicate that doing so is partly a matter of caring for the health of their family (Frontczak, Andersen, & Wargocki, 2012; Andrea Mortensen, Heiselberg, & Knudstrup, 2018). This points to a potential for not only addressing hazards and health risks but also advertising positive environments that improve health and well-being, e.g. through the promotion of sleep quality, restitution and stress-recovery.

Another way to promote good indoor environment in dwellings is to educate occupants on IEQ topics in a way that matters to them and is easy to understand. A first step could be to make the IEQ performance of dwellings accessible to prospective tenants, so they can prioritise and make informed decisions on their choice of dwelling. If we already have highly critical consumers that focus on health related topics, the information simply needs to be made available in a clear and easily understandable way.

1.3. RESEARCH OBJECTIVES

1) Provide a framework for holistic indoor environmental research to guide and expand multi-disciplinary research initiatives.

2) Promote the priority of indoor environmental performance aspects through knowledge dissemination and clear incentives for different stakeholders.

3) Enable holistic indoor environmental quality assessment and labelling, through the development of a new assessment tool (and methodologies to support this).

4) Demonstrate how indoor environmental aspects can become active design criteria by designing an assessment tool that provides design decision support.

1.4. DISSERTATION OUTLINE

This dissertation presents research on the topic of 'holistic indoor environmental assessment' as a compilation of six manuscripts dealing with different, but related research questions as elaborated below. The dissertation consists of six chapters that tie the manuscripts together in a coherent narrative while providing supplemental context, considerations and reflections on the work. The dissertation opens with broad scopes and 'long-term implications', and gradually turn towards narrower topics and more practice-relevant research, with a focus on design processes.

Chapter 1 outlines the background, challenges and objectives of the research.

Chapter 2 presents a state of the art review within holistic indoor environment, which also provide suggestions for definitions of the terms comfort, health and well-being (Paper A). The chapter also positions the dissertation within the field of IEQ research by employing a holistic and occupant-centred perspective that suggests the promotion of a positive IEQ dimension.

Chapter 3 investigates the approach and functionalities of leading comprehensive assessment tools and compare them on IE criteria content and weighing (Paper B). Based on the potentials and limitations of current tools, the paper provides recommendations for the design of future tools.

Chapter 4 describes the process of designing a holistic IEQ assessment tool, including providing practical, contextual and strategic context for the work presented. A newly developed tool is presented from both a purpose and functionality perspective, as well as a more specific content and assessment angle (Paper F – Appendix A). The chapter also discusses methodological approaches to IEQ assessment scoring and presents a study that establishes context-specific relative IEQ weights (Paper C).

Chapter 5 demonstrates the use of the developed IEQ assessment tool in design processes through two early-stage design experiments (Paper D). The tool is tested against the identified limitations of current practice, and for the fulfilment of potentials for future IEQ assessment tools in early design stages.

Chapter 6 propose directions for future research into topics such as holistic IEQ assessment, early-stage performance assessment tools, and the promotion of good indoor environment in buildings from both a political/legislation and an occupant/motivation perspective (Paper E – Appendix D). The chapter also discusses the presented research and highlights the main conclusions of the combined research contribution.

CHAPTER 2. HOLISTIC INDOOR ENVIRONMENT

The first shelters constructed by humankind served to create a safe and functional place to live. Primary concerns included protection from the elements and a place to hide from wild animals. Now our expectations for buildings are much higher, including high-level functionality, good quality indoor environments, and to some extent safety from other people (privacy, burglary protection). Also, we often expect buildings to be durable and aesthetically pleasing. Energy efficiency and environmental sustainability concerns are deliberately not included in the list of 'purposes' for erecting buildings, but instead are significant 'consequences' of buildings. It is essential to distinguish between these when we prioritise building performance. If we keep pushing energy reduction solutions without due consideration to the comfort and health of occupants, we forget the purpose of building. If we continue down that road, the most environmentally sustainable building is the one we do not build. Instead we should pursue how to accommodate the combined requirements of the occupants with the least possible negative environmental impact.

2.1. CAN A BUILDING BE 'HEALTHY'?

There is a growing focus on health-related topics in the built environment. However, many sources speak of 'healthy buildings', when we should instead speak about healthy occupants. While the increased interest to label buildings as healthy is positive from an occupant perspective, we have evidence that indoor air pollution is often much higher than outdoor air pollution (CISBO, 2019). Thus, the term 'healthy buildings' should be used with caution, particularly for buildings designed and operated to meet comfort requirements (rather than, e.g. compliance WHO health guidelines for exposures). Recognising that indoor exposures are a significant determinant of population health, initiatives such as the HealthVent project suggests designing buildings for health requirements instead of comfort requirements (Carrer et al., 2018).

2.2. HOLISTICALLY POSITIVE INDOOR ENVIRONMENTS

In addition to ensuring that indoor environments do not reduce comfort or compromise the health of occupants, buildings could be designed to produce stimulating indoor environments. Research indicates that the indoor environment can be designed to promote positive moods and emotions, which could support occupant's mental health and resulting physical health as expanded in Chapter 2.3, Paper A below.

A *comfortable* indoor environment is one thing; a *healthy* indoor environment is another, and a *stimulating* indoor environment completes the trinity and allows for a great indoor environment.

2.3. DEFINING HOLISTIC INDOOR ENVIRONMENT

Paper A

"Framing holistic indoor environment:

Definitions of comfort, health and well-being"

Rohde, L., Larsen, T. S., Jensen, R. L., & Larsen, O. K., Framing holistic indoor environment: Definitions of comfort, health and well-being, Indoor and Built Environment (E-pub - ahead of print). DOI: 10.1177/1420326X19875795.

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Framing holistic indoor environment: Definitions of comfort, health and well-being

Lasse Rohde, Tine Steen Larsen, Rasmus Lund Jensen and Olena Kalyanova Larsen

Abstract

In research and assessment of indoor environmental quality (IEQ), the terms 'Comfort', 'Health' and 'Well-being' are often used interchangeably without a clear definition of terms or effects on conditions for occupants. This calls for a systematic restructuring of the ontological approach to IEQ and, based on a meta-analysis of recent IEQ literature, the authors suggest three substantial contributions: 1) A framework consisting of comfort, health and well-being as three equal branches of IEQ to increase focus on previously neglected aspects and make inter-domain relations more transparent. 2) The identification of key IEQ trends and by extension suggestions for formal definitions of three main domains as part of a multidisciplinary conceptual framework for working holistically with IEQ. 3) The introduction of positive stimuli to IEQ assessment as opposed to the predominance of focus on the absence of negative parameters of current practice. Through including this positive stimuli dimension, the field of IEQ shifts from 'not bad' to 'truly good', encouraging the design of enriched environments to further positive experiences improving occupant well-being.

Keywords

Indoor environmental quality, Occupant well-being, Mental health, Positive stimuli, Taxonomy, Review

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Introduction

The creation of an indoor environment (IE) shielding us from outside conditions is the fundamental reason for erecting buildings. However, historically, the field of indoor environmental quality (IEQ) has received less attention than other building-related topics such as structural aspects, materials and energy consumption. Recently, IEQ has started to gain more attention in research, policymaking, standardisation and building regulations. Unfortunately, different interpretations of what constitutes good IEQ exist, and key terms like comfort, health and well-being are sometimes used interchangeably. The lack of generally accepted, well-defined terms leads to confusion within IEQ research, ambiguous IEQ assessments and a lack of clarity in implications for occupants.

Comfort, health and well-being

Half a century ago, IEQ standards were mainly concerned with setting comfort criteria for thermal comfort and air quality, with Fanger's Predicted Mean Vote (PMV) model and derived Predicted Percentage Dissatisfied (PPD) index as the most noticeable contributions for thermal comfort[1] and the equivalent Percentage Dissatisfied (PD) index for perceived

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air quality.[2] In the last few decades, calculation and assessment methods have been developed for disciplines such as prevention of noise and promotion of daylight.[3,4]

Alongside this, decade's worth of research into indoor health has been performed as summarised in historical overview papers.[5,6] These list significant developments of indoor health research starting with the measurement of indoor air pollutants in the 1960s (nitrogen dioxide from gas stoves, tobacco smoke, asbestos fibres, radon, lead paint, Carbon Monoxide (CO), Volatile Organic Compounds (VOCs), Total VOCs (TVOCs), sulphates) followed by research on their health effects (i.e. lung cancer risk from tobacco smoke, asbestos and radon; and respiratory diseases from nitrogen, second-hand smoke and biological agents such as *Legionella*, allergens and house dust mites). Current issues of note include burning of biomass fuels for cooking in developing regions, and hypersensitive reactions, asthma and dampness/mould-associated allergies in developed world.[7] In addition to the health effect of indoor air, recent research points to a broader range of previously neglected health aspects of IE, introducing a range of parameters not considered by the comfort discipline.[8]

Following their historical overview, Samet and Spengler[6] state that 'A more comprehensive rethinking is needed on the physiological, sociological, ergonomic and psychological characteristics of the built environment that affect health and well-being'. This is backed by sources pointing to the urgency of multidisciplinarity in both research and design of IE.[9–11] The authors of this paper argue for well-being as an inherently positive third domain, alongside comfort and health, supported by recent findings showing correlations between qualitative parameters and positive mental health or well-being.[12]

As indicated by the brief historical overview given above, the three domains of comfort, health and well-being exist at different levels of maturity concerning IEQ (Figure 1). The comfort domain is fully incorporated and well defined with only a few significant developments in the last few decades, while the health domain is somewhat less defined and still being incorporated into regulations and practice. Finally, the notion of well-being seems mentioned in IEQ literature but has yet to be developed as a separate domain. As a result, the domains of comfort and health are discussed primarily from the perspective of setting clear boundary conditions between domains, to help identify the scope and content of the suggested well-being domain.

Terminology of well-being

Despite its common usage, there is a high degree of terminological confusion with the term well-being. Table 1 illustrates how the word well-being has overlapping meanings with comfort and health by consulting two well-recognised dictionaries.[13,14] Both list definitions and a selection and keywords of which those that overlap with well-being has been included in the table.

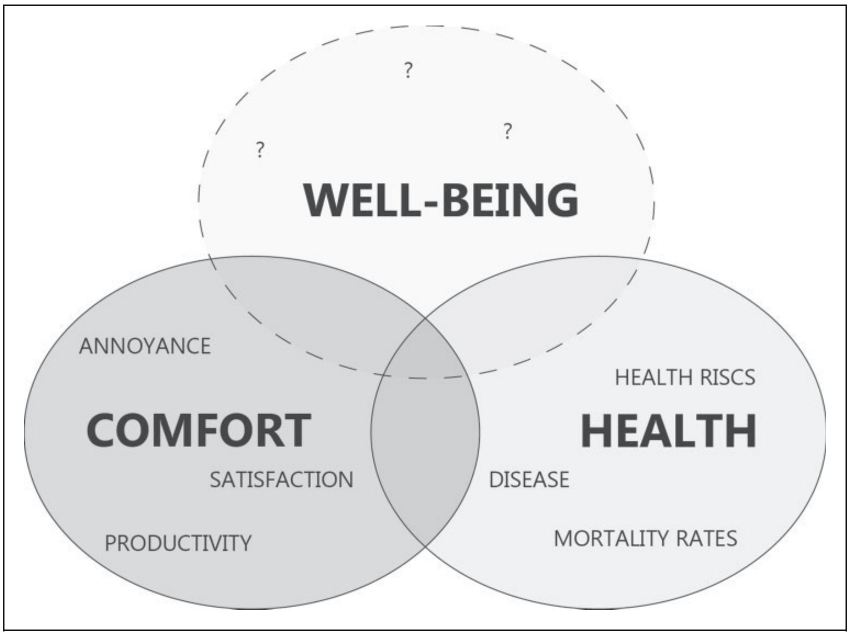

Figure 1. Conceptual illustration of the lacking consensus on the indoor environmental well-being domain. This paper identifies main topics of the well-being domain and suggest research disciplines, types of study and concrete examples to support the suggestion of a new domain definition.

Table 1. Examples of *definitions*, *synonyms* and *related words* of the terms comfort, health and well-being in recognised dictionaries.

Merriam-Webster Keyword	Definition (Dictionary)	Synonym (Thesaurus)	Related words (Thesaurus)
Comfort	Consented *well-being*/A satisfying or enjoyable experience		*Well-being*, Happiness, Gladness, Delight, Joy, Pleasure, Inspiration
Health	The condition of being sound in body, mind, or spirit/A condition in which someone is thriving or doing well	*Well-being*, Wholeness	
Well-being	The state of being happy, *healthy*, or prosperous		*Health*, Satisfaction, Content

Oxford Dictionary Keyword	Definition	Synonym (Thesaurus)	Related words (Thesaurus)
Comfort	Things that contribute to physical ease and *well-being*	*Well-being*, Enjoyment	
Health	A person's mental or physical condition	*Well-being*	
Well-being	The state of being *comfortable*, *healthy*, or happy.	*Health*, *Comfort*	

The results were selected to show how the distinction between these terms is unclear (when a term appears under the search result of another keyword, the words are italicised).

Interestingly, well-being is listed as either one or both of 'definition' and 'synonym' for both comfort and health in both dictionaries. Similarly, the words comfort and health both appear in the *definition* and *synonym* lists for well-being. Without a precise definition of well-being within the field of IE, there is a risk that the broader conventional interpretations of the word are used. Some publications do not distinguish between well-being and comfort, i.e. papers that discuss IE influence on health and well-being,[6] or health, well-being and productivity.[15,16] Other publications use well-being as a reference to health-related aspects.[17]

Well-being is a term frequently used in IEQ literature, but there is little consensus about the meaning. The authors of this paper believe that the lack of a term definition inhibits the inclusion of a growing body of cross-disciplinary studies relevant to understand how occupants' well-being is affected by the built environment. Despite significant number and scope, these studies have not been associated with IEQ research, as they do not fit traditional interpretations of the IEQ comfort and health disciplines. Significant, well-documented results await integration into the current field of IEQ, which could contribute to working holistically with occupant's well-being. The reluctance to introduce qualitative parameters into an engineering field is evident, but cross-disciplinary research within the built environment has started to quantify subjective parameters by suggesting new research methods better fit for the current deterministic approach to IEQ. Even the well-established field of thermal comfort had undergone such change of perspective when the adaptive comfort theory challenged Fanger's deterministic heat-balance model,[1] suggesting that thermal comfort also depends on subjective psychological, behavioural and physiological aspects.[18,19] Similarly, air movement in thermal IE research was initially concerned with annoyance from draughts 25 years ago, while current research treats some air movement as positively contributing breezes, causing thermal delight and aerodynamic pleasure.[20] Research into well-being from a positive psychology perspective has been growing in the past few decades based on the development of different reliable measures allowing a systematic study of the topic. For well-being to establish itself as an independent and recognised aspect of IEQ (as a supplement to the existing comfort and health disciplines), the boundaries and interrelationships of the well-being domain need to be defined.

The purpose of this paper

The authors of this article suggest establishing a third domain of IEQ that treats positive contributions to subjective well-being, by creating a framework for a range of studies linking both qualitative and quantitative parameters in the built environment with the mental well-being of occupants. Advances in affluence and lifestyle in high-income countries have led to the ambition to improve the psychological well-being (happiness, life-satisfaction, quality of life, positive functioning) of people, rather than merely focusing on mortality rates. Similarly, advances in IEQ comfort requirements in tightened standard regulations, and a growing effort to ensure healthy IEQ have pointed to an unrealised potential for promoting the overall IEQ by improving conditions for well-being (i.e., positive emotional responses to IEQ). Further improvements of IEQ conditions for comfort (i.e., narrow comfort intervals to lower PPD) and for health (i.e., increased ventilation rates) may result in increased mechanisation and energy consumption, and according to studies in office environments,[21] this mechanisation can be inversely correlated with the well-being of occupants. Instead, the authors of this paper seek to draw the contours of an IE well-being domain that systematically incorporates positive stimuli for the improvement of the overall evaluation of IEQ, and through this, promote further research on the topic.

In continuation of the brief historical overview and terminology issues presented above, the paper is divided into three sections. First, the Theory section argues for positive stimuli as the missing link in current IEQ assessment. Second, the Methodology section illustrates a conceptual framework for holistic IEQ assessment, including these positive stimuli. Finally, the Results section suggests a preliminary definition of the well-being domain as the first step towards inclusion into a holistic IEQ field. The latter is accomplished by collecting influential IEQ definitions from a variety of sources on topics such as comfort, productivity, assessment, health impact and mental health. The intention is to gain insight into how these definitions differ and which parts can be adapted to a common interpretation. Based on the selective review of IEQ-related definitions, this paper suggests definitions for each of the domains of comfort, health and well-being as part of a coherent framework for IEQ. The varying levels of maturity of these domains mean that the redefinition would span across a fusion of existing comfort definitions, an adopted general health definition for IE and an all-new definition of well-being concerned with positive stimuli and emotions. This results in distinct individual domain definitions that complement one another in the hope that it will lead to an unambiguous framework working with one of these aspects of IEQ – or all of them in the case of a holistic approach.

Theory

Before proceeding to examine the boundaries of IEQ well-being, this chapter presents a four-step argument for a new holistic perspective to IE. Parts 1 and 2 build a case for the inclusion of positive IE contributions through illustration of limitations in the current IEQ perspective, while Parts 3 and 4 take the first step towards a new multidisciplinary framework.

Why do we aspire for neutrality?

IE engineering is mainly focused on preventing discomfort, dissatisfaction and long-term causes of diseases and conditions; but why should IEQ settle for low levels of dissatisfaction when it could be truly good? Why is thermal comfort only about preventing discomfort? Why is building acoustics solely concerned with limiting noise? Current comfort practice assesses IEQ on a scale from dissatisfaction to satisfaction (annoyance to acceptance, discomfort to comfort, unacceptable to acceptable), while IEQ health uses metrics such as health risks, mortality rates, stressors and cause–effect relations. Thus, practice dictates assessing IEQ by measuring the presence of unwanted effects rather than the presence of positive contributions.[11] As a result, we do not know whether occupants are happy or not. The framework presented in this paper suggests widening the current scale going from bad to neutral, to also include 'the positive half' from neutral to good (Figure 2).

The notion of 'something more than neutrality' is shared by Brager, who mentions the concept of alliesthesia describing the physiological basis for thermal pleasure or delight, as a way to challenge thermal boredom.[22] Also, in his later works, Fanger challenged the modest requirements of today's standards, calling for paradigm shifts required to move from the unambitious '20% unacceptable/80% barely acceptable' towards 'also acceptable for sensitive persons' and further to 'perceived as fresh as outdoor mountain or sea air' or even better i.e. 'out of this world'.[23]

Is there more to IEQ than comfort and health?

There is plenty of evidence that buildings meeting international standards do not necessarily produce satisfied occupants, from both office environment surveys and post-occupancy evaluations of dwellings.[24–26] While the solution to this likely includes issues in design versus operation, (mis)use of assessment methods or knowledge on interaction effects,[10] this lack of satisfied occupants could indicate the presence of IEQ aspects that we have yet to identify and incorporate into our understanding of good IE.

To exemplify this, consider the following thought experiment – an imaginary room devoid of positive stimuli:

> A 3 x 3 m room with a room height of 2.3 m, a 0.5 m^2 square window positioned high on a north-facing wall and an opaque door giving access to and from the room. All surfaces are smooth and coloured a matte light grey. The artificial light is adequate, uniform,

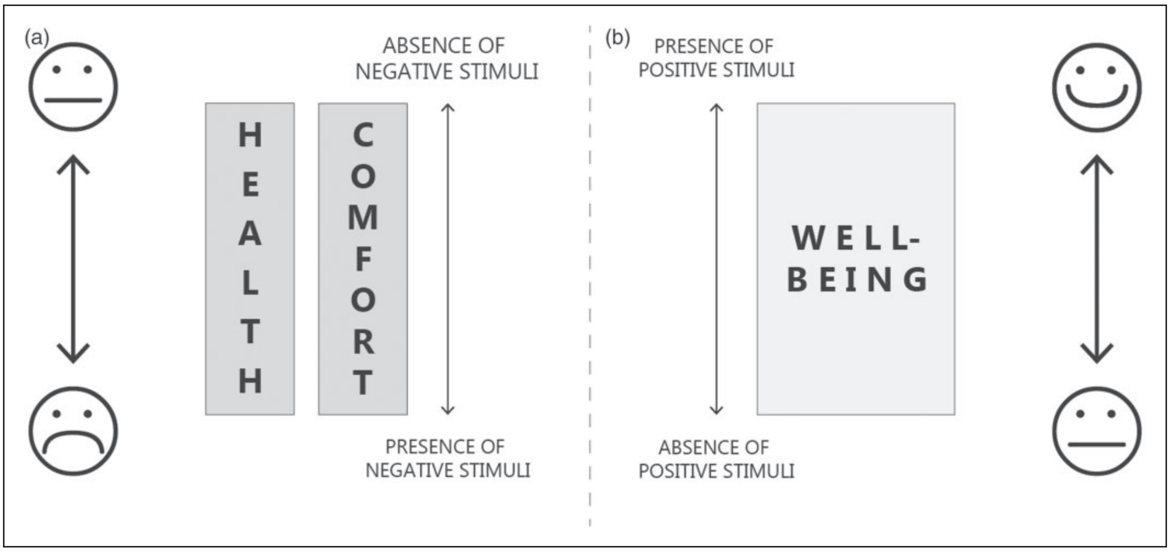

Figure 2. Current practice (a) assesses IE on a scale 'from bad to neutral'. By also assessing the presence/absence of positive stimuli (b), the suggested framework (a + b) extends the scale to also cover 'from neutral to good'.
IE: indoor environment.

> neutral in colour, and it does not flicker. The room is completely soundproof, and the air is clean and odourless. The window does not open. All surfaces and the room air are thermally homogenous at all times.

This imaginary room likely fulfils all (or most) current criteria for comfort and health, yet it is unlikely to invoke positive subjective evaluations as it may be experienced as two-dimensional and uninspiring. In the book, *The Eyes of the Skin*, Pallasmaa advocate 'architecture of the senses', criticising that minimalistic spaces 'house the intellect but leave the body and imagination homeless'.[27] In an argument for multi-sensory spatial experiences, Pallasmaa writes that

> Flatness of surfaces and materials, uniformity of illumination, as well as the elimination of micro-climatic differences, further reinforce the tiresome and soporific uniformity of experience. All in all, the tendency of technological culture to standardize environmental conditions and make the environment entirely predictable is causing a serious sensory impoverishment. Our buildings have lost their opacity and depth, sensory invitation and discovery, mystery and shadow.[28]

Further support for the importance of perceived and emotional effects of spaces include Merleau-Ponty's thoughts on the interconnectedness of multi-sensorial interaction and experience,[29] Aalto's notion of 'extended Rationalism' in *The Humanizing of Architecture*,[30] Zumthor's acknowledgement of architectural atmospheres[31] and the experiential effects of daylight, colour, sound and texture in the book *Experiencing Architecture* by Steen Eiler Rasmussen.[32]

The stimulus-deprived room exemplifies that pleasantly experienced IE requires more than the absence of negative stimuli. The question is, what could change the perception of this room? It covers the current requirements (a) in Figure 2 but lacks positive contributions (b). The authors suggest two statements below to exemplify room conditions that, despite their qualitative and subjective nature, can be widely accepted to contribute to this positive dimension. Compared to the stimulus-deprived room example above, the statements should be read as improvements regardless of individual preferences or cultural/professional backgrounds.

> A comfortable and healthy indoor environment with access to direct sunlight; a play of light and shadow accentuating spatial qualities and sense of depth, enhanced texture of materials, and variations of light intensity, colour and direction.

and,

> A comfortable and healthy indoor environment with the opportunity to open the window; creating voluntary flows of fresh air, expose occupants to pleasant sounds and smells, and improve the contact to the context outside.

Conceptual framework: Vitruvian IEQ Triangle

In *The Ten Books on Architecture* (*De Architectura*), Roman architect and engineer Vitruvius presents the Vitruvian Triangle – a structure of architectural quality supported by the three pillars of Utilitas (utility or function/commodity), Firmitas (firmness or durability/solidity) and Venustas (beauty or delight/atmosphere).[33,34] According to this, architecture must have a practical function, must be structurally sound and must be beautiful – without the latter, it is merely a building.

The authors of this paper suggest introducing well-being as a third domain, alongside the well-established domains of comfort and health. By adopting the structure of the Vitruvian Triangle, the three domains correspond to the fundamental laws of good architecture. Good IE exists in the space between comfort (function/commodity), health (durability/solidity) and well-being (delight/atmosphere)[21] (Figure 3). The absence of comfort means failing to accommodate intended activities; absence of health has long-term consequences for occupant health and absence of well-being is an environment devoid of sensory pleasure.

The concept of the triangle suggests that the domains are conceptually equal in importance and that none be ignored in the creation of good IEQ. One of the central messages of the Vitruvian Triangle is the interconnectedness of the three aspects (the Vitruvian Triade), how architectural quality depends on the synthesis of all three aspects, i.e. when the proposed structural system (durability) also has positive implications for the function and beauty of the architecture. Indications of this interconnectedness exist within the field of IEQ in studies showing how increased experience of well-being can improve comfort

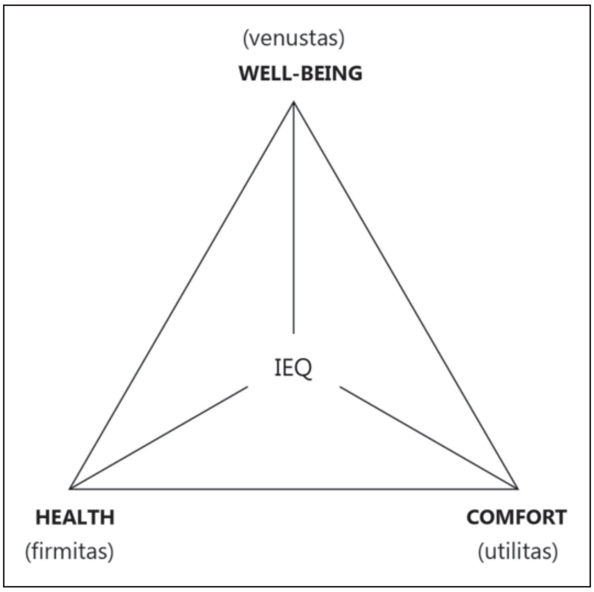

Figure 3. Suggestion for a three-branched framework for defining the solution field for good indoor environment inspired by the concept of the Vitruvian Triangle (for Architecture).
IEQ: indoor environmental quality.

(e.g. presence of plants makes users feel more thermally comfortable[35]) or compensate for reduced comfort (e.g. quality views increase tolerance of glare[36,37]). Similarly, the mental stimuli from IE well-being parameters can have derived physiological implications – several sources of evidence support positive emotions with positive effects on health through physiological, hormonal and immune function.[38] On the other hand, the notion of well-being is somewhat redundant if the IE is hazardous for occupants.

An example of well-being within visual IE could be introducing positive parameters (alongside 'avoidance parameters' like glare and flickering lights) such as access to views of a particular type and quality based on studies indicating that it improves the perception of overall IEQ.[39] Also, access to direct sunlight could contribute to well-being and overall IEQ through the visual feedback from shadows and play of light, the aesthetic quality of enhanced texture of materials, the mental effects of a visualised daily cycle, the sensation of the skin's exposure to sunlight or touching a surface warmed by the sun.

Conceptual model for holistic IEQ

The proposed conceptual model for holistic IEQ has a 'man' as the point of origin with the three domains of comfort, health and well-being in the innermost of three circular layers (Figure 4). The second layer lists which human conditions are affected by the IEQ, while the third and outer layer shows examples of which branches of science have ties to each of the three types of human conditions. Please note that the third layer is a non-exhaustive exemplification of how a variety of sources contribute to a holistic IEQ model, and that the model is deliberately made without separations between the three domains and their corresponding second and third layers, to show that at this stage, the model is open to a degree of overlapping between domains. Also, note that the three domains comfort, health and well-being are only conceptually equal at this point to stress the importance of bringing the less researched domains up to speed – not because there is evidence to conclude equal influence on occupants.

Each of the three domains affects occupants in a certain way. The comfort domain affects occupants through sensory input – often in short-term or immediate effects. Changes in the IEQ can, either consciously or unconsciously, influence the comfort perception of occupants, typically referred to as the perceived IEQ. For the health domain, this paper has adopted the model suggested in *The Indoor Environment Handbook*,[8] that the influence on occupants is mapped by IE effects on the 11 bodily systems of the human body. Each system can be disturbed by physical stressors, many of which are tied to IE

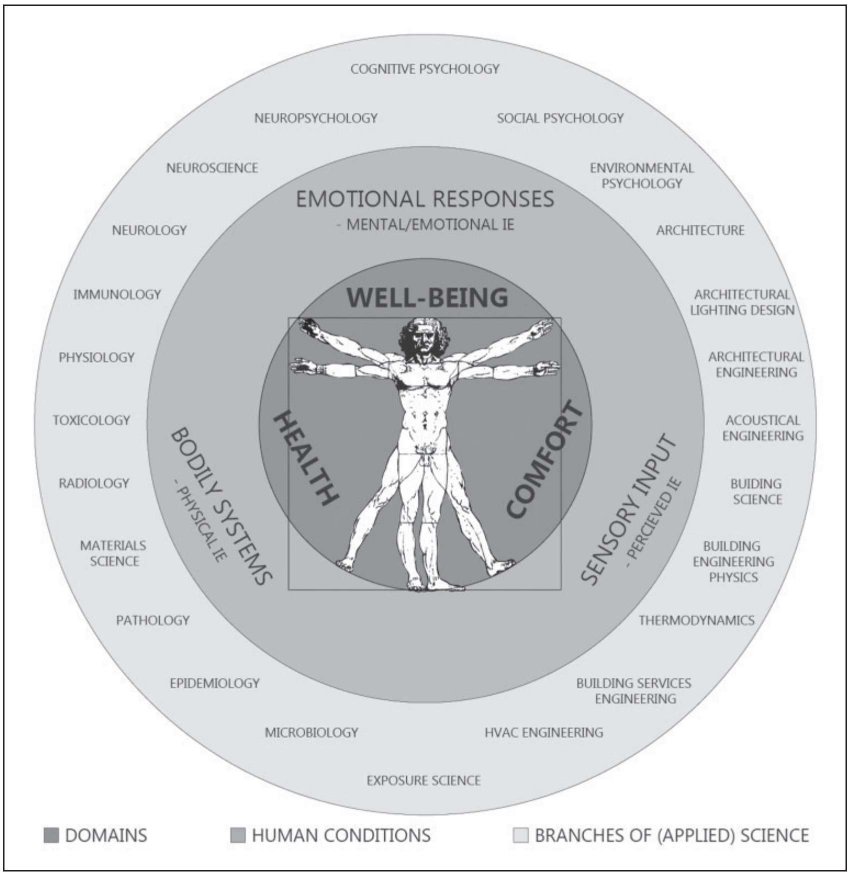

Figure 4. Conceptual multidisciplinary model of holistic indoor environment.
IE: indoor environment.

factors, potentially resulting in various diseases and conditions. Unlike the comfort domain, occupants often do not perceive these disturbances of the bodily systems, and the malignant effects may be seen in the long term only. The well-being domain covers positive emotional responses from the interplay between the occupant and the immediate indoor and outdoor environment. Further research into behavioural sciences fields like cognitive and environmental psychology, as well as branches of neuroscience may help map the many potential IE influences on mental health. While clear domain boundaries may be years away, the well-being domain is suggested here as being the positively contributing psychological counterpart to the physiological stressors of the health domain, as well as the positively contributing emotional response counterpart to the neutral or negative stimuli of the comfort domain (Figure 2).

The authors of this article realise that the conceptually flat three-branched structure might be skewed towards one or two domains, but at the time of writing, there are insufficient data to compare the impact level of even the two most researched domains. The impact on occupants is also likely to vary based on project-specific factors and as such could change from project to project, e.g. building type (intended use, duration of stay, time of the day, etc.), occupant lifestyle (general living conditions, health status, age, gender, etc.), cultural background (expectations, preferences) and climate (climate zone, season, etc.).

Rather than making assumptions of an absolute hierarchy of the three domains, this model draws attention to the possibility to influence conditions of occupants based on a broader scope of parameters than the ones currently in use. While the separation of IEQ terms above and the proposal of distinct definitions below suggest rigidity, Figure 4 indicates that all three domains are connected by their influence on IEQ conditions for occupants. By altering one IEQ parameter to improve conditions for comfort, one might accidentally worsen the conditions for occupant health. In the words of Koen Steemers,[9] 'To truly enhance human well-being, building design needs to move beyond optimising single parameters such as temperature and humidity, to more holistic approaches that take their cues in health-supporting human behaviours'. Since current IEQ practice is studied in separated disciplines, there is a risk that suboptimisation of single parameters might lead to a worse overall IEQ for occupants. By viewing IEQ influence on occupants from a well-defined holistic perspective, we break with the silo thinking and make the effort to improve overall IEQ conditions a balancing act.

Methodology

Semantics of IE

To restructure the IEQ framework, there are three main semantic work tasks, namely taxonomy, classification and definition. Suggesting a new conceptual model for IEQ that ties together selected key terms is thus an exercise in taxonomy while arranging and grouping derived elements such as parameters, metrics and source type based on these terms is a classification task. An essential part of this is the suggestion of new definitions of key terms, in the light of the new taxonomy.

As the new framework seeks to reorganise previously separated key terms, a Web of Science search was used to compare the most commonly used terms in recent IEQ research. The search combined a 'three-aspect IEQ topic search string' for publication topic, consisting of variations of the aspects 'Indoor Environment', 'Occupants' and 'Buildings' (see Table 2 'Aspect'), with one of each of the 11 selected terms (see Table 2 'Term') to check for term occurrence. All searches were restricted to publications written in English and published within the last two decades.

From the data in Table 2, comfort and health are apparently well-established domains, with widely used metrics or keywords connected to them. The term well-being appears less frequent, but its occurrence rate has doubled in the most recent decade (compared to the previous one) accompanied by the increased occurrence of metrics and keywords related to well-being. Closer inspection shows that while health occurrence only drops slightly, the physical health metrics tied to it (#6 and #7) drop drastically. When looking at the increased occurrence of term #9, it seems the reason for this could be papers addressing psychological, mental or emotional health instead of health concerning diseases and death rates. These results indicate that while the role of well-being has yet to be clearly defined, increased attention is given to the mental health and emotional conditions of occupants.

Methodology for definitions of comfort, health and well-being

As indicated by data in Table 2, the comfort field has been well established for decades (less so for visual and

Table 2. Occurrence search for selected terms within recent publications showing topic search string, selected terms, frequency of articles in which the term appears in the topic and the occurrence rate.

Aspect	**Three-aspect IEQ topic search string** (Aspect #1 AND Aspect #2 AND Aspect #3)				
#1	'Indoor Climate*' OR 'Indoor Environment*'	**Pool of publications from the previous decade (1999–2008) = 709** (containing Aspect #1 AND #2 AND #3 in their Topic)		**Pool of publications from most recent decade (2009–2018) = 2427** (containing Aspect #1 AND #2 AND #3 in their Topic)	
#2	Building* OR Hous* OR Home* OR Residence* OR Dwelling OR *Flat* OR Apartment* OR Office* OR School* OR Workplace*				
#3	Human* OR Occupant* OR Resident* OR People* OR Inhabitant*				
Term	Term search (Aspect #1, #2, #3 AND Term #X[a])	Frequency	Occurrence rate	Frequency	Occurrence rate
#1	*Comfort*	193	0.272	914	0.377
#2	*Satisfact*	37	0.052	251	0.103
#3	Productiv*	55	0.078	176	0.073
#4	*Acceptab*	41	0.058	132	0.054
#5	*Health*	284	0.401	881	0.363
#6	Disease*	57	0.080	117	0.048
#7	Mortality OR Morbidity OR 'Death rate*'	30	0.042	57	0.023
#8	Well-being OR Wellbeing OR 'Well Being'	18	0.025	118	0.049
#9	Psycholog* OR Mental* OR Emotion*	18	0.025	96	0.040
#10	'Quality of Life' OR 'Life Quality'	8	0.011	38	0.016
#11	*Pleas* OR *Happy OR *Happiness	3	0.004	30	0.012

[a]The term performance was also considered but excluded as it is particularly prone to bias as it appears in papers using it without relation to occupants but instead to e.g. processes, methods, software (such as '... performance of the tool...' or '.... performing this investigation...').
IEQ: indoor environmental quality.

acoustic comfort though), while IE health has been the focus in the recent decade or two and IE well-being is somewhat new ground. The suggested three-branched conceptual model (Figure 4) intends to build on the existing IE fields, such as the well-established comfort discipline and the growing body of health-related research. Thus, the point of departure for the definition of comfort is well-established existing definitions of IE comfort including discussions of where they overlap, where they differ and how to best interpret this to the new conceptual framework. As there are no widely accepted definitions of IE health, to the best of authors' knowledge, this paper will instead look to the broader general definitions of health and attempt to adapt them to the field of IE. For the well-being domain, the interpretations are almost as many as there are sources. Examples of existing definitions will be listed, and a new definition of well-being is suggested as a positive counterpart to the 'absence of discomfort and ill-health' of the comfort and health domains (Figure 2).

In the search for existing definitions, a wide selection of well-established sources from different disciplines has undergone a cursory examination. This screening was initiated with some of the most influential sources such as specific leading authors, journals, organisations and standards (authoritative sampling or judgement sampling) and then expanding the collection by looking at the most relevant works cited (chain sampling or referral sampling). The sampling purpose and process are illustrated in Figure 5. The differences in source type and discipline tradition make it difficult to set specific requirements for journal impact factor or number of citations. Instead, the selection of sources for each domain was based on the subjective evaluation of a combination of three sampling criteria listed below:

- Clarity and relevance of definition (Consistency of content, Application to IE)
- High impact (International recognition, Extent of influence, Citation count, Impact factor)
- Variation in source type and origin (Type, Discipline, Field of study)

While the number of sources scanned for IE definitions is extensive, source inclusion intends to provide a nuanced discussion within a reasonable space limit. While most major building assessment methods and a large number of the ASHRAE and ISO standards screened are excellent sources of IE knowledge, the combination of the three sampling criteria limits the inclusion to a few sources. Based on a screening of

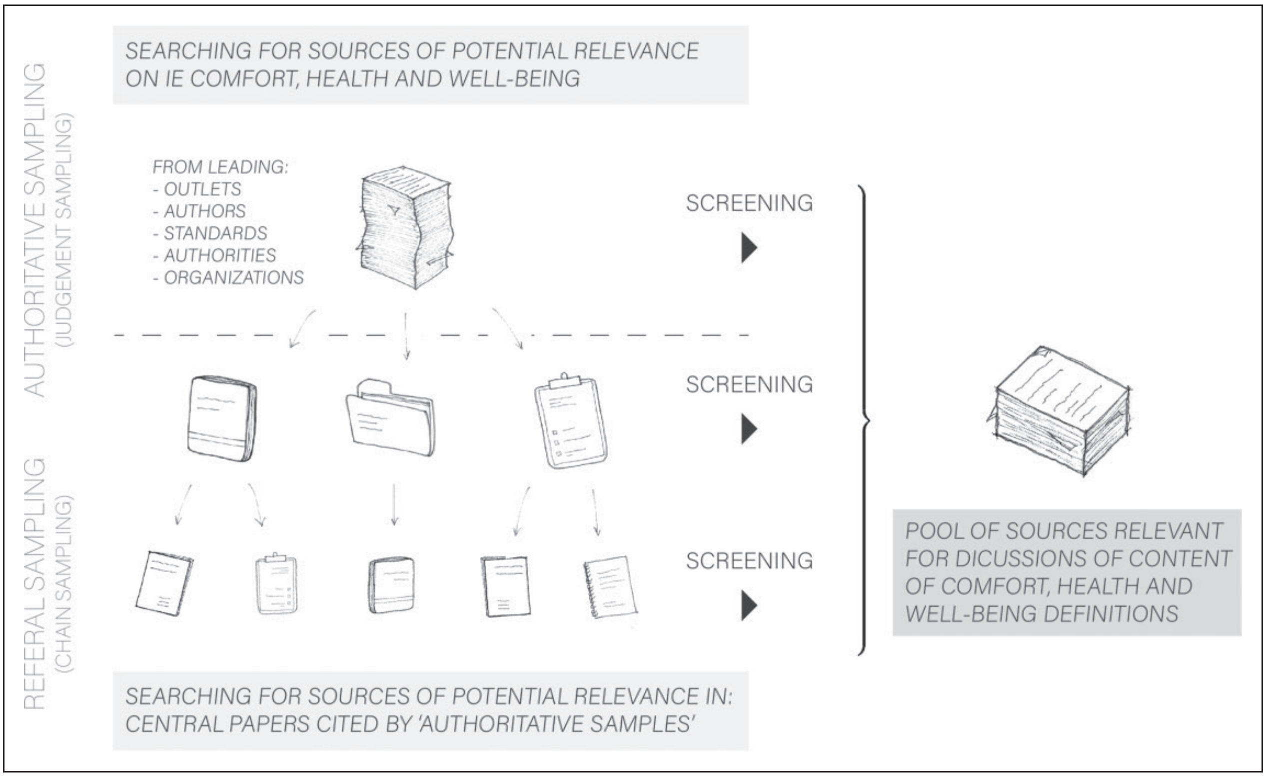

Figure 5. Diagrammatic overview of the sampling procedure, combining authoritative and referral sampling to collect a diverse pool of sources relevant for a discussion of IE domain definitions.
IE: indoor environment.

the selected sources, the most prevalent, significant and clearly stated definitions will contribute to an overview of the topics.

Source overview for the three domains

The third sampling criterion is particularly important to get a sufficiently broad and multidisciplinary perspective on the suggested definitions for the health and well-being domains. To provide a holistic interpretation of IEQ influences on occupants, quantitative studies custom for IEQ research in Engineering and Medicine are complemented by research fields typically associated with qualitative research. The integration of such findings into a causality-based tradition is challenging, yet, as expressed by Koen Steemers[9] in an essay on health and well-being from an architectural design perspective, this gap is already being bridged:

> As we move from the deterministic-medical to the subjective psychological end, the common perception is that the emphasis changes from quantitative to qualitative. However, it is now evident that even within the sphere of subjective parameters, there are emerging methodologies and indicators that can be defined.[9]

For the definitions suggested in the Results section, input was collected from a wide variety of source types. While all three definitions include contributions from peer-reviewed papers (found primarily through Web of Science and PubMed), supplementary sources have different origins. The following section lists non-exhaustive examples of sources that can contribute to each of the three IEQ domains, including both laboratory tests and field studies.

For the comfort domain, the most important sources are national/international standards (here primarily ASHRAE and ISO), legislations tools and green building certifications listing a range of comfort criteria, typically based on climate chamber test studies or field surveys. Also, performance criteria for productivity and satisfaction are found in field studies of office buildings – studies that also include sick building syndrome indicators relevant to the health domain.

A large body of medicinal literature list dose–response relations and health performance indicators, while controlled setting studies explain about cognitive function. Grey literature, including public health research listing physiological health markers, as well as health impact publications and government reports listing statistics for admissions and mortality rates can be excellent sources. Finally, healing architecture field studies list parameters related to 'quality' and 'recovery' relevant for both the health and well-being domains.

Other sources of well-being include controlled setting studies identifying physiological health markers and endocrine markers, and virtual environment stress tests casting light on the integration of cognition and emotion. This is complemented by field studies of both office environments and dwellings indicating factors that are important for 'quality of life'. Finally, various agencies, councils and consortiums have assembled their own 'experts of the field' to suggest scope and content for each of the three domains.

Results: Definition suggestions

As a part of the suggested conceptual model above, the following will present a brief review of the three key terms, showing selected existing definitions and discussing the proposed content of these terms. This process follows a three-step structure:

(I) Comparison of existing definitions of the term
(II) Elaboration of the term coverage (including exemplification of content)
(III) Suggestion for a clear definition (in the light of the suggested three-branched framework)

As mentioned in the Introduction, the process of reaching clear definitions will differ for the three domains depending on their current state of maturity. As specified in the Methodology section, the sources discussed below were selected to give a nuanced discussion within a reasonable space limit.

Comfort

According to Paul and Taylor,[40] IE comfort is concerned with physical/physiological comfort with IE aspects such as visual, thermal, atmospheric and acoustic comfort. The wide range of topics, considered by different professions, complicates making a precise overall definition. One example of an overall comfort definition comes from one of seven concepts of the WELL Building Standard[41] stating that it 'focuses on significantly reducing the most common sources of physiological disruption and irritation and on enhancing acoustic, ergonomic, olfactory and thermal comfort . . .' ('air' and 'light' have separate concepts in this standard). To get closer to the comfort metrics of each IE discipline, the following lists examples from established sources of IE comfort.

Comfort was traditionally concerned with thermal comfort and indoor air quality, based on Fanger's definition of thermal comfort 'the state of mind in which a person expresses satisfaction with the thermal environment'.[1] Recently, the adaptive comfort approach has introduced social, cultural and psychological factors, and expanded the classic definition also to include '... and is assessed by subjective evaluation'.[42] The use of the term satisfaction as a comfort metric is repeated in other comfort definitions, such as 'Satisfaction is the state of feeling that one's needs are fulfilled, by implication, conditions that produce satisfaction or comfort are those that one prefers'.[43] While the metrics for indoor air quality are very different from those of thermal comfort, definitions of acceptable indoor air quality are similarly concerned with user satisfaction, i.e. 'air toward which a substantial majority of occupants express no dissatisfaction concerning odour and sensory irritation...'.[44]

Although historically a separate discipline, acoustic comfort is well established and is included in many leading assessment tools including DGNB, LEED and BREEAM (under the term 'acoustic performance'). While concerns for room acoustics (or architectural acoustics) working with the quality of the sound environment is typically reserved for concert halls and the likes, prevention of noise (classification schemes for sound insulation levels) is part of most national standards for all buildings. One such Greek standard[45] reads 'The acoustic comfort of buildings is the capacity to protect occupants from noise and offer an acoustic environment suitable for the purpose the building is designed for'.

Visual comfort is an emerging field of study, and the list of included metrics differs widely between sources. Most sources agree to address the quantity and quality of light (daylight and artificial lighting) available compared to the given visual task. In non-residential settings, avoiding annoyance from light is equally important including flicker, glare and poor colour rendering of artificial lights, as well as glare from natural light[43] including disability glare, discomfort glare and dazzling glare leading to distraction and irritation.

Restrained activity. One aspect of comfort that is often overlooked is the psychological effects of insufficient privacy, especially relevant in dwellings. Rasmussen[46] lists three concerns of acoustic performance concerning insulation between neighbouring dwellings: 1) absence of unwanted sound, 2) desired sounds with the right level and quality and 3) opportunities for activities without being heard by other people or annoying them. While the first concern is a typical comfort issue, the second concern could include both architectural acoustics and exposure to pleasurable sounds like trickling water or birds chirping (which is treated further in the Well-being section). The third concern is a psychological effect of noise, with long-term adverse physical implications, or as Rasmussen elaborates,[46]

> It is important to observe that acoustical comfort for a person is related to the person not only as a receiver of sound but also as a sound source. Exposure to noise from neighbours can be annoying, but it can be equally annoying to know that one's activities can be heard by other people, implying a lack of privacy.

Acoustic privacy is also crucial in non-residential settings evident in office environment surveys or acoustic screen importance in healing architecture studies.[47] Reduced comfort through compromised privacy is also relevant for olfactory senses (atmospheric comfort) and exposure to views from the outside (visual comfort).

The definitions listed above contain an element of subjectivity (and individuality) where the subject 'expresses satisfaction' or 'expresses no dissatisfaction', using concepts like 'state of mind', 'subjective evaluation', 'feeling' and 'prefer'. This points to comfort being how occupants perceive their IE, meaning physiological implications derived from the mental perception of the physical IE.

(I) Based on the listed definitions, IE comfort implies the fulfilment of 'preventing annoyance' and 'ensuring accommodation'. Some definitions refer to the annoyance aspect such as, 'significantly reducing disruption and irritation', 'no dissatisfaction with respect to ... sensory irritation' and 'protect occupants from'. Other definitions state that IE should accommodate the occupant's use of the space, such as, 'suitable for the purpose the building is designed for', and 'one's needs are fulfilled'. The proposed definition should cover both of these two aspects, with (un)compromised privacy as part of the accommodation aspect.

(II) Based on the reviewed comfort definitions within the four main fields of IEQ (thermal, atmospheric, acoustic and visual) the common denominator is, improving the overall conditions that lead to perceived occupant satisfaction, as well as preventing/reducing factors identified as causes of annoyance.

Suggesting indoor environmental comfort to be defined as

> IE conditions that facilitate a state of satisfaction of bodily wants in occupants, based on their individual preferences and their given activity, and that limit physical stressors causing annoyance.

Health

General definitions of health can be split into three approaches with different views of what constitutes good health. The so-called medicinal model defines health by its absence of diseases and mortality rates. In contrast, the 'holistic model' of health considers health as 'a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity', according to the 1946 WHO definition.[48] The most recently developed approach is the 'wellness model' stating that 'Health is a resource for everyday life, not the objective of living; it is a positive concept, emphasising social and personal resources, as well as physical capacities'.[49]

The evolution of general health definitions is moving towards broader definitions. The main criticism of the deterministic medicinal model is its narrow focus on solving (mainly physical) health issues, and its inability to tackle permanent health conditions such as disabilities, physical impairment, chronic diseases and carriers of fatal genes. However, since those concerns are not relevant for an IE-related definition of health, the medicinal model is well suited for adoption to IE as the logical approach to diagnosing and treating diseases based on objective indicators is fit to identify and sort parameters for healthy IE. The advantages of the more holistic dynamic models are mostly negligible for the purpose at hand, while the disadvantages are many including subjective assessments, vague terminology and a poorly defined approach to the conceptions of health consequences and health determinants. There are noteworthy contributions of the more holistic interpretations of health, however, including the introduction of positive health and resilience,[50] the clear distinction between physical and mental health and the notion of treating health and well-being separately.[51]

IEQ literature contains many examples of IE parameters acting as indicators for diseases and conditions. This research is well developed and has been worked into regulations for years, such as sufficient access to daylight, noise dampening, radon protection and banned substances like asbestos, Polychlorinated biphenyl (PCB) and formaldehyde. Also, in the developed countries, the removal of combustion pollutants such as carbon monoxide and nitrogen dioxide through exhausts and chimneys is mandatory. Other research is still in a stage of suspected cause–effect relations, while some have clear evidence of some substances or pollutants being harmful, but these have been proven challenging to measure and assess. Examples include mechanical vibrations,[52] micro-organisms,[53] VOCs – as well as Very VOCs (VVOCs) and Semi VOCs (SVOCs)[54] – and secondary emissions like ozone-initiated indoor chemistry.[55] In particular, there are many indoor air pollutants of interest from biological pollutants and organic gasses like Toluene and Formaldehyde to inorganic gasses like Ozone, as well as particulate matter, especially the ultrafine particles. The list of hazardous chemicals is increasing, and the body of knowledge on IE parameters with negative health impacts is growing. One particularly ambitious attempt to systemise litterature into a comprehensive structure has been made. The ambition is to map the influence of these IE parameter stressors according to the 11 bodily systems they could influence.[8]

(I) The definition examples above show the difficulty of making an 'all-purpose' general health definition as each one is defined by the critique of its predecessor, i.e. 'absence of disease and mortality' as opposed to 'not merely the absence of disease and mortality'. A similar dissociation lies in breaking away from the static and final 'complete physical, mental and social well-being' towards the more dynamic interpretation of health as a force or resource and 'not the objective of living'. Rather than following this trend of opposition, this paper seeks common ground for the IE health domain.

(II) With a point of departure in the 'absence of disease and mortality rates' approach of the medicinal model, this definition adapts to a cause–effect relation well suited to identify IE parameters acting as stressors of bodily systems. Combining this with holistic health definitions, aspects such as positive health, resilience and restitution should be included.

(III) Based on the reviewed definitions for general health, the appropriate direction for defining IE health lies in the prevention or reduction of disease and condition-causing parameters, while improving conditions for resilience and restitution to mitigate the effect of exposure.

Suggesting indoor environmental health to be defined as:

> IE conditions that promote physical resilience and restitution of occupants, and limit physical stressors causing infirmity, disease and years of potential life lost.

Well-being

As mentioned in the Introduction, well-being receives increased mention in IE literature, but is often merely a synonym for comfort or health or defined as the result of comfort and health combined.[11,21,56] In a well-being overview, Watson[57] argues for a conceptualisation of well-being separated from comfort and health. Sharing that viewpoint, this paper will suggest an objective well-being definition with unique content in relation to other terms and a point of departure in the holistic model presented above (Figure 4). Distinction between physical health (Health domain) and mental health (Well-being domain) in this paper lies in the difference between stressors of bodily systems (immunogenic stimuli) versus the chain of interactions between environmental stimuli, sensory receptors, emotional response and immune system activation (symbolic stimuli from the environment).[58,59]

With the context of IEQ in mind, the focus will be on hedonic well-being covering moods and everyday experiences of happiness, sadness, anger and stress,[60] as opposed to the broader philosophical interpretation deriving from the Greek concept of Eudaimonia. The connection between emotional states and environmental stimuli is strongest with emotions, feelings and affect, which are short-term and specific, compared to the longer-lasting moods and temperaments. A discussion of different positive emotions or nuances between terms like delight, pleasure and flourishing is outside the scope of this paper. Happiness is suggested as a measure for IE well-being as it is clearly a positive mental concept (positive emotion) and works well with the prefix un- (like uncomfortable and unhealthy). This paper uses a psychological interpretation of the term happiness as an emotional or mental state of well-being ranging from contentment to joy.[61]

The Well-being Institute in Cambridge approach well-being from an applied psychology angle, and has reviewed recent mental well-being research for main topics, including, 1) recognising that well-being is more than the absence of ill-being, 2) that it needs to be studied separately and 3) the strong possibility that increased well-being in the population might be a more effective way to fight mental disorders than by focusing on treatment.[38] In continuation, Huppert and So[12] suggests a new framework for defining well-being by positioning it as the positive counterpart to common mental disorders such as depression and anxiety, which corresponds well with the intentions behind Figure 2. The article cites several sources equating the term flourishing with 'a high level of mental well-being and it epitomes mental health', stressing that we should break away from the assumption that the presence of well-being is a natural consequence of the absence of pathology.[12]

For the built environment, The Feeling Good Foundation defines well-being in continuation of the WHO definition of health: 'Spaces that do not reduce and support the wellbeing, of an occupants' emotional, mental and physical state'.[62] Both of these definitions emphasize improving conditions for occupants through positive IE contributions with a focus on emotional and mental health. The challenge is to identify IEQ factors that influence this spectrum, but according to Steemers and Manchanda[21] 'There is a growing evidence that perceptions of control, contact with nature, general pleasantness, are important for the overall well-being of occupants'. The following section is divided into three topics (see Figure 6 at the end of the section), each with a few examples, from the perspective that well-being is defined as:

1. The positive counterpart to IE comfort; first as the presence of positive stimuli for occupant happiness as opposed to the absence of negative stimuli causing annoyance and second as a preference for stimuli variation as opposed to monotony.
2. The positive counterpart to IE health; first as the positive psychological counterpart to physiological stressors and second as mental resilience as a respite from stress.

Positive stimuli and positive emotions. In an extensive review, Ortiz et al.[63] list connections between IEQ and emotions from environmental psychology studies, sick building syndrome research and healthcare designs. IEQ aspects are linked to subject moods through physiological symptoms, cortisol levels, immune regulation, depression, evidence of positive health outcomes, nature restoration theory and attention restoration theory. While avoiding sources of increased stress risk and the resulting negative emotional responses are somewhat addressed in IE literature and practice, the emotional health benefits of positive stimuli leading to positive emotions are mostly overlooked. Frandsen et al.[47] present a literature study on how hospital spaces could affect patient healing, through a combination of stress-reduction and improved well-being, listing documented evidence for a range of IE factors. Examples of positive contributions of that study include maximised sensory impressions including sounds, smells and sight, as well as the particularly well-documented effects of views to natural scenery.[64,65]

Empirical research supports that environmental factors can induce a state of positive affect (PA),[66,67] which is a term used in behavioural sciences to describe people's experience of positive influences such as sensations, emotions and sentiments.[68] People who experience PA feels pleasant, relaxed and happy, resulting in cognitive and behavioural advantages, e.g. more open-minded, improved self-quality and better at coping,[69,70] as well as being linked to increased life expectancy, improved sleep and reduction of stress hormones.[70] The evidence for occupant's emotional responses to the IE, coupled with positive

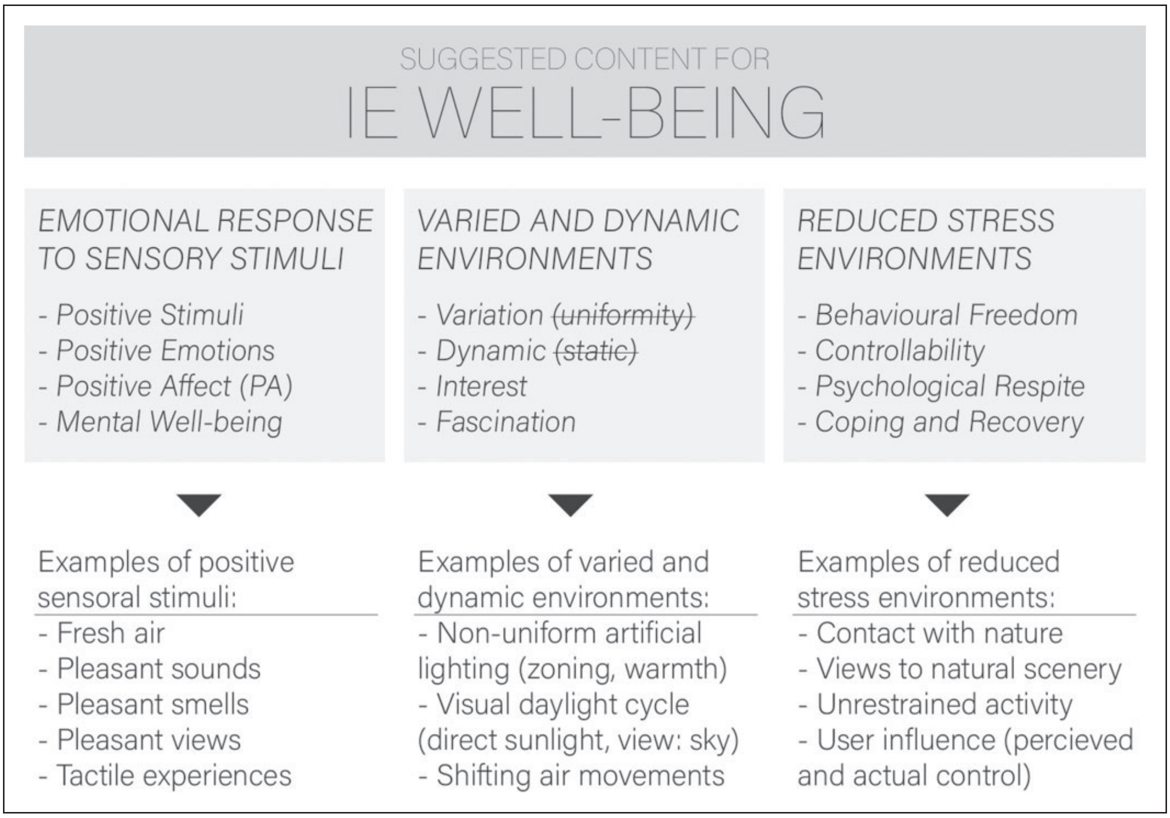

Figure 6. Diagrammatic content summary of the proposed well-being domain, including indoor environmental examples for each of the three suggested topics. IE: indoor environment.

stimuli-induced PA point towards a potential for nurturing positive counterparts to discomfort parameters and bodily stressors.

In a paper on psychological processes in the lighting–behaviour relationship, Veitch[43] writes about IEQ and PA. Veitch[43] refers to experiments by the social and environmental psychologist Robert Baron testing his hypothesis that a state of PA induced by fragrances[67] or lighting[66] can influence cognitive performance and positive social behaviour. These experiments indicate a correlation between occupant well-being and IEQ parameters such as the warmth of light (spectral power distribution) and exposure to pleasant smells.

Another example is Chen and Chang[71] exploring the impact on physiological and state-anxiety well-being, based on experiments of participant response to different window views and the presence of plants. The findings include a hierarchy of physiological and psychological well-being implications for different combinations of window views and indoor plants. Chen and Chang[71] back this by listing several studies showing that visual stimuli from natural scenery induce positive psychological and physiological effects in occupants including, a preference of natural scenery (vs. urban), higher aesthetic responses, an increase in positive psychological stimuli and more positive feelings of well-being.

Interest and fascination. IEQ engineering favours homogenous environments, applying control systems to avoid fluctuating concentrations of pollutants or to improve occupant satisfaction by keeping the thermal environment as constant as possible. However, many studies point to occupants preferring a more dynamic environment.

Both laboratory and field studies of thermal comfort show that perceptible air movement is preferable, not only as thermal compensation in warm conditions but also for its refreshing effect when experiencing cold sensations.[72,73]

For lighting conditions, Veitch[43] lists a series of studies showing that variability and 'interest' are preferable, leaving sufficiently non-uniform luminous conditions to be desired. A similar conclusion is reached in an experiment comparing a standard institutional lighting solution of ceiling mounted lighting fixtures with uniform distribution, to low-hanging pendants creating zones of focused light.[74] Although 'dark corners' resulted in not complying with regulations requiring uniform light distribution, the pendant set-up showed noticeable noise decrease as a result of improved task concentration. The differentiation of light intensity combined with the use of warmer light is the assumed cause of this beneficial effect, as the area of lowered and increased focus is associated with a relaxed atmosphere.

Kaplan[75] argues for the content of outdoor views being vital for 'fascination' (or involuntary attention): 'The environment must have extent. It must, in other words, be rich enough and coherent enough so that it constitutes a whole other world... must be of sufficient scope to engage the mind'. In addition to the much-repeated evidence for natural scenery and greenery noted above, Kaplan[76] notes that windows with access to the sky add information on current weather, clouds and sunset/sunrise. Examples of varied views preferred over monotonous views can be found in the requirements for the LEED criteria Quality Views such as views to different settings ('multiple lines of sight') and content variation in views ('flora/fauna/sky', 'movement' and 'objects at a distance').[77]

Controllability and coping. Occupants actively seek to optimise their interaction with the environment, but as Shin[78] notes 'An individual may feel dissatisfied or uncomfortable if the social and physical constraints of the place are rigid and therefore do not allow a level of modification necessary for optimisation'. Four different modes of behaviour may occur during this interaction (thermal IE examples in parenthesis): 1) environmental modifications (thermostat adjustment), 2) behavioural adaption (lowered activity level), 3) normative adaptions ('seasonal acceptance') and 4) withdrawal (leaving the room). Environmental modifications may be impossible (noise from neighbour's), and withdrawal may be inappropriate, meaning that many everyday stimuli are associated with a lack of control and these threats (in evolutionary terms) start a chain of hormonal reactions activating the fight-or-flight response.[63] This puts a high strain on normative (expectations) and behavioural adaptions, resulting in reduced comfort or restrained activity – or even chronic stress (allostatic load) if all four modes of behaviour fail. Thus, controllability (perceived and actual control) in the shape of environmental choices is vital in reducing stress-related health issues and in improving experiences of comfort and well-being.

Psychoneuro-immunological research has built a biological basis for the mind's role in health and disease, through bidirectional interactions between the brain and the immune system, including the association between negative psychosocial factors (stress, depression) and negative outcomes (morbidity, mortality).[58] Concerning PA, however, Khosla[79] describes a movement away from negative thoughts and behaviours within coping research, towards focusing on positive aspects of life – how emotions and moods improve coping processes. This paper also refers to empirical evidence for PA providing psychological respite shielding against stress and improving post-stress restoration. A wide range of positive affective states influences our coping abilities, including positive emotions and moods, positive experiences in everyday life and sensory pleasure. One such example is the contact with nature associated with both psychological and cognitive benefits,[80,81] such as recovery from stressful experiences[82] and the replenishment of attentional capacity following cognitive fatigue.[75]

The 'broaden-and-build' theory of positive emotions suggests that positive emotions and positive meaning are reciprocal; positive emotions broaden thinking, improving conditions for finding positive meaning in life, while positive meaning triggers positive emotions.[83] This again facilitates coping with adversity, and a positive cycle of strengthened psychological resilience and emotional well-being is built – a mirror image of the depression-causing downward spiral of negative emotions and pessimistic thinking well known in cognitive literature.[84] Thus, access to quality views, plentiful daylight, exposure to direct sunlight, as well as positive experiences of fragrance, sound, tactility, texture, colour, shapes and spatial qualities could induce positive mental states in occupants and thus boosts psychological resilience and reduces the risks of mental health issues.[83]

(I) The definitions discussed have two main things in common: 1) they emphasise emotional and mental health or mental well-being and 2) they focus on positive contributions. The 'Feeling Good Foundation' definition promotes spaces that support 'occupants' emotional, mental and physical state'[62] while the 'Flourishing-definition' explicitly defines itself as the positive counterpart to mental disorders: 'Well-being is seen as lying at the opposite end of a spectrum to the common mental disorders',[12] stressing the need to break away from the assumption that absence of pathology equals presence of well-being.

(II) The definition should include beneficial psychological and mental effects exemplified here by the presence of positive stimuli, controllability in the shape of environmental choices, as well as environments that create interest through variation and dynamics resulting in positive emotional responses. Although non-exhaustive, the list of examples above shows the scope of such stimuli with examples included for sound, smell, spectral and spatial distribution of light, thermal exposure and views to the outside.

(III) Based on the reviewed definitions and examples of IE well-being affecting the mental and emotional health of occupants, the definition should promote a wide range of parameters that are likely to have positive psychological implications for occupants and improve conditions for mental resilience and restitution.

Suggesting indoor environmental well-being to be defined as:

> IE conditions that afford mental resilience and restoration, offer variation, provide controllability and advance positive stimuli to improve occupant happiness.

Discussion

The suggested conceptual framework of definitions for holistic IEQ stresses the need for a multidisciplinary approach. However, this inclusive approach results in well-being parameter examples being a mixture of qualitative studies or context-specific experiments/surveys based on theories and methods borrowed from fields of engineering, medicine, biology, chemistry, neurology, architecture and social sciences. For the suggested model of holistic IE to advance from its current conceptual stage, a substantial research effort will be required to quantify the qualitative positive stimuli and adopt social science tendencies to the evidence-based fields of engineering and medicine. Designing buildings to promote sensory pleasure and experiences of delight to induce positive emotions in everyday life of occupants is not new to the built environment, however. It has been the livelihood of architects for millennia to integrate an interplay of views, materials, light and sound into their compositions, to conceive spaces full of atmosphere creating positive experiences. The novel part is to quantify it and include it in IEQ assessment.

We need an alternative direction for improving occupant's assessment of their IEs. The current practice of improving control leads to higher expectations resulting in increased energy consumption to approach static conditions despite dependency on a dynamic outdoor environment. By following thermal standards, we create a demand for thermal neutrality, instead of a slightly varied environment where occupants can choose a thermal zone that fits their personal preferences, current thermal state and activity. Instead of rewarding increasingly static thermal environments, we should include the occupant's possibility to expose themselves to positive thermal stimuli as an option to improve beyond minimum requirements – moving from not bad to truly good. Allowing occupants to influence their environments, by introducing elements of variation, interest and positive stimuli as preferred by the individual, could be the key to approaching higher occupant satisfaction responses.

Another implication is the potential to map IE parameters and indicators affecting comfort, health and well-being, respectively, by identifying their contributions about the coverage of these suggested definitions. This mapping will enable the prediction of consequences for comfort, health and well-being of occupants from changes in the environment, such as a suggested renovation proposal. If used the other way, it could help identify ideal conditions for optimising IEQ with specific intentions, i.e. targeting a growing amount of conditions caused by stressors of the respiratory system. Furthermore, this overview will enable architects and engineers to design for an IE that is a well-balanced combination of considerations to comfort, health and well-being of occupants by making informed decisions about how the design affects IEQ conditions of occupants.

Conclusion

The review above shows that IE comfort definitions are well established, while the health domain lacks a common definition specific for IE, and there is little consensus on the definition of well-being. This term dilution is addressed through distinct term definitions suggested in this paper, as well as proposed conceptual equality of the three domains promoting the less researched aspects of health, and in particular well-being, to the IE disciplines. The well-being domain is here defined as 1) the positive emotional response counterpart to the neutral or negative stimuli of the comfort domain and 2) the positive psychological counterpart to the physiological stressors of the health domain. This definition results in a holistic interpretation of IEQ, with the introduction of positive stimuli leading to positive emotions, improving mental coping and promoting occupant happiness.

Authors' contribution

The paper was written by LR. The research idea was initiated by LR with structural suggestions by TSL, RLJ and OKL. Revisions of text and figures were performed by LR, TSL, RLJ and OKL. All authors have read and approved the final manuscript.

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2.4. MENTAL HEALTH – A SOCIO-ECONOMIC INCENTIVE FOR WELL-BEING

Nearly two decades ago, the World Health Report presented the consequences of neglecting mental health for both individuals and society (WHO, 2001). Nevertheless, poor mental health such as mental illness, stress, and sleep disturbances is of growing concern globally. As poor mental health also cause increased morbidity risk from physical health issues, arguments have been made for the significance of improving mental health and wellbeing for both physical and mental health benefits (Hallam, Bilsborough, & De Courten, 2018). The connection between indoor environment and positive mental health presented in Paper A indicate a potential to limit mental illness by supporting mental health, promoting restorative opportunities, and providing symptom relief. This approach is in line with the goals of a publication on mental health preventive action by the Danish Health Authority which lists important *preventive* factors, including good conditions for physical health and sleep quality (Sundhedsstyrelsen, 2018).

2.4.1. ECONOMIC CONSEQUENCES OF MENTAL ILLNESS

Even a small potential for IE to influence positive mental health has strong economic incentive as mental health expenses are growing. In 2001 WHO predicted that by 2020 depression would be the second-highest cause of disability in the world (WHO, 2001). According to the WHO Fact sheets, it is now the leading cause affecting 264 million people, with a global economic productivity loss of US$ 1 trillion per year due to depression and anxiety alone (WHO fact sheets, 2019). According to report 'The Global Economic Burden of Non-communicable Diseases' mental illness was estimated at US$ 2,5 trillion and projected to cost over US$ 6 trillion globally by the year 2030 through lost potential and expenses for treatment (World Economic Forum, 2011). This cost level exceeds frequenters of WHO's 'top 10 causes of death' statistics such as cardiovascular disease, and even exceeds the combined cost of chronic respiratory disease, cancer, and diabetes.

In Denmark, mental problems cause half of all long-term absence and early retirement (Danske Regioner, 2009; Vilhelm Borg & Andersen, 2010). A report from 2016 reveal the combined additional yearly costs in Denmark resulting from poor mental health to be DKK 7.1 billion for treatment (from more than 50,000 admissions, 660,000 outpatient visits, and 1.1 million doctor contacts) and DKK 29 billion from lost production (due to 6,000 years of lost life, and 25.7 million days of short and long-term absence) (Statens Institut for Folkesundhed, 2016). In addition, the yearly combined costs for poor sleep adds up to DKK 3.8 billion for treatment and DKK 22 billion from lost production (Statens Institut for Folkesundhed, 2016). This provides a significant economic incentive to improve physical and mental restoration, e.g. by providing appropriate temperature, limiting low-frequency noise, and supporting circadian rhythm. According to field studies on nighttime ventilation, sleep quality can be improved with straightforward measures with immediate positive effects on subject mental state and performance (Strøm-Tejsen, Wargocki, Wyon, & Zukowska, 2014).

2.5. OCCUPANT PERCEPTION AND INTERACTION EFFECTS

Although different indoor environmental disciplines are often researched, designed and assessed separately, there is plenty of evidence for turning towards multi-disciplinary and collaborative efforts. While it is evident that there are many conflicting aspects within the individual fields of IE, such as daylight vs glare, and view out vs view in privacy within visual IE, many regulations and optimisation tools only address parameters in isolation. Overlaps also exist between different disciplines such as between visual IE aspects influencing thermal comfort perceptions, psychologically rather than physiologically. A recent example is studies showing subjective thermal perception to be influenced by the psychological effects of daylight intensity and colour of glazing (G. Chinazzo, Wienold, & Andersen, 2018; Giorgia Chinazzo, Wienold, & Andersen, 2019).

Even built environment aspects that we traditionally perceive to be unrelated to IE evaluations can influence occupant perception and comfort votes (typically researched from an environmental psychology perspective). More systematic knowledge of such interaction between IEQ aspects could increase acceptability of IE or be used to widen control intervals to reduce energy consumption such as for artificial lighting or excess temperature regulation.

The ASHRAE guideline 'Interactions affecting the achievement of acceptable indoor environments', has mapped the available research on interaction effects by categorising them into medicinally inspired interaction types such as synergistic and antagonistic (ASHRAE Guideline 10, 2016). Examples of synergistic interactions from the ASHRAE guideline include the risk of lung cancer being a factor 5 greater by combined exposure to tobacco and asbestos (rather than merely the sum of the two), and subjective warmth increase more due to a combined temperature and humidity increase than a sum of their separate contributions.

The currently available knowledge on interactions between (and among) IE aspects is limited, particularly within acoustic indoor environment. Also, it remains unclear how such correlations could be implemented in future IE standards. Current comfort standards are based on Fanger's PMV model (Fanger, 1970), but as pointed out by de Dear we are unsure how to combine dissatisfaction from multiple sources, even within thermal comfort (e.g. combining PD from local and global comfort) (de Dear, 2004). However, if current and future research on IE interactions is combined in a systematic collaborative framework, it could be a key component in improving the acceptability of both individual aspects and overall IEQ. Specifically, it may provide some answers to why comfort prediction sometimes fail to reflect occupant comfort votes. For the assessment of overall indoor environment the identification and labelling of IE correlations could help inform future holistic assessment methods, on how to combine the contributions of the many separately evaluated factors.

CHAPTER 3. REVIEW OF IE TOOLS IN EARLY DESIGN PROCESSES

The potential impact of IEQ has been presented in Chapter 1, along with arguments for the importance of a holistic perspective. This was followed by a suggested framework for a multidisciplinary holistic IEQ research perspective and proposed definitions for the three vital IEQ aspects; Comfort, Health and Well-being (Chapter 2). This framework, and the listed impacts of IEQ, provide the foundation for the research to improve conditions for high-quality IE in dwellings. There are many ways to support the development of good IEQ in dwellings, including providing for a range of different conditions and actions, both before, during and after the design of the building (see Figure 1). The following chapters will present research from an assessment and design process perspective to promote the realisation of high quality holistic indoor environments. The research supports the development of a new holistic IEQ assessment tool, which aims to produce concrete solutions to the proposed actions in the *Design* category of Figure 1, as well as indirect partial solutions to the *Demand* category.

The design of holistic IEQ requires design proposals that are well-balanced both among IE aspects and with the combined interest of functionality, energy consumption and aesthetics. If building requirements are solved in turn, the design optimisations for an individual parameter may have negative consequences for other vital parameters. This is particularly true for interconnected IEQ aspect, as some building characteristics influence a range of performance aspects. Such characteristics include orientation, volume, surface area, glazed area, construction type, and the choice of components - particularly windows. For instance, rooms with large room heights are not only spatially attractive, but often have favourable conditions for daylight access, air quality, and thermal comfort. On the other hand, conditions for acoustic indoor environment are potentially worsened, as there is an increased risk of excessive reverberation time. Thus, it is crucial to strategically address all the main IEQ categories simultaneously to enable well-informed design decisions. The following section provides a status on how current assessment methods address IEQ aspects, to provide valuable guidance for the design of the new holistic IEQ assessment tool.

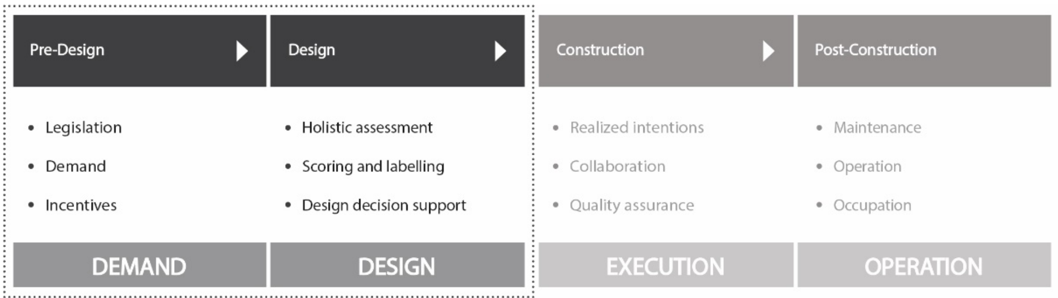

Figure 1 – Overview of how each phase in the creation of a building (top row), require different conditions and actions for realising holistic IEQ (bullets). Each such group of actions are combined into a category of indoor environmental prerequisites (bottom row), of which only the first two are addressed in this dissertation.

3.1. STATUS ON ASSESSMENT METHODS FOR INDOOR ENVIRONMENT

Paper B

"How should assessment methods for Indoor Environment

be designed to facilitate decision support?"

Rohde, L., Jensen, R. L., Larsen, O. K. & Larsen, T. S., How should assessment methods for indoor environment be designed to facilitate decision support?, Architectural Engineering and Design Management (under review).

How should assessment methods for indoor environment be designed to facilitate decision support?

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ABSTRACT

This paper seeks to improve conditions for the design of good indoor environment (IE) in dwellings based on a critical analysis of current practice. Methodologically this includes four steps; 1) reviewing existing literature on assessment methods for key topics; 2) linking topics to specific stakeholders and design actions by categorizing them to different project stages; 3) analyzing five major sustainable building certification systems to identify the potentials and limitations of these; 4) making recommendations for the design of future assessment methods. Certification system analysis contains an in-depth investigation of both qualitative and quantitative aspects. The quantitative part includes comparisons between overall certification structure, IE content, and weighting consistency. The qualitative part investigates whether the certifications promote the design of high-quality IE by supporting building owners and design teams with specific tasks at key project stages. Results reveal that the certifications analysed are insufficiently equipped to 1) further dialogue between different stakeholders, 2) accommodate design team demands in the early design stages, and 3) disseminate results on different levels of aggregation. Future assessment methods are recommended to accommodate these demands by implementing four new facilitating modules; Dialogue, Calculation, Design, and Communication.

KEYWORDS building rating system; assessment tool; decision-making; design process; occupant comfort; occupant health; residential; dwelling

Introduction

The EPBD directives of 2002 and 2010 have made energy performance certificates mandatory (Council of the European Union 2002; The Council of the European Union 2010), resulting in a dominating energy-consumption focus in all building phases. With no occupant-centred mandatory counterpart, there is a risk that this energy-focus has consequences for the design of a good indoor environment (IE) (Mortensen et al. 2018; Rohde et al. 2019b).

The research and development project REBUS (REBUS 2016) is developing an indoor environmental quality (IEQ) assessment tool called IV20 (Larsen et al. 2019), which is working to implement the findings of this paper. To support the development of IV20 the quantitative analysis of content and weightings in this paper focus on IEQ in multi-story dwellings in a temperate climate. The recommendations for future assessment methods presented in this paper are however considered applicable to all building-related environmental aspects and any building type.

The first generation of environmental assessment methods has been widely used in the built environment for the last two to three decades. While most of the second generation methods include all three pillars of sustainability and have transitioned towards a top-down approach (Lützkendorf et al. 2011), the social aspect including IE remains overshadowed by the predominant focus on environmental sustainability. Also, energy aspects dominate the available strategies and tools for early project assessment and decision-support tools (Abdul Hamid et al. 2018; Catalina and Iordache 2012; Ferreira et al. 2013). Topic-specific tools have been tailored to measure environmental performance or improve economic sustainability, but social values assessments remain less developed, and only a few widely used tools are explicitly developed for IE (Thuvander et al. 2012; Zuo and Zhao 2014).

It is well-documented that the ability to impact functionality and performance in building design is higher and less costly in the early design stages (Bragança et al. 2014; Kovacic and Zoller 2015). Concerning IE, the earlier IEQ aspects are introduced; the better conditions will be for well-integrated, cost-effective solutions towards great IEQ (Brager 2013).

The importance of tools applicable to early design stages had been addressed previously (Jrade and Jalaei 2013; Markelj et al. 2014; Oti and Tizani 2015), concluding that current assessment methods are often not applicable for this purpose. If the assessment methods rely on detailed design information before it is available, then the method is incompatible with the conceptual phases of the design (Andrade and Bragança 2016; Ding 2008). From a design perspective comprehensive assessment methods are passive tools (no user interaction) that at best influence decision making indirectly (IEA Annex 31 2001), while according to Baldwin et al. (Baldwin et al. 2000), interactive tools “provide calculation and evaluation methods which enable the user or decision-maker to take a pro-active approach (to explore a range of options in an interactive way)”. If possible, future tools should include active elements to directly influence design developments (guidance, exploration, comparison) in addition to post-design assessment (benchmarking, labelling, validation). In addition to making the tools operational in the early design stages, there is great potential for improvement in many areas of what, how and when IE aspects are addressed.

This paper identifies aspects of importance derived from existing literature on assessment methods and combines these with an investigation of stakeholder actions at different stages in the creation of buildings (RIBA 2013). This leads to a qualitative analysis of leading assessment methods to identify differences and overlaps in the identified aspects, supported by the key findings of a quantitative analysis on content, structure. Based on the literature reviewed and analysis presented, this paper provides recommendations for next-generation assessment methods for key stages of planning, designing, and communicating good IE.

Methodology

This paper categorises a collection of recommendations from previous literature on first and second-generation assessment methods. Current leading assessment methods are compared on IEQ topics and investigated to check whether they satisfy the identified recommendations. Several articles have previously compared building assessment methods, from perspectives such as Environmental/Social/Economic content balance (Doan et al. 2017; Gu et al. 2006; Illankoon et al. 2017; Jensen and Birgisdóttir 2018; Superbuildings 2010); Criteria consensus (Alyami and Rezgui 2012); Phases of life cycle included (Doan et al. 2017); 'Purpose, Use, and Users' (Gu et al. 2006) or all of the above (Andrade and Bragança 2016; Haapio and Viitaniemi 2008). Also, a recently published paper has made a detailed comparison Visual comfort assessments in widely used tools (Giarma et al. 2017). The investigation presented in this paper combines criteria consensus checks for both Visual, Acoustic, Thermal and IEQ content specifically for dwellings, as well as comparison of relative IEQ weights. Also, assessment methods are investigated from a functionality perspective, assessing their ability to support practitioners in promoting the design of good IEQ. Finally, this paper differs from previous research, by including two less established but expanding assessment methods (the WELL and LBC certifications systems).

It is common practice that new assessment methods build on previous initiatives (Cole 2006), but some risks are involved in relying on developed methods including the selection of aspects (as context and purpose might differ), and the risk that it may deter innovative ideas (Malmqvist 2008). To avoid these pitfalls, this paper analyses current leading assessment methods on topics based on 1) identified relevant project stages, 2) recommendations from previous analyses on assessment methods and 3) context and purpose for the development of a new tool for IEQ assessment (IV20).

The RIBA Plan of Work Overview (RIBA 2013) divides a building project into eight successive project stages, including objectives and tasks for different stakeholders at each stage. This paper is concerned with the early project phases influencing the *design* of good IEQ, as opposed to the *realisation* of good IEQ, which would also include construction, observation and occupancy. The design-influencing project stages are: 0 Strategic Definition, 1 Preparation and Brief, 2 Concept Design, 3 Developed Design and 4 Technical Design (Fig. 1).

This paper will identify critical tasks for the development of design-influencing assessment tools at each project stage, building on the realization that 'The full potential for positive change, owing to stakeholders understanding their respective spheres of influence, can only be realised fully, if the assessment system meets the needs of all those who come into contact with it.' (Lützkendorf et al. 2011).

Topics for investigation

The assessment methods are investigated in two ways. First, through a quantitative analysis on Content, Structure and Weightings (Topic 1-3) presenting the main findings from a technical report made as a supplement to this paper (Rohde et al. 2019a). Secondly, through a qualitative analysis based on the collected experiences from the development of previous assessment methods and conclusions on analysis of first and second-generation assessment methods (Topic 4-7). The qualitative topics have been gathered from literature that declares both limitations of existing methods, recommendations for future methods, and key aspects/purposes for assessments methods in general (Cole 1998, 1999, 2005; Lützkendorf et al. 2011). Topics have been categorised by the project phase and condensed into eight points of influence (EPI) as depicted in Figure 1. The EPI represent eight desired functionalities for assessment tools and is used to guide the qualitative analysis of assessment methods presented in the Results section.

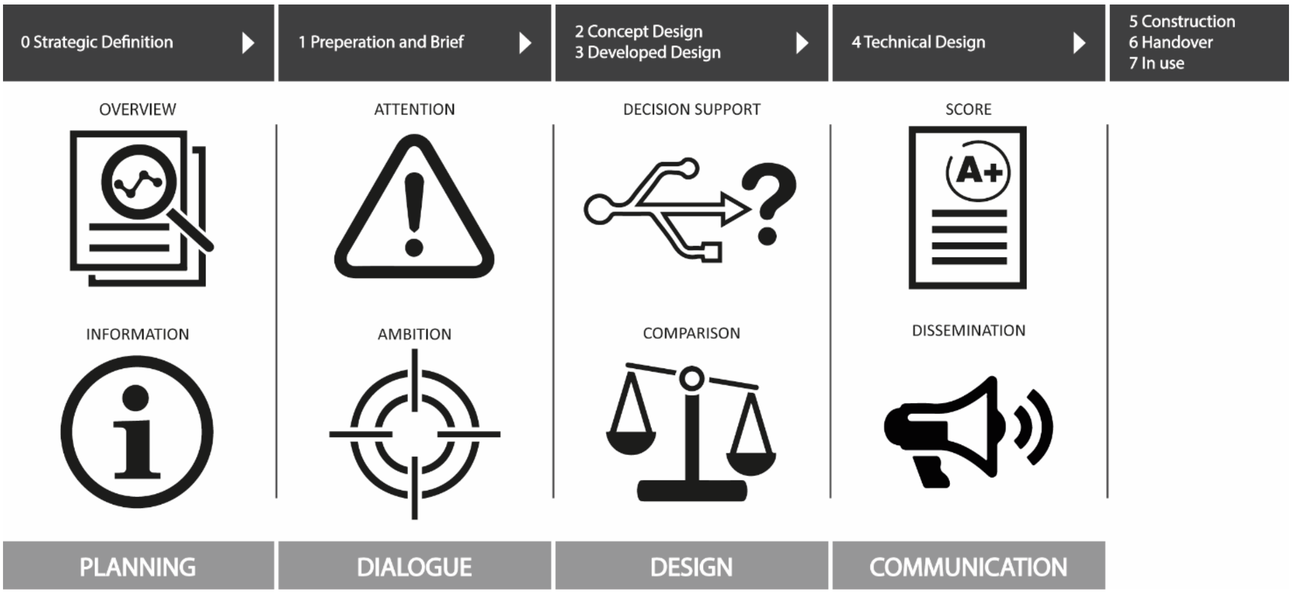


Fig. 1. Eight points of influence (EPI) identified as key aspects for future assessment methods, listed chronologically by project phase (RIBA Plan of Work Overview, black bar). The EPI are paired into four overall tasks for improving conditions for informed design work (grey bar).

Quantitative analysis

The certification schemes investigated for BREEAM, LEED and DGNB (see 'Assessment methods investigated' below) have been designed for, or adapted to, the assessment of dwellings. As a result, some criteria have been excluded compared to the assessment of other building types within that certification family. Reasons for criteria exclusion include criteria considered to be 'inapplicable', 'of limited importance' or 'too expensive' for the assessment of dwellings. Specific examples of certifications manuals excluding criteria for dwellings include 'view out' (BREEAM), post-construction IEQ measurements (BREEAM), reverberation time (BREEAM), glare (BREEAM and DGNB), and electric lights (DGNB). The LEED for Homes v4 certification scheme, which is recommended to access dwellings using LEED (Private communication 2018), has excluded thermal, acoustic and visual IE main areas entirely, compared to inclusive schemes such as LEED New Construction. The analysis has been performed using the credit library of LEED for Homes, but criteria content will be indicated in parenthesis for LEED New Construction to indicate the significant differences between the two schemes. WELL and LBC certifications cover all project types and do no distinguish criteria. For all certifications investigated, the authors have excluded criteria not relevant in a (Danish) residential context, including criteria related to requirements for furnishings and supplementary electric lighting, for which the occupants are responsible. Also, 'workplace criteria' such as specific requirements for workstations, cleaning protocols, smoking bans, sound masking and thermal zoning have been excluded from this comparison. For more information on the comparison procedure and the adaption of certifications to assessment of dwellings refer to (Rohde et al. 2019a).

TOPIC 1 - CONTENT

IE criteria are renamed and categorised into five main IE categories to ease cross-certification comparison, followed by a short discussion on content inconsistencies. This overview followed by a brief account on which assessment methods include mandatory criteria.

TOPIC 2 - STRUCTURE

Shows the 'architecture' of each method, by listing the levels of aggregation used in the assessment along with an overview of the application of weights, scoring and labelling.

TOPIC 3 - WEIGHTINGS

The weighting topic covers two simple IE weighting indexes. The first index (1) shows the combined influence of IE topics on the total certification score – indicating the level of IE priority of each method at a glance:

(1)

$$\text{IE content vs overall certification index} = \frac{\sum(\text{all IE topics}_{\text{max score}} \times \text{weight factors})}{\sum(\text{all topics}_{\text{max score}} \times \text{weight factors})}$$

The second index (2) calculates the relative influence of the four main IE categories and a fifth 'user influence' category:

(2)

$$\text{Relative influence of main category index} = \frac{\sum(\text{single IE topic}_{\text{max score}} \times \text{weight factors})}{\sum(\text{all IE topics}_{\text{max score}} \times \text{weight factors})}$$

Results are compared to existing literature indicating no consensus on weightings between methods (Andrade and Bragança 2016; Frontczak et al. 2012; Jensen and Birgisdóttir 2018).

Qualitative analysis

As all assessment methods prioritise criteria, they are used by design teams and building owners to guide project planning and early-stage decisions. However, without being developed for that purpose, there is a risk that design teams revert to a simple 'point-chasing' strategy to accommodate certification level requirements set by the building owners rather than experimenting with project-specific design proposals (Cole 1999, 2005). The risk of point-chasing makes it vital that credits awarded are balanced based on the final endpoint (Todd 1996) (here the influence on occupants) rather than skewing weights to match political ambitions for a specific topic or scaling to reflect increasing costs for above-par performance.

TOPIC 4 - PLANNING

Assessment methods structured as a series of disconnected indicator optimisations will lead to single-parameter symptom treatment. For instance, too high summer temperatures caused by extensive glazing may be solved by blinds or tinted windows; blocking access to daylight and views. Early-stage interventions include external solar shading, different facade orientation or overall building design adaptions with less negative impact on cost or IEQ performance. Point chasing can be prevented by guiding early project planning by structuring input, assessment, scoring and labelling to emphasise the connections between criteria. A holistic assessment can increase awareness of compromises between aspects by indicating the combined influence on the common final endpoint (here: occupants).

Overview Concerning overview, the tool should:

- structure information in a coherent and comprehensible manner; and
- provide a common language between the design development participants.

The assessment method should provide an overview of the content and structure of the assessment that is easy to read for all stakeholders. This overview should show all IEQ criteria, including a brief (non-specialist) description of their influence on occupants and an indication of their influence on the overall assessment.

Information Concerning information, the tool should:

- establish a body of knowledge and expertise within the design team and the building industry; and
- facilitate and enhance communication among and between stakeholders.

Once the overview has been established, the material should give immediate access to precise descriptions of individual parameters with references to literature and international standards on assessment type, scoring, criteria weights, and influence on occupants.

TOPIC 5 - DIALOGUE

When used as planning tools, comprehensive assessment methods influence the content, priorities and timing of design team considerations. A well-designed tool should provide a platform to further dialogue between stakeholders, and ensure that building owners and design teams establish a shared vision of the project.

Attention Concerning attention, the tool should:

- collect detailed building information to perform assessment and explain expected performance; and
- identify project potentials and limitations to provide design criteria for design teams.

The assessment method should assist design teams in identifying challenges or areas of high potential through a preliminary investigation. For renovation projects, this means assessing the existing building and site conditions to use a point of departure for later design explorations. This investigation indicates 'the low-hanging fruits', and provides a baseline to use for setting the ambition level of the renovation. For new construction, the preliminary assessment can help identify the potentials and limitations of the site, which can guide the overall design approach.

Ambition Concerning ambition, the tool should:

- allow building owners to set 'higher than standard' ambitions, and demands; and
- promote dialogue on including realistic aims and objectives in the project brief.

With the results of the preliminary investigation, the client and design team can make use of the common understanding of IEQ to engage in a goal-setting dialogue about the desired IEQ level. Flexible goal setting will allow clients to raise the bar for performance within a specific topic or sub-topic.

TOPIC 6 - DESIGN

Building professionals agree that practice suffers from insufficient (or too late) integration of different stakeholders (Thuvander et al. 2012), although it is common accepted that the early design stages have the most significant potential impact on final performance (Brager 2013). An assessment method that accommodates holistic thinking and integrates different stakeholders in the early project phases could improve final performance while keeping costs low.

With the benefits of early implementation in mind, the assessment methodologies are compared with a short discussion of potentials and limitations. Operational evaluations are a prerequisite of early implementation influenced by aspects such as the following.

- In-data requirements (amount, precision)
- In-data collection type (manual, intelligent, automated/BIM)
- Assessment type (checklist, calculation, simulation, measurement, survey)
- Time consumption for operation/verification, and
- Specialist requirements for operation/verification

Decision-support Concerning decision-support, the tool should:

- process a higher detail level than required for regular assessments using information accessible during design;
- quickly predict and visualise performance and guide design strategies to improve it; and
- promote decision-making by linking design criteria and engaging stakeholder interests.

Once the goal setting is in place, the assessment method should guide the design team towards appropriate design choices during the design exploration by predicting the expected performance based on a range of input variations and by presenting this information to the design team in a useful way.

It is important to note that the tool should not generate design suggestions, but rather show the potential IEQ performance consequences of a given design strategy suggested by the design team.

Comparison Concerning comparison, the tool should:

- compare alternative design strategies to facilitate timely decisions by the design team and clients;
- highlight priority issues and suggest the possible trade-offs between options; and
- generate nuanced evaluations that enable comparisons on several levels.

Assessment methods should implement a nuanced evaluation of the criteria whenever possible, so that design teams can get more accurate feedback and choose better solutions from a holistic perspective. Assessments should allow for comparisons of:

- criterion relative to benchmark (goal);
- criterion with another criterion in the same assessment (compromise);
- criterion with the same criterion in another assessment (compare); and
- overall score with other buildings (label)

Graphical representation of before/after comparisons and differences between design alternatives should be implemented directly into the tool. This will improve functionality for design teams, enable informed design compromises, and improve collaboration with other stakeholders.

TOPIC 7 - COMMUNICATION

Result dissemination should be designed for individual stakeholder preferences (Lupíšek et al. 2010; Lützkendorf et al. 2011; Thuvander et al. 2012). Preferences for result detail level vary from individual results (sub-topics and un-assessed project info: researchers, academics, architects), to partially aggregated (topic group: contractors, facility managers, clients), and fully aggregated (label: authorities and users) (Lupíšek et al. 2010; Lützkendorf et al. 2011). As the methods used to depict results directly affects how results are understood and by whom (Gann et al. 2003), effective communication requires consideration of the presentation style preferred by individual stakeholder groups.

The conflicting interests when accommodating both scientific relevance and wide dissemination (Malmqvist 2008), should be addressed through hierarchically structured information levels (nesting principle), graphical interpretation of results, and specific suggestions for project improvements.

Scoring Concerning scoring, the tool should:

- provide a comprehensive graphic display of performance that signals progress relative to declared ambitions;
- offer different levels of assessment output that enables selective scrutiny of sub-areas; and
- be able to assess and rank both completed buildings and evolving designs.

The assessment should result in an IEQ performance score that can be used to rank the project and to match it with the intended goals. The scoring of overall IEQ should be based on the contributions from subareas in a structure that logically connects successive detail levels, including transparent score allocations. If this hierarchical tree structure is made visible in the scoring, the transparency of the evaluation is improved.

Dissemination Concerning dissemination, the tool should:

- offer design feedback by linking performance back to its cause (link to cause);
- guide remedial work by linking with information to improve on deficient performance (link to action); and
- provide building owners with a means to explain building qualities to prospective occupants

A flexible communication strategy is required to match the requirements of different stakeholder groups on the detail level, terminology, and presentation style. Important dissemination tasks include linking performance to design criteria, suggesting areas of improvement, and explaining the influence on occupants. The results should become a platform for a dialogue between buildings owners and other parties such as occupants (inherent building qualities as a selling point), design teams (link to cause, link to action), and the public (social responsibility, topic awareness).

Assessment methods investigated

Development of the IV20 tool intends to promote IEQ in deep renovation of social housing in Denmark, specifically by assessing the potential IEQ before and after a renovation. The IV20 tool is developed based on the following premises:

- Context: *Multi-storey residences in a temperate climate.*
- Content: *holistic IE - thermal, visual, acoustic, IAQ; comfort, health, and user interaction.*
- Functionality: *Status determination, labelling, design proposal evaluation.*
- Operational: *Low cost, fast and easy to use*.

Five assessment methods were selected for analysis in this paper to cover the most widely used certification systems relevant to the context and purpose stated above. The chosen methods meet the following inclusion criteria:

- they assess indoor environmental quality;
- they can be applied to assess dwellings; and
- they are well-recognised internationally.

While the assessment methods differ in both methodology, standards applied, and documentation requirements, the most crucial differences originate from the aspirations of the individual certification standards, expressing itself in the content and weightings contained. A moderate range of methods was selected to allow for greater depth of analysis. Brief arguments for selection of each tool is given below:

- Building Research Establishment Environmental Assessment Method (BREEAM) was the first widely used sustainable building certification developed greatly influencing subsequent tools.
- Leadership in Energy and Environmental Design (LEED) is currently world-leading and has increased focus on IEQ topics compared to BREEAM.
- Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) aims to be 'a human-centred assessment tool' with equal focus on all three pillars of sustainability (United Nations 1992).
- WELL is a comprehensive social sustainability-only standard that is designed for dual certification with environmentally focused standards such as LEED and BREEAM.
- Living Building Challenge (LBC) is a visionary certification standard aiming for buildings to create positive impacts on both occupants and the local and global environment.

Assessment methods are selected to be a good representation of the available methods from perspectives such as history, coverage, IE focus, and innovation. Basic tool facts are presented in table 1, refer to (Rohde et al. 2019a) for a more extensive introduction of each tool.

The analysis of each assessment method is primarily based on the information available in official manuals and official certification websites. Both scientific and non-scientific articles have been used as supplementary sources.

Results

The results section is divided into the seven topics of investigation presented in the Methodology section. Topic 1-3 cover the quantitative analysis, presenting the main results from the supporting technical report (Rohde et al. 2019a) in tables and figures. The qualitative analysis contains analysis topic 4-7, each of which is split into two subsections corresponding to the eight points of influence presented in Figure 1.

Table 1. Overview of the five certification systems selected for analysis in this paper.

Acronym / Full Name	Version Analysed	Institute / Origin / Certification launch	Certifications in Total	Main Topics and Purpose
BREEAM / Building Research Establishment Environmental Assessment Method	BREEAM International New Construction 2016 (fully-fitted dwellings) (BRE 2017)	BRE - Building Research Establishment (1921) / United Kingdom / 1990	> 566,000 certifications [a] / 80 countries	- BREEAM was the first sustainable building certification developed and is widely accepted to have influenced most major systems developed since, such as LEED, Green Star, and CASBEE. - BREEAM is a criteria-based tool that assesses building performance on set target values for criteria with varying allocation of points. - BREEAM addresses a wide scope of topics but primarily focuses on environmental and energy-related aspects, on both content amount and assigned category weights.
LEED / Leadership in Energy and Environmental Design	LEED for Homes v4 (USGBC 2019)	USGBC - US Green Building Council (1993) / USA / 1998	> 94,000 projects [b] (> 40,000 certified) / 600 million m^2 [c] / 165 countries	- LEED is a criteria-based certification system that uses a simple checklist format to compare building performance to predefined standards. - LEED assess buildings on a point-based system with varying amounts of credits, rather than applying weights. - LEED addresses five areas of sustainability, but with the main focus on environmental and energy-rated aspects.
DGNB / Deutsche Gesellschaft für Nachhaltiges Bauen	DGNB System - New buildings criteria set - version 2018 (DGNB 2018)	DGNB – German Sustainable Building Council (2007) / Germany / 2007	> 2,200 projects (certified and precertified) [d] / 61.7 million m^2 / 21 countries	- DGNB gives the three pillars of sustainability, equal consideration (and weight) and is very human-centred (compared to BREEAM or LEED). - DGNB is a criteria-based tool built on European Union standards that evaluates a building based on a total performance index, capped by a minimum performance index for each category. - DGNB also address the three cross-category aspects of technical, functional and process-quality, to ensure that the finished product has a high-quality standard.
WELL	WELL v2 Pilot (IWBI 2019)	IWBI - International Well-building Institute (2013) / USA / 2013	1,280 projects [e] (1,137 registered and 143 certified) / 24.7 million m^2 / 43 countries	- WELL is the first certification standard focused exclusively on occupant health and wellbeing (no credits for resource conservation), and is very concerned with the building in a running state. - WELL is a very flexible criteria-based tool that accommodates different approaches to building performance within a given topic. - WELL, addresses 'all' traditional IE aspects, with a vigilant focus on chemicals in materials, as well as a holistic biological focus of body (movement, nourishment, water) and mind (community, mind).
LBC / Living Building Challenge	Living Building Challenge Standard 3.1 (ILFI 2016, 2017)	International Living Future Institute (2009) / USA / 2010	380 projects [f] (317 registered and 73 certified – of which 15 achieved Living Certification) / 23 countries	- LBC is a certification standard focused on improving occupant health and wellbeing, supporting local communities/environments, and conserving planet resources. - LBC does not use points, weights or scores but is built on a list of imperatives that must be fulfilled to achieve certification. - LBC certification is difficult to achieve due to the mandatory nature of all topics; a rigours in-use documentation and a long list of banned materials and chemicals.

[I] https://www.breeam.com/ #certifications, #countries (accessed January 2019)
[b] https://new.usgbc.org/leed #projects, #countries (accessed January 2019)
[c] https://www.usgbc.org/articles/us-green-building-council-releases-annual-top-10-states-leed-green-building-capita #m2 (per January 2018)
[d] https://www.dgnb-system.de/en/current_issues/press-releases/2017/dgnb-witnesses-record-number-of-certifications #certifications, #m2, #countries (per September 2017)
[e] https://www.wellcertified.com/en/articles/iwbi-launches-well-v2 #certifications, #m2, #countries (accessed January 2019)
[f] https://living-future.org/contact-us/faq/ #certifications, #countries (per May 2017)

TOPIC 1 - CONTENT

Table 2 shows a content overview for each tool, grouped into five main IE categories: Thermal, Air Quality, Visual, Acoustic and User Influence. The listed content has been regrouped and renamed to allow cross-certification comparisons (Rohde et al. 2019a).

Table 2. Content overview of the five certifications regrouped into five IE categories: Thermal IE, IAQ, Visual IE, Acoustic IE, and User influence.

Thermal		BREEAM	LEED	DGNB	WELL	LBC
Operative temperature	Operative temperature (winter/summer)	x	(x)	x	**X**	
Cooling	Cooling/air conditioning (precautions concerning drafts and humidity)	x		x	x	
Draft	Drafts (winter and summer)	x	(x)	x	**X**	
Radiant temperature	Radiant temperature asymmetry and floor temperatures (winter/summer)	x	(x)	x	**X**	
Monitoring	Monitor thermal parameters (dry-bulb temp, relative humidity, air speed)				**X**	**X**
Rel. Humidity	Humidity control (relative humidity within set intervals)			x	x	
IAQ		BREEAM	LEED	DGNB	WELL	LBC
Vent. Rates (quantity)	Ventilation rate (quantity, air distribution strategy, intake/exhaust position)	x	**X**	x	**X**	**X**
Filtration	Air filtration (standards for installed filters, commissioning)	x	**X**	x	x	
Pollution mapping	Particle pollution maps (and optionally radon concentration maps)			x		
Air quality test: Organic gasses	Threshold levels for VOCs and Formaldehyde			x	**X**	**X**
Air quality test: Other	Thresholds for inorganic gasses and particulate matter (and others)		**X**		**X**	**X**
Pollutant monitoring	Monitoring of indoor air pollutants	x	**X**		**X**	**X**
Emission control	Emission control (VOCs, SVOCs, formaldehyde)	x	x	x	x	**X**
Humidity control/inspection	Humidity controlled vent. (shower), or condensation & mould management		x		x	
Envelope/entryways	Envelope and entryways (walk-off systems, entryway air seals)		x		x	**X**
Reduce pollution: construction	Pollution from construction work (duct sealing, filter replacing, flushing)				**X**	
Reduce pollution: combustion	Pollution from combustion-processes (fireplaces, boilers, heaters etc.)		**X**		x	
Reduced pollution: uncontrolled pathways	Envelope sealing to minimise uncontrolled pathways for pollutants (leakage sealing, blower door test, reducing pollutants from the garage)		**X**			
Visual		BREEAM	LEED	DGNB	WELL	LBC
Daylight (quantity)	Daylight (quantity)	x	(x)	x	**X**	**X**
Daylight (distribution)	Daylight (distribution)	x	(x)	x	**X**	
Daylight (quality)	Daylight (color rendering (Ra), or visual balance/brightness management)			x	x	
Sunlight/Daylight exposure	Sunlight/Daylight exposure (quantity - as a positive contribution)			x		*
Electrical light (quantity)	Electrical light (quantity)	x			x	
Electrical light (quality)	Electrical light (quality - colour, flicker, uniformity, circadian rhythm etc.)	x	(x)		x	
Electrical light (glare)	Electrical light (glare)	x			x	
View out (quantity, access)	View out (quantity - access to view, view angle)		(x)	x	x	*
View out (shading obstruction)	View out (obstruction from solar shading, worst case)		(x)	x		
Acoustic		BREEAM	LEED	DGNB	WELL	LBC
Airborne sound	Sound insulation levels (noise from traffic, neighbours, other indoor rooms)	x	(x)	x	x	
Impact sound	Impact sound (floors, stairs and balconies)	x	(x)	x		
Reverberation time	Reverberation time (inside dwelling)		(x)		x	
Background noise	Background noise (HVAC, external noise intrusion)		(x)		**X**	
Privacy and Zoning	Privacy and Zoning (internal walls, bedrooms, loud/quiet/mixed zones)				**X**	
Noise measurement/mapping	Ambient noise measurements, or the use of existing noise maps			x		
User Influence		BREEAM	LEED	DGNB	WELL	LBC
Ventilation boost	Forced ventilation rate in rooms with dynamic people loads (easy to use)			x		
Ventilation regulation	Regulation of ventilation on room level			x		
Operable windows	Operable windows (manual, or mechanical with override)	x			x	**X**
Temperature regulation	Adjustable temperatures on room level	x	x	x	x	
Electrical light controls	Controllable electric lights (dampening, extra intensity, color adjustment)	x	(x)		x	
Electrical light automation	Automation of electric lights (circadian and visual requirements)				x	
Shading adjust. (view out)	Adjustable external solar shading to accommodate view out			x		

Note: x = content included **X** = content mandatory () = content included in LEED New Construction

_ = expanded in technical report (Rohde et al. 2019a) * = included indirectly through 'BiophilicEnvironment'

From a content-perspective LEED for Homes and LBC are inappropriate for assessment of overall IEQ in dwellings, as they have major shortcomings in all categories except for Air Quality. LEED for Homes does not assess the three categories of Thermal, Visual and Acoustic (although included for other LEED project types), while LBC lacks Thermal (except for monitoring) and Acoustics. DGNB and WELL have good coverage of the main IE categories. BREEAM has decent coverage, with some lacks including air quality tests (organic gasses), daylight quality, view out (access), and initiatives to avoid humidity issues.

Several aspects only appear in a single certification, such as the IAQ initiatives: Pollution mapping (DGNB), Reduced pollution: Construction (WELL), and Reduced pollution: Uncontrolled pathways (LEED). For Visual content, DGNB is unique in covering Sunlight/Daylight exposure and View out: shading obstruction. For Acoustic aspects, DGNB is the only one covering Noise mapping (DGNB), while WELL alone handles Reverberation time, Privacy and Zoning, and Background noise. Also, View out quality (positive view content, and absence of colour balance distortion), and View in (risk of annoyance and reduced privacy from exposure to view from the outside) are entirely absent across all five assessment methods.

Several certifications dictate the fulfilment of selected mandatory criteria. Within IE this is mostly the case for LEED (IAQ) and WELL (all main IE categories), as shown in bold in Table 2. For LBC all criteria are mandatory.

TOPIC 2 - STRUCTURE

Certification systems vary in aggregation structure and scoring, as apparent from Table 3, which shows aggregation levels for the certifications analysed. The table provides, at a glance, information on topics, weighting factors, point ranges and certification levels, with IE-specific numbers shown with a grey highlight.

TOPIC 3 - WEIGHTINGS

Table 4 lists the main categories containing IE topics along with the listed category weights for each certification. The far-right column shows the combined overall IE content weight for each scheme, calculated as a corrected weight percentage, after purging for content not relevant for IEQ in dwellings (as described in the Methodology section). This comparison indicates the extent that IE topics are included, prioritised and weighted for each assessment method. Note that Table 4 only maps topics awarding points and thus does not represent the number of mandatory criteria without allocated points.

By calculating relative weights (or points) by IE category, Figure 2 shows how IE content priorities differ between certifications. Not all main categories are represented in each certification, and the category contributions within a method vary up to a factor of five. LEED for Homes only considers IAQ and is thus not suited for an inter-area comparison.

Thermal is evaluated evenly for WELL, BREAM and LBC, while DGNB puts a higher emphasis on the topic. LBC and WELL prioritise IAQ with many requirements, including mandatory air quality tests and pollutant monitoring. Visual is well-represented across all certifications, in particular for BREEAM where it is the main contributor. Acoustics is covered sufficiently by WELL, DGNB and BREEAM, but is missing from LBC.

The User category is present in all five assessments with relatively even contributions but vary in content. LBC only includes operable windows, and LEED only considers thermal regulations, while the other three methods handle both.

DGNB and WELL handle artificial light regulation, while DGNB also includes regulation of mechanical ventilation and adjustable solar shading.

Table 3. Overview of Content structure, Levels of aggregation, and Indication of IE content amount for the five analysed assessment methods.

Aggregation levels	BREEAM	LEED	DGNB	WELL	LBC
Topic Groups	**9 Environmental Categories** (+ Innovation Category) 1 Category	**6 Categories** (+ Innovation, + Regional Priority Categories) 1 Category	**6 Qualities** 1 Quality	**10 Concepts** (+ Innovations) 4 Concepts	**7 Petals** 1 Petal
Main Topics	**57 Issues** 4 Issues	**40 Credits** 7 Credits	**37 Criteria** 6 Criteria	**112 Features** (89 Optimizations + 23 Preconditions) (24 Optim. + 7 Precon.)	**20 Imperatives** 2 Imperatives
Weighting Factors	**Category weight factors** (in %, varies) (14.4%)	**Credit point caps** (varying credit point caps) (point range: 1-3)	**Criteria weight factors** (rank 1-7) (rank 2-5)		
Sub Topics (with points)	**Criteria** (varying amount of credits) (varying amount of credits: range 1-4)	**Options** (varying amount of points) (varying amount of points: range ½-2)	**Criteria Indicators** (0-100 pts for all criteria) (0-100 pts)	**Optimisation Parts** (varying amount of points, range 1-3) (varying points: 1-3)	
Sum of Points	**Overall score** (sum of % achieved vs available credits for each Category multiplied by Category weight factors)	**Total points from Categories** (sum of points from Options)	**Total performance index** (sum of % of achieved vs available Criteria Indicator points multiplied by Criteria weight factors)	**Total points from Concepts** (sum of: points, from Optimizations - min 2 / max 12 for each Concept)	
Certification	**Certification** (Pass ≥ 30, Good ≥ 45, Very Good ≥ 55, Excellent ≥ 70, Outstanding ≥ 85)	**Certification** (Certification ≥ 40, Silver ≥ 50, Gold ≥ 60, Platinum ≥ 80)	**Certification** (Silver ≥ 50%, Gold ≥ 65%, Platinum ≥ 80%)	**Certification** (Silver ≥ 50, Gold ≥ 65, Platinum ≥ 80)	**Certification** (yes / no)
Additional requirements	Minimum levels for some Criteria must be fulfilled 1 Criteria with min level	All 18 Prerequisites must be fulfilled 7 Prerequisites		All 23 Preconditions must be fulfilled 7 Preconditions	All 20 Imperatives must be fulfilled 2 Imperatives
			No Qualities can score lower than a threshold below a given certification level. E.g. for Platinum all Qualities (except SITE must be ≥ 65%)	WELL Core Certification option: Certification requires 40+ points (min 1 per Optimization)	Petal Certification option: Certification requires fulfilling 3+ Petals, one of which must be Water, Energy or Materials

Note: Underlined text shows key numbers for IEQ.

Table 4. IE contribution in % of the overall assessment score calculated for each of the five assessment methods

Certification	Indoor Environmental content: Main IE Category Names	Indoor Environmental content: Main IE Category Weights	Indoor Environmental content: Corrected IE content weights
BREEAM	Health and Wellbeing	14.4%	9.8%
LEED	Indoor Environmental Quality	16.3%	15.3%
DGNB	Sociocultural and Functional Quality	22.5%	16.0%
WELL	Thermal, Air, Light and Sound	30.9%	27.5%
LBC	Health + Happiness	10%*	10%*

Note: *LBC does not use weights, so the % given is merely a relative content fraction.

The last pie chart of Figure 2 shows averaged category weights for the three certifications that include all five categories. The chart distribution shows comparable main IE category weights when averaged across certifications (user category with approx. half relative influence). This indicates that although individual certifications differentiate widely between category weights there is no agreed consensus on category priorities across certifications.

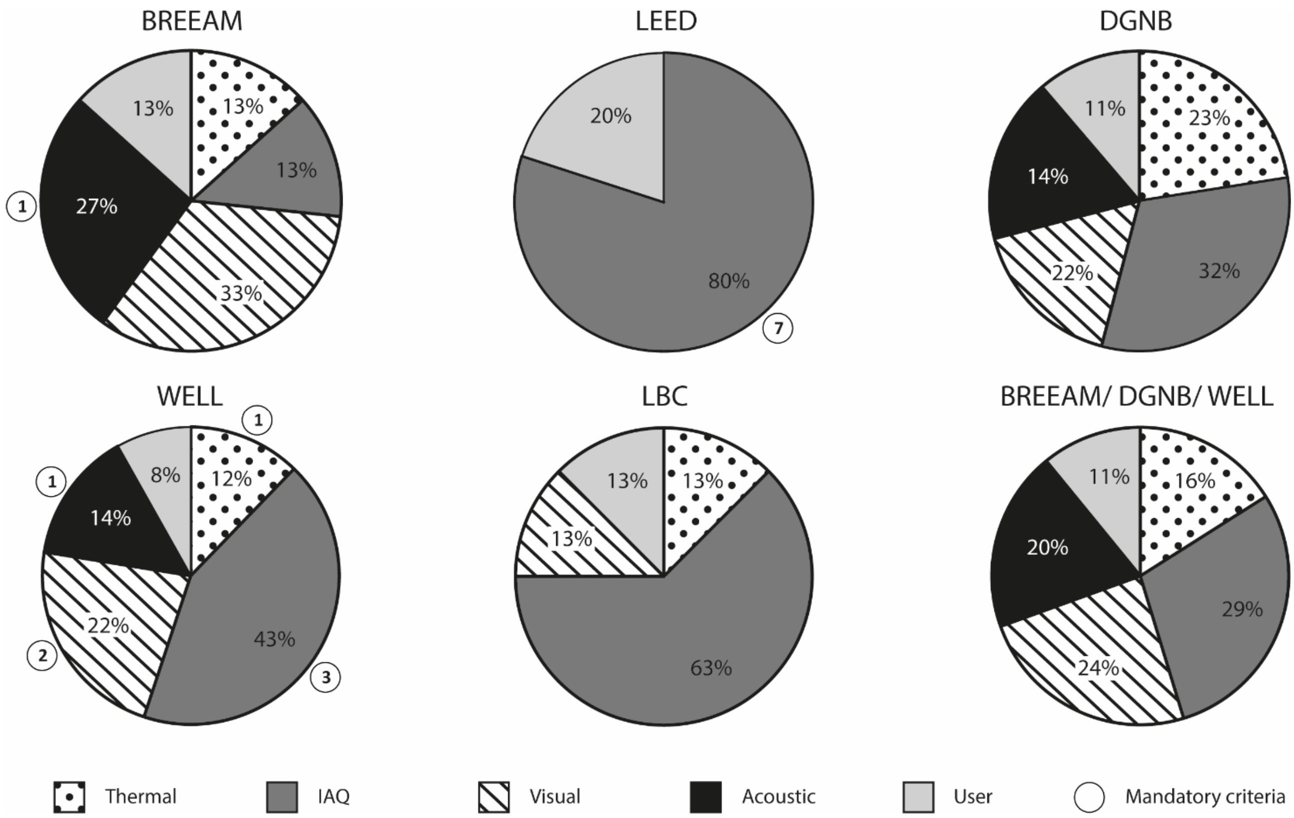


Fig. 2. Pie charts of relative IE topic contributions for five assessment methods, as well as an averaged contribution chart for the three methods that include all four main IE areas (BREEAM, DGNB and WELL). The small circles indicate the number of mandatory topics that do not award points.

TOPIC 4 – PLANNING

Overview The overviews given in the methods analysed (if any) are tables of content, matrices or scorecards, with names and sometimes points/weightings on group and topic level only. The online version of the WELL manual (IWBI 2019) provides an excellent overview of the different levels of the assessment (topic group/main topic/sub-topic) through a graphical concept overview with collapsible menus for 'Feature' information including brief easy-to-read descriptions of the effects on occupants.

Information Most of the analysed methods provide too superficial information to establish a platform for knowledge building and sharing. Again, WELL gives the most detailed and systematic descriptions referencing international standards (both EN, ISO and ASHRAE), citing IE literature, and providing full-page descriptions for each 'Concept'. Also 'Feature' intro texts follow a comprehensive format of Intent, summary, issue, solutions and impact (including consequences for occupants).

TOPIC 5 - DIALOGUE

Assessment methods should provide a robust platform for initial dialogues, by providing criteria performance grading that allows for detailed status determinations and goal setting on different levels of detail (combined IEQ > IE categories > individual sub-criteria targets). The analysis shows room for improvement in supporting dialogues about deciding the design strategy and setting project-specific design criteria requirements.

Attention None of the methods analysed provides sufficiently nuanced IEQ assessments appropriate for revealing project potentials and limitations. DGNB is the method best suited for relative comparisons between the main IE areas as it scores all of them on the same 0-100 scale before applying varying criteria weights (Relevance factor 2-5). WELL and BREEAM is divided into four main IEQ areas, but the number of points available for each varies up to a factor 2, which skews comparisons. LEED for Homes and LBC cannot be used for inter-area comparisons as LEED for Homes only addresses a single main area (for dwellings), and LBC does not work with scores.

Ambition The assessment methods rank buildings on 3-5 overall certification levels, which is inappropriate for setting more detailed IEQ performance goals (other than shortlisting specific criteria to meet). The methods generally do not provide flexible goal-setting, although WELL Online provides a digital platform to develop project-specific scorecards, which can be modified by the project team.

Ambitious clients may opt for 'Outstanding' or 'Platinum' certification levels to improve conditions for occupants, but without an initial dialogue and a more detailed goalsetting, they may as well get something different. Also, there is insufficient support for realistic goal-setting, as no link is provided between criteria or between the preliminary assessment and the goal-setting.

TOPIC 6 - DESIGN

Decision support The assessment methods are developed for post-design assessments and require extensive calculation, simulation, measurement or surveys for most IE criteria. This requires skills outside of the design team and is often too time-consuming to be of relevance for decision support in the early design stages. Other criteria are scored based on simple checklists but do not provide a level of detail necessary to provide decision support on a design strategy level.

It would be preferable if the assessment methods could organise available building data on the current design and continuously generate performance results to provide design teams with feedback on their designs. Results should be visualised to promote design explorations and guide design teams through connecting performance to specific building characteristics.

Comparison The assessment methods grade overall performance of projects in 3 to 5 levels of success (see Table 3), allowing comparisons between certified projects and some degree of benchmarking to monitor progress in the industry. For IE concerns, the methods are inappropriate for all levels of criteria comparison as they do not provide the multiple levels of fulfilment of individual criteria necessary to measure the effects of design alternatives. WELL, LEED and BREEAM are mostly based on compliance evaluations, and a few 'improved' or 'enhanced' criteria options allowing for a 'yes/some/no distinction'. LBC does not distinguish per definition.

DGNB use 2-4 level threshold levels for many criteria and allows for interpolation between threshold levels. This allows for more nuanced comparisons between projects and inter-project criteria comparisons, but the assessment resolution is too low to compare design proposals as most building characteristics are likely to be consistent between design proposals (such as site, orientation and typology). The risk of yes/no evaluations is that almost fulfilling a criterion, i.e. slightly exceeding air pollution thresholds, will appear equally good as exceeding the threshold by several factors.

More scoring intervals for individual criteria will help motivate design teams to improve IE conditions for occupants to the highest obtainable level (reasonably achievable concerning the economy, buildability, and compromises with other IE and non-IE parameters), rather than optimise to either barely meet threshold limits or to completely ignore them.

TOPIC 7 - COMMUNICATION

Score The assessment methods analysed favour matrix-based scorecards that accumulate points on topic group and main topic level to issue an overall label. The scorecards do not allow for additional levels of detail, which are presented in an untreated form in text-heavy reports. As the DGNB and BREEAM rating systems give intermediate results (in points achieved vs points available), they do convey some information on the degree of fulfilment on either main topic or topic group level.

Scoring should provide a clear indication of the relative performance on all relevant topic levels such as topic group (overall IE), main topic (thermal), subtopic (drafts) and indicator (air velocity). If such information is made available in a hierarchical tree structure directly in the scoring system, the transparency of the evaluation is improved. DGNB has developed an excellent visual representation of overall performance (sunburst diagram), but the figures are manually generated after certification and thus is of little use for evolving design work. Scoring utilisation would greatly benefit from being continuously updated with auto-generated figures similar to the DGNB sunburst diagram.

Dissemination The assessment methods analysed communicate results based on the aggregation of criteria, with matrices and scorecards as their core structure. While these table-based score summaries help give an overview of the assessment content and relative performance, they provide no link to building input or consequences for occupants.

Effective dissemination should facilitate the use of assessment results as an extended product declaration between building owners and prospective tenants, which would double as a catalyst for public IEQ awareness. Also, results should link the performance to building characteristics indicating areas of potential improvement to building owners (as per the Energy Performance Certificates).

Discussion and recommendations

The content overview provided in Table 2 clearly shows that the certifications differ widely in IE criteria inclusion and weighting. Some of these ‘inconsistencies’ can be explained by deliberate differences in priority between certification systems, but the degree of discrepancy is remarkable. As the investigated assessment methods all refer to research on the potential impacts of IE performance, one might expect less significant differences in interpretation of literature. Results also indicate large content variations within individual certifications, depending on project type. For instance, LEED for Homes is limited to a single IE main category (IAQ), unlike other project types such as; schools (IAQ, acoustics); hospitality and retail (IAQ, thermal, visual); warehouses and healthcare (IAQ, acoustic, thermal, visual).

Several studies indicate that green office buildings and office buildings with green certifications have positive IEQ performance compared to non-green and non-certified buildings (Allen et al. 2015; MacNaughton et al. 2017). However, previous literature has pointed to issues with 'green-washing' either from missing consensus between assessment methods (Wallhagen and Glaumann 2011) or from high emphasis-criteria ensuring certification while neglecting other topics (Illankoon et al. 2017). If the market-leading tools used to demonstrate good IEQ in office buildings do not contain a correspondingly well-developed assessment scheme in the certification of dwellings, 'health-washing' could be a matter of concern.

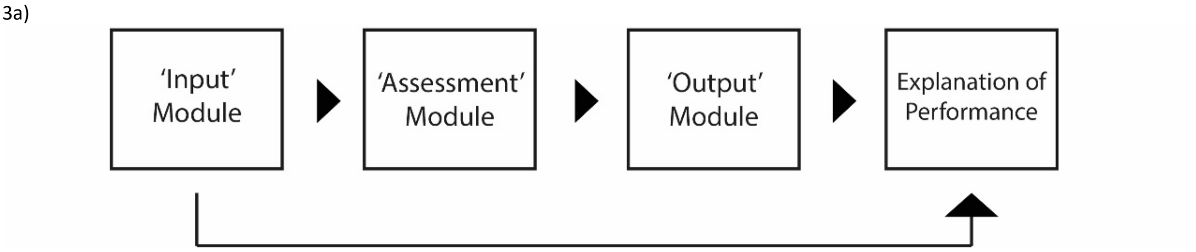
In their categorisation of assessment tools Haapio (Haapio and Viitaniemi 2008) conclude that "The use of tools is not obvious; where and when they should be used, who should use them, and how the results from the assessment should be utilised." By indicating which stakeholders perform which actions in every project stage, the EPI can help answer 'where', 'when' and 'who' should use future tools. By developing functionality-specific modules that facilitate tool application for previously unsupported phases, the 'use of the tool' should be both expanded and more straightforward to operate.

Twenty years ago Cole (Cole 1999) made a figure of three core modules that were part of all the assessment methods, as well as indicating a much needed fourth component that could disseminate the output (Figure 3a - reproduction of original figure). In this framework, the modules represent three different functionalities: 1) 'Input' - data collection, 2) 'Assessment' - assigning performance scores to investigated criteria, and 3) 'Output' – weighting and labelling. Cole (Cole 1999) also calls for an additional explanation of the performance, as the output profile is of little value in itself.

The analysis of current assessment methods shows that although the 'input', 'assessment' and 'output' modules have developed through several generations, no additional modules or significant functionalities have been added. As evident from the one-directional 'input > assess > output' flow indicated in Figure 3a, the assessment process is too static, and the output is considered too late to influence project design. Based on the results from the analysis of leading assessment methods and the EPI identified in the Methodology section, four new modules have been suggested for inclusion in future design-oriented assessment tools as shown in Figure 3b.

The **Dialogue module** activates all stakeholders in the early pre-design phases and provides a platform for identifying goals and priorities of the project. The primary concern is to incorporate issues even before the project is conceptualised. By making use of the overview and information provided by the core structure of the assessment method, the dialogue module should allow for well-informed, flexible goal-setting, preferably with a visual representation of the level and origin of the different requirements (such as Building Codes or client priorities). The **Input module** gathers building data through simple registrations or extractions from building information models. Instead of assessing performance directly based on checklists and simple indicators, a **Calculation module** calculates or simulates the potential performance. This enables much more precise and nuanced foundation for the **Assessment module**, module. The assessment results are fed into a **Design module** that compares the assessment with the goals set in the pre-design phases and enables design space exploration. After the optimisation and selection of design proposals, the modified input is fed back into the input-calculation-assessment cycle, and the Design module enables design alternative comparisons with earlier design proposals. The **Scoring module** aggregates result in an overall IEQ label that again may lead to further iterations depending on the ambitions and goals set in the planning stages. Finally, a **Communication module** disseminates results using bespoke presentation templates that consider terminology use, result detail level and the type of presentation suited for different stakeholder groups.

3a)



3b)

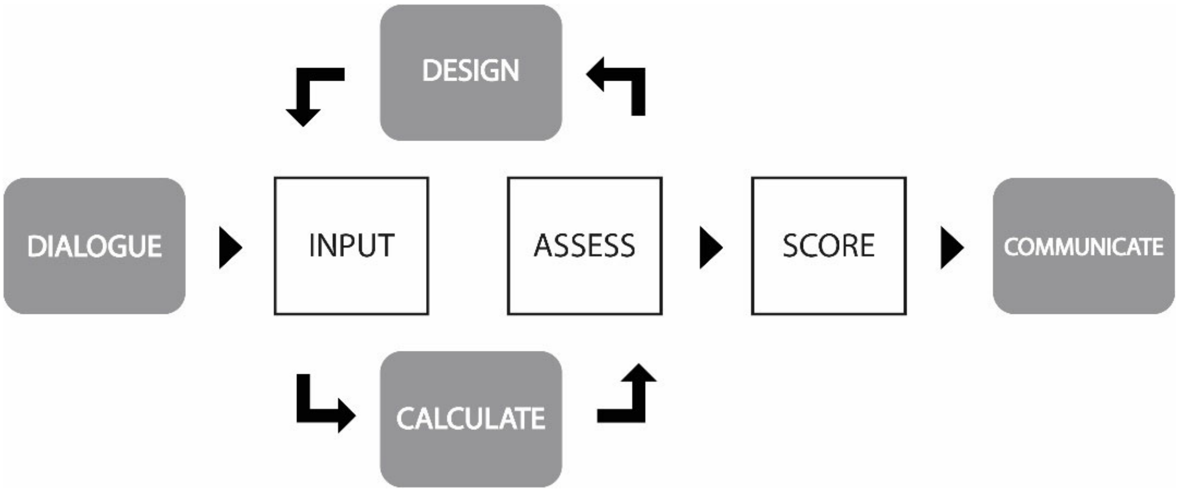


Fig. 3. 3a) Core modules of assessment methods in existing tools, according to Cole (Cole 1999) – reproduced figure. 3b) Framework for future generation assessment methods with four new facilitating modules as suggested in this paper.

Implementation of the four modules will ensure coverage of the EPI identified in the Methodology section as follows: Dialogue (Overview, Information, Attention, Ambition), Calculate and Design (Decision-support, Comparison), and Communicate (Scoring, Dissemination).

While the three 'traditional' modules can be sufficient for static tasks such as status determination or labelling of finalised projects, the expanded model is also fit to accommodate the complexity and dynamics of developing designs. The proposed iterative assessment functionalities support the cyclical nature of iterative design processes (Hansen and Knudstrup 2005) and are capable of supporting decision making. Note that design iterations can be evaluated on different levels, including fully aggregated (Score: 'B'), partially aggregated (Assessment: 'Thermal C' or 'Drafts A'), specific indicators (Calculation: 'hours over 28 degrees') – or even raw building data (Input: 'window g-value').

Conclusion

This paper has presented an updated overview of five major assessment methods, including an in-depth analysis of included IE content, as well as a critical analysis of their potential to inform design processes. Results show that the analysed assessment methods lack consensus on both IE content and weighting. Well-established methods such as BREEAM and LEED have almost no overlap in assessed content (for dwellings), and mandatory criteria differ widely between methods in both topic and amount.

IEQ contributions to the overall assessment vary from 9.8% in BREEAM to 27.5% in WELL, while the relative IE main category weights differ up to a factor five. It is recommended that future assessment methods attempt to bridge these differences by adopting a holistic approach to IEQ content, and by reconsidering the available evidence for the considerable weighting differentiation present in current methods.

The analysis indicates that the current assessment methods functionality could be improved by adding four facilitating modules to accommodate specific tasks at various project phases. In addition to providing a valuable platform for knowledge and dialogue between stakeholders, these modules will enable in-process assessments resulting in better IEQ design solutions.

We feel that early-stage IEQ assessment has the potential to make IEQ a design-parameter on equal terms with functionality, energy and statics. An IEQ assessment tool that successfully implements the functionalities listed above could motivate different stakeholders to prioritise IEQ and help put IEQ on the political agenda.

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No potential conflict of interest reported by the authors.

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CHAPTER 4. DESIGNING A HOLISTIC IEQ ASSESSMENT TOOL

This chapter presents selected steps in the development of a new holistic IEQ assessment tool called **IEQ**Compass (Appendix A – Paper F). Based on the critical analysis of current leading assessment methods (Chapter 3.1, Paper B) section 4.1 summarises some of the initial considerations and ambitions that helped shape the design direction of the assessment tool.

4.1. DESIGN CRITERIA FOR THE TOOL

4.1.1. CONTENT

Current assessment tools are inconsistent in their inclusion of IEQ criteria for the assessment of dwellings (Paper B). To avoid this, a comprehensive scan of IEQ literature was performed to create a gross list of potentially relevant IEQ criteria. The list was narrowed to an operational set of essential criteria for the combined impact on occupant comfort and health and was used to shortlist content for the **IEQ**Compass tool. The tool also includes criteria that are not yet well-researched if they are assumed to have a significant impact on occupants, such as reduced privacy from exposure to view in. In addition, the tool includes a few well-being criteria that promote positive stimuli, whenever the effects are quantifiable and well-documented, such as views to the outside and access to direct sunlight. This is also true for criteria that assess not only quantity but also the quality of, e.g. daylight and view out. Finally, the tool includes aspects that allow occupants to exercise control, to provide varied and controllable environments.

4.1.2. WEIGHTS

The assessment tools investigated distinguish highly between the four main IE areas, but with no consensus on which areas should weight most (Paper B). The same is true for IEQ literature that establishes area weights relative to overall IE satisfaction. The lacking consensus of subjective evaluations in literature could be the result of project-specific differences, such as climate conditions, cultural preferences, building typology and prevalent building conditions. As a result, weight differentiation among IE categories (such as thermal vs visual) should be considered carefully, and criteria weights should always be developed for specific contexts.

Building on previous conclusions that overall satisfaction/dissatisfaction cannot be determined by only investigating individual IE aspects (Humphreys, 2005), the **IEQ**Compass tool assesses overall IEQ by weighting the combined contribution of all aspects. As limited knowledge exists on the many possible interactions between and among IE aspects, the tool aims to ensure that all IEQ aspects perform at a satisfactory level. This approach is based on the assumption that the impact of moderate performance for a group of aspects is less aggravating than a combination of excellent and inferior performance of the same group of parameters. As formulated in the ASHRAE guideline on interaction effects: *'An environmental factor that is rated as least satisfactory is also likely to be rated as the most important one'* (ASHRAE Guideline 10, 2016). Future research into synergistic and antagonistic interactions ('cocktail effects') among IE criteria could provide a more sophisticated treatment of the combined effects of IE criteria.

Relative IEQ weights will be developed specifically for the tool with special care to represent both the potential influence on subjective evaluations and health impacts (Chapter 4.6 - *Determining indoor environmental criteria weights through expert panels and surveys*).

4.1.3. DESIGN

The current leading assessment tools have been developed mainly for validation and labelling of performance, and as a result, they are largely unfit for providing design decision support (DDS) in the critical early design stages. The challenge lies in accommodating quantitative and scientifically validated indicators preferred by specialists while also providing architects with qualitative and decision-supportive indicators (Dammann & Elle, 2006). One approach is to automate a series of calculations for predicting IEQ performance aspects. Unlike earlier attempts at developing IEQ indexes for a few aspects based on regression models (Catalina & Iordache, 2012), the **IEQ**Compass tool includes broader range of aspects, and provide more nuanced assessments. By assessing the potential IEQ based on building model data, the results can be scientifically valid, and yet available for decision support in the early design stages.

The tool accommodates the identified requirements for providing DDS (Paper B), particularly the ability to deliver fast performance predictions on a level of detail appropriate for comparing design proposals. Also, the tool assists in the dissemination on assessment result through graphical representation of design variation comparisons, and assessment scoring on different detail levels.

4.2. ASSESSMENT OF IEQ – WITHOUT OCCUPANTS

Building performance can either be based on the *realised* performance of the building, such as from measurements or occupant surveys or based on the *potential* performance of the building, such as from building performance simulations (BPS). While both have strengths and weaknesses, the **IEQ**Compass tool builds on BPS because of three main advantages for the current purpose: 1) it allows IEQ assessments during design development, which is a prerequisite for design decision support, 2) it allows building labelling without user behaviour bias, which is vital for comparisons between project, and 3) it is potentially much less costly than alternatives, which is critical to widespread implementation.

4.2.1. REALIZED IEQ

Occupant surveys such as questionnaires that collect IE-related occupant responses can gather data that no other assessment type can, such as personal factors (states, moods, traits), perceived well-being (or absence thereof), and descriptive information on physical and psychosocial stressors (Bluyssen, 2014). However, occupant surveys are prone to a long list of biases, particularly of concern for the comparability between building labels. Such biases include responses being influenced by (Bluyssen, 2014):

a. behaviour (such as inappropriate use)
b. personal factors (‘non-standard’ preferences and expectations)
c. demographic factors (age, gender, social status, income, education level)
d. health factors (lifestyle, physical and mental health conditions)
e. life events (emotional effects of marriage, unemployment, childbirth, death in the family)
f. interpretation of questionnaire (misunderstood questions, inappropriate use of scale)
g. response bias (social desirability, response acquiescence, recall bias, indifference to topic)
h. date and time (seasonal change, day/night cycle, period assessed)

Surveys can potentially provide information on the perceived accumulation of physical and psychological influence over time. However, responses risk being influenced either by past events and exposures or by the perception of the current experienced performance as the questionnaire is filled, meaning that the specific time of the response could significantly impact results.

Unlike surveys, physical measurements have the advantage of avoiding subjectivity (bias points ‘c-g’), yet share many of the other limitations listed above. While physical measurements provide an objective assessment of the realised indoor environment, it still risks labelling the influence of current users instead of the potential building performance (bias points ‘a’ and ‘b’). Also, measurements depend highly on the timing and time intervals of measurements (bias h’).

Many of the listed bias can be partially accounted for by collecting a high number of responses, performing measurements with short intervals over long periods, and making various data corrections to improve assessment robustness. However, such initiatives may increase the costs of assessment significantly.

4.2.2. POTENTIAL IEQ

Although BPS simulation can be both time-consuming and expensive, it does not have to be. The **IEQ**Compass combines input, calculation, assessment and dissemination in a single tool, leading to reduced time consumption (approx. 3-4 man-hours to register and score a dwelling) and minimal total expenses (Larsen, Rohde, Knudsen, Jønsson, & Jensen, 2019). The tool calculates the potential building performance based on different building characteristics combined with built environment data, such as climate data sets (see Appendix B input type examples). This enables labelling that is exclusively dependent on building variables, which is vital for transparency in comparisons between assessments. However, the tool also includes qualitative assessments for a few aspects that are difficult to assess quantitatively without measurements, such as window air tightness and material emissions. By assessing potential IEQ performance, the **IEQ**Compass tool provides fast and inexpensive assessments that are reliable, comparable, and available during design.

4.3. INTRODUCING **IEQ**COMPASS

A new IEQ assessment tool called **IEQ**Compass has been developed to perform holistic IEQ assessment of Danish multifamily residential buildings as part of the REBUS project (REBUS, 2016). The tool is the result of a multidisciplinary collaboration between researchers, experts and consultants within different IEQ disciplines, as well as buildings developers and professional building owners. The paper "**IEQ**Compass – A Tool for Holistic Evaluation of Potential Indoor Environmental Quality" (Paper F – Appendix A) describes the purpose, content, functionality and process of developing the new tool, as well as presenting an application example. In addition to providing detail on performing the assessment, the paper shows a dissemination example of assessment results in the form of a performance label and a graphical results figure called an IEQ Design Compass.

The research presented in this dissertation has supported the development of the **IEQ**Compass tool in various ways. Contributions include:

- Suggestions for qualitative and user behaviour content (Paper A and B).
- Recommendations and requirements for tool functionality (Paper B).
- Established relative content weights for IE assessments (Paper C – Chapter 4.6).

The **IEQ**Compass tool serves as an exemplification of the perspectives and recommendations of Chapter 1, 2 and 3. Also, the **IEQ**Compass is used to test the prospect of holistic IEQ assessments in early design processes as presented in Chapter 5.3, Paper D. The paper presenting the **IEQ**Compass tool is included in an appendix to reflect that the author of the dissertation contributed to the paper as a co-author. For the sake of chronology readers are encouraged to read Paper F – Appendix A, before the continued reading of the dissertation:

*"**IEQ**Compass – A Tool for Holistic Evaluation*

of Potential Indoor Environmental Quality"

4.4. HOLISTIC ASSESSMENT METHODOLOGY

Early indoor environmental research was originally concerned with single components of IE such as thermal comfort or noise, resulting in comfort models, threshold values and identification of qualitative indicators. In the 1990's, research on the combined influence on occupants resulted in concepts such as Sick Building Syndrome (SBS) and Building-related Illness (BRI). Comprehensive building assessment methods (such as BREEAM and LEED) has gained favour in the last two decades, using a bottom-up approach that simply adds up the different contributions. Although such methods represent a more comprehensive perspective, they still rely on single-aspect, component-related evaluations and make no connections between the many indicators included in the assessments.

As a suggestion for assessment indicators, Bluyssen describes three different categories of health and comfort indicators (Bluyssen, 2010):

- **Occupant/end-user** (productivity, sick leave, symptoms or complaints, building-related illnesses, health adjusted life indicators)
- **Dose/parameter** (different pollutant concentrations, indicators such as ventilation rate, noise levels, lighting intensity and temperature)
- **Building and components** (building and component characteristics such as the possibility to cause dampness, or different types of building and component labelling)

Bluyssen adds that: *'Of these groups of indicators, the second one is used most frequently in guidelines and standards. The first category is discussed a lot, and the third one seems the most promising at the moment'* (Bluyssen, 2010). The book *The Healthy Indoor Environment* (Bluyssen, 2014) presents a framework for an integrative and multidisciplinary *systems approach* to IEQ that assesses the potential performance of a building through a combination of building-related indicators.

However, significant gaps in the knowledge on interaction effects, user behaviour and preferences, and the combined impact on occupants prevent us from applying such ambitious top-down perspective at this point. Instead, the **IEQ**Compass suggests an integrated holistic bottom-up methodology:

Holistic content and scoring

- Evaluation of the combined implications on occupant health, comfort and well-being
- Combined assessment of all four main IE areas: thermal, visual, acoustic and IAQ
- Context- and typology-specific criteria selection that gathers all relevant IE aspects
- Criteria contributions from all relevant aspects combined to an overall IEQ label
- IEQ label with score cap based on lower boundaries for each main IE area

Holistic results and design

- Assessment results are calculated and communicated on different levels:
  - Complex/detailed information for experts and consultants
  - In-depth insight for professionals and investors
  - Comprehensible key information for occupants

- Improved transparency of connections between design choices and the resulting IE:
  - Overview of which areas each input can influence
  - Resulting changes in all IE areas for each design decision
  - Comparisons between different design alternatives

For now, the **IEQ**Compass rely on component-related standards and assess overall IEQ performance by adding the individual IE contributions without addressing interaction between (and among) indicators and occupants. However, two significant steps have been taken in the direction of a holistic assessment perspective by providing (1) simultaneous assessment of all relevant aspects, and (2) transparency of how certain building characteristics influence multiple indicators. This is crucial as it provides design teams with information on performance trade-offs, which is imperative to providing solutions with high overall IEQ. Existing approaches assess IEQ aspects either separately or in sequence, which leads to a risk of unintentionally worsening overall IEQ performance due to sub-optimisation.

For example, indoor acoustics could be dependent on soft surface materials for sound absorption, which may result in both increased primary (VOC's) and secondary emissions (adsorption on surfaces), and inhibit cleaning. The IAQ could be improved by mechanical ventilation, which may contribute to low-frequent noise, or be dependent on natural ventilation, that expose occupants to noise from the outdoors. Facilitation of this interconnectedness of the IE is made possible by combining performance calculation, scoring and weighting in a single tool, which automatically assesses all relevant aspects based on the same building model. Sharing the same input source also removes the risk of inconsistency errors due to separated calculations (i.e. window area increased to promote daylight, but not updated in thermal assessment).

Many examples of conflicting interest in the indoor environment can be found in both practice and standards (ASHRAE Guideline 10, 2016). Building characteristics often influence two main IE areas in opposite directions (such as solar shading), and a few even influences all four main areas (such as façade glass area). Mutually conflicting conditions can also occur between categories within areas, such as the compromise between occupant visual privacy and the access to daylight, sunlight and views. Design teams should take carefully balance such conflicting interests, and if possible, seek out alternative or complementary strategies to obtain satisfactory performance if an aspect risk being compromised. Less robust indoor environments risk resulting in a Catch-22 situation such as attempting to achieve good IEQ by operating a window in a stuffy room near a highly trafficked road.

4.5. IEQ CRITERIA WEIGHTS

Criteria weighing is a much-debated aspect of all assessment methods, particularly for comprehensive assessment methods that combine environmental, social and economic sustainability aspects into a single score or label (such as BREEAM, LEED and DGNB). Although **IEQ**Compass ‘only’ addresses IEQ, it combines a variety of different indicators and metrics. Unlike assessments where contributions can be added such as for LCC (cost), LCA (CO_2) and energy compliance (primary energy), holistic IEQ assessments face three initial challenges related to weighting and scoring:

1. Combining the results of quantitative and qualitative assessments (by translating qualitative results into numbers)
2. Comparing calculations with different output formats
3. Correlating relative importance between IE aspects

The standard EN 15251 recommends that overall IEQ in buildings be classified according to satisfaction with individual indoor environmental conditions (CSN EN 15251, 2007). Although this suggests a simple bottom-up strategy for adding contributions, it does not address how to add aspects not related to satisfaction. As suggested by Todd (Todd, 1996) relative weights should be derived by assessing the final endpoints of concern – for IEQ this would be occupant comfort, health and wellbeing. Different methods have been used to establish the relative importance of IE aspects, but most approaches are limited to tackling the influence on a single IE domain, such as health risks from medical literature. Although many different types of subjective comfort evaluation studies exist, there is little consensus between findings (Zalejska-Jonsson & Wilhelmsson, 2013). Also, such studies are highly dependent on both the specific context of the study, such as the room type and the performed activity, as well as on the participant's preferences, expectations and physical condition.

This calls for a methodology that allows generation of context-specific, cross-domain weights for IEQ aspects that reflect the combined evidence for occupant impacts. A methodology was developed and tested based on a multidisciplinary expert survey that allowed the integration of a variety of disciplines as the individual experts subjectively combined the contributions from different sources. However, although expert priorities ideally integrate all potential influences on occupants, the prioritisation of too many parameters can be too complicated. Another challenge is that subjective, relative weights depend on the individuals surveyed, both privately (personal preferences, subjects current living conditions) and professionally (field of interest, practical experience, educational background). These methodological challenges are addressed in Chapter 4.6, Paper C – *Determining indoor environmental criteria weights through expert panels and surveys*, along with developed methodology and the resulting relative IE weights.

While the authors realise that, there is no such thing, as a universally applicable weighting index, it is important to acknowledge the necessity of establishing systematic context-specific weights. Pre-weighted criteria decided by a large group of experts is much more consistent and robust than customizable project-by-project weights. The specific conditions of individual projects may be unique, but fixed weights ensure transparent comparisons between projects and is a prerequisite for IE labelling.

4.6. ESTABLISHING RELATIVE IE WEIGHTS

Paper C

"Determining indoor environmental criteria weights

through expert panels and surveys"

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Determining indoor environmental criteria weights through expert panels and surveys

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ABSTRACT

A growing focus on occupant comfort, health and wellbeing have 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 hypothesise 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 prioritisation and the Analytic Hierarchy Process (AHP) 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.

KEYWORDS Indoor environmental quality; dwelling; comfort; health; multiple-attribute decision-making; AHP

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, 2019). An essential step towards improving indoor environmental quality (IEQ) is to quantify, prioritise 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, 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, 2019).

Some literature has been published on relative IEQ weights, but there is little consensus between findings as summarised by Zalejska-Jonsson & Wilhelmsson (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 (M. Frontczak et al., 2012; Monika Frontczak, Andersen, & Wargocki, 2012). Other studies do the same through a correlational method that combines occupant satisfaction questionnaires with field measurements data (Bluyssen, Aries, & 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 summarised by Malmqvist & Glaumann (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 (Rohde 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 (Monika 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 (Todd, 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 (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 (Rohde et al., 2019).

In addition to handling IE comfort aspects separately, this research leans towards Chapells and Shove's (Chappells & Shove, 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 Leamann & Bordass (Leaman & 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. Realising that both content and weights depend on the context and use of the building, criteria selection and prioritisation 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 multifamily 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 prioritise 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 generalised 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 emphasised 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 (3 or 4 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 randomised 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 (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 (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 specialised 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, organisations, 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).

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

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.

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 version of the survey results (dark green colour), and they will not be commented further. A few categories have had small adjustments (light green colour), 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 (yellow and red colour). 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), 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

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)

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 recognised 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 normalised pairwise comparison matrixes. Consistency checks for the four AHP's ranged from 0.51%-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 prioritised 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, & Olesen, 2009; Monika 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

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)

systems may be challenging to operate, and they may be in doubt how to influence what. Finally, users may forget to utilise 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 prioritised 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 summarise 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 prioritising 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 prioritise 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 decrease 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 depend 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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CHAPTER 5. TESTING IEQCOMPASS IN EARLY DESIGN PROCESSES

5.1. CHALLENGES IN CURRENT PRACTICE

Building design has always been an art of compromise. Architects are trained in the art of balancing diverse aspects such as building shape, contextual integration, aesthetic identity and functionality. Recently, building designers have been faced with increasingly strict environmental performance requirements (energy labelling, LCA, healthy materials), which heavily influence decisions from building shape and orientation, to the selection of components and finishes. Building designers must consider environmental performance already in the early design stages, where the impact potential is highest (Bragança, Vieira, & Andrade, 2014; Kovacic & Zoller, 2015), but when ambitious goals are set for e.g. energy consumption, it may come at the expense of other crucial aspects. This is particularly the case for build environment elements that can only be assessed qualitatively (such as aesthetics) or those that are often not assessed quantitatively in the early design stages - such as the indoor environment.

Design teams must recognise all relevant performance demands from the beginning of the project, and integrate them into early concept developments, with consideration to how design alterations influence the project as a whole. For this to be possible, the design team must have the necessary resources available at the right design stages, depending on the individual project. For the integration of IEQ measures, the resources required include a combination of domain expert knowledge within the design team, early-stage IE consultancy, and highly responsive decision support tools. The hypothesised benefits of using a tool like **IEQ**Compass as a DDS tool include known trade-offs, less sub-optimisation and IEQ as active criteria in early design.

The **IEQ**Compass is tested for its ability to inform design teams and influence their decisions to produce better designs solutions from a holistic perspective. The test consists of two design experiments as presented in Chapter 5.3, Paper D – *Holistic Indoor Environmental Quality assessment as a driver in early building design*. According to the work presented so far, the tool accommodates actions in the *Design* column of Figure 2, which is a detailed adaption of Figure 1 based on the work presented so far. Interviews with practitioners performed after the design experiments (Paper D) also deal with potential indirect contributions to some of the actions presented in the *Pre-design* column.

In addition, the interviews present reflections on structural challenges, for instance concerning participation in architectural competitions. The compensation of the design team labour is very low, or non-existent for open competitions, and the uncertainty of proceeding to the next round of the competition is very high. This means that architects might not collaborate with engineers, even though decisions taken in the competition phase are crucial for the resulting building performance (Kanters & Horvat, 2012).

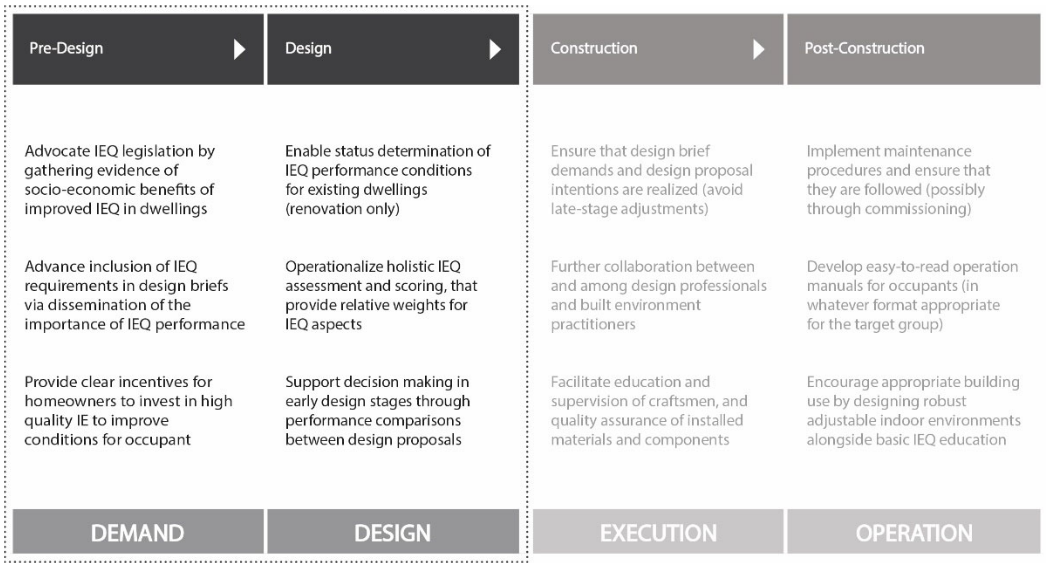

Figure 2 – (adaption of Figure 1, Chapter 3) Examples of initiatives to further the realisation of holistic IEQ for different phases in the creation of a building (top row). The presented research supports initiatives listed in the Design category directly while indirectly supporting those in the Demand category.

5.2. DECISION SUPPORT

Decision-support can be provided on many levels, but in the earliest conceptual stages, architects often resort to heuristic assessment methods, such as rules of thumb, to keep up with the dynamic design processes. The **IEQ**Compass tool has been developed to support early-stage decision-making using fast-paced building performance simulation instead of less precise heuristic predictions. This allows the design team to lead the creative process and provide creative solutions to complex qualitative and quantitative problems, while the **IEQ**Compass plays the role of an assistant that the design team can consult when needed. This approach is different from performance-based design (or performance-driven architecture) where the architecture is derived directly from the BPS (Shaviv, Kalay, & Peleg, 1992)**.**

Many recent DSS tools rely on automated generation of design variations combined with optimisation techniques, 'replacing' critical design thinking. This design automation makes it difficult to respect architectural integrity and may cause the design team to lose control of the design direction (Negendahl, 2015). Relying on optimisation techniques is problematic also because the idea of an optimal solution builds on the assumption that all relevant aspects are taken into account. This, however, is not possible in a field as complex and multi-faceted as architecture, and the approach is particularly questionable because vital qualitative aspects such as functionality and aesthetics can only be assessed through subjective evaluations by highly trained individuals. The author believes that a multidisciplinary design team equipped with the right DSS tools can perform integrated design practice with a holistic view on environmental and social sustainability performance - while respecting qualitative aspects such functionality, aesthetics and atmosphere - to produce high-performance architecture.

5.3. IEQ ASSESSMENT IN EARLY-STAGE DESIGN

Paper D

"Holistic Indoor Environmental Quality assessment

as a driver in early building design"

Rohde, L., Jensen, R. L., Larsen, O. K., Jønsson, K. T., & Larsen, T. S., Holistic Indoor Environmental Quality assessment as a driver in early building design, Building Research & Information (under review).

Note: Appendix C contains supplementary material (photographs, drawings and posters) from the design experiment cases presented in the paper.

Holistic Indoor Environmental Quality assessment as a driver in early building design

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ABSTRACT

Research and practice agree that decisions taken early in a project have a higher impact and are less costly. Current building performance assessment methods are not suited to accommodate the responsiveness required for early design processes and are often used for validation in the later stages where the feedback has little design impact. Tools developed specifically for early-stage design decision support (DDS) are either too simplistic, provide no solution to addressing indoor environmental quality (IEQ) holistically, or risk worsening the overall IEQ by optimizing performance indicators in isolation. Most comprehensive building assessment methods evaluate several topics but follow a linear approach which fails to support holistic performance feedback and fails to meet the demand for assessment speed.

This paper presents application examples of a holistic IEQ assessment tool (**IEQ**Compass) in design processes. The design experiments demonstrate that the approach applied can meet the current challenges of early stage DDS according to literature. The most important findings from the experiments show that the **IEQ**Compass provides: (1) seamless early-stage assessments through rapid-feedback on changing designs, (2) timely decision support by guiding design teams with criteria overviews, design comparisons and holistic assessments, and (3) dialogue and communication support between architects, engineers and clients.

KEYWORDS Decision support; design process; indoor environmental quality; assessment tool; integrated design; potential IEQ

Introduction

The built environment is faced with increased complexity and ambitious technical performance requirements. This challenges all actors in the building industry, particularly the design teams who are tasked with balancing the many, often conflicting, interests such as energy performance, indoor environmental quality (IEQ), and cost. It is commonly known that decisions taken in the early design stages have the greatest potential influence on the project results (Brager, 2013), which puts an enormous responsibility on the design team. Architects are trained to integrate qualitative elements such as aesthetics, functionality, atmosphere and context, but the rapidly increasing complexity and technical performance requirements challenge the way they evaluate and balance early design stage decisions. The challenging conditions call for tools that can provide design decision support (DDS) in the early design stages, by providing design teams with easily accessible data on complex technical topics.

The Energy Buildings Performance Directive (The Council of the European Union, 2010) has successfully made energy efficiency a priority in the built environment, and recent versions mention the promotion of comfort, health and wellbeing for occupants (European Union, 2019). As we spend 90% of our time indoors (Klepeis et al., 2001), IEQ has a significant influence on the comfort, health and wellbeing of inhabitants (Rohde, Larsen, Jensen, & Larsen, 2019b) and should be an essential part of early building design. However, IEQ improvements face a series of challenges, including that IEQ is sometimes regarded as inversely correlated with cost and energy performance. Another major challenge is that IEQ is a complicated concept composed of different topics managed by a variety of experts within disciplines such as HVAC, acoustics and material sciences. A combination of lacking demand, expertise and DDS tools mean that IEQ is often not adequately resolved, with consequences for the inhabitants. E.g. the struggle to limit heat losses and increase passive gains to conserve energy in temperate climates has made many new buildings prone to too high temperatures (Brunsgaard, Heiselberg, Knudstrup, & Larsen, 2012; Morgan, Foster, Sharpe, & Poston, 2015).

Traditional design practice leaves the early design stages to the architects, who often have no specialized training in IEQ or energy efficiency (Kanters & Horvat, 2012). When the consultant engineers join the design team, the concept has already been developed, and significant changes are time-consuming and costly (and thus rare). The technical aspects of conceptual design are thus often developed based on intuition and rules of thump (Kanters, Dubois, & Wall, 2013), and possibly evaluated as part of the developed design based on engineer experience. Performance assessments typically rely on advanced simulations that are not performed until the technical design stage, where the concept is almost final, and the design options are minimal. Design teams need early-stage DDS, allowing them to perform early-stage assessments and compare design proposals. IEQ performance assessment depends on simulation software that is not operational in early design stages for a range of reasons previously summarized, including time-consumption and rapid change of design (Østergård, Jensen, & Maagaard, 2016). Also, current building performance simulation (BPS) tools are not suitable for architectural design work due to complexity and incompatibility with the architect's working methods (Attia et al. 2009). Literature and surveys indicate that the use of BPS tools in early design is limited by the tools being developed for experts, researchers and physicists, and not for design practitioners (S. Attia, Beltrán, De Herde, & Hensen, 2009; Negendahl, 2015; Østergård et al., 2016).

Most studies agree that high performance buildings is best achieved with both architectural and engineering expertise present in the design team, but they suggest different approaches. In a review of how BPS is used in the early design stages, Negendahl (2015) provides a summary of three collaborative relationships between architects and engineers based on previous literature (Klitgaard, Kirkegaard, & Mullins, 2006; Petersen, 2011): (1) engineers assisting architects, (2) engineer/architect 'hybrid' practitioners, (3) engineers and architects in a design team. If the engineer performs as an assistant to the architect, Mora (Mora, Bédard, & Rivard, 2008) suggest assistance be provided as design performance analysis, without interfering with the creational design processes. The engineer should assist the generation of design alternatives in a way that complement the design process by being a creative and flexible process, rather than a systematic design space exploration using automated design alternative generation (Struck, de Wilde, Hopfe, & Hensen, 2009). The second way to ensure integration of both architectural and engineering aspects in the early design phase is through practitioners with equal understanding of aesthetic, functional and technical aspects. This is similar to the third approach where the combined expertise of a design team possess the skills required to support integrated design processes (IDP), which has given rise to different collaborative methods (Gramkow, 2007; Karlessi, Hollsten, & Amann, 2014). One such method is through multi-disciplinary kick-off workshops that promote IDP through early introduction of technical expertise and improved collaboration between disciplines (Alhava, Laine, & Kiviniemi, 2015; Kerosuo, Mäki, & Korpela, 2013).

The introduction of relevant expertise in the early design stage is a prerequisite for successful DDS, but the availability of suitable BPS tools is also required to provide consistent feedback on the design direction (Jrade & Jalaei, 2013; Oti & Tizani, 2015). Tools have been developed previously for early stage DDS and evaluation of energy performance in buildings, such as for Net Zero Energy Buildings (S. G. Attia & De Herde, 2011). Most such tools use parametric automation systems to systematically explore design spaces, evaluated through (multi-variate) linear regression models or regression based meta models (Asadi, Amiri, & Mottahedi, 2014; Gerber & Lin, 2014; Hester, Gregory, & Kirchain, 2017; Hygh, DeCarolis, Hill, & Ranji Ranjithan, 2012; Østergård, Jensen, & Maagaard, 2018), while others use simpler metrics to act as performance indicators (Schade, Olofsson, & Schreyer, 2011). The availability of similar tools for IEQ decision-support is much more limited, and predominately limited to single-aspect evaluations and optimizations such as for daylight (Mavromatidis, Marsault, & Lequay, 2014), solar (Nault, Peronato, Rey, & Andersen, 2015), envelope design (Negendahl & Nielsen, 2015), and window layout (Oh, Sung, & Kim, 2017). A few studies provide multi-objective IEQ optimization, but still only include a limited amount of aspects, such as thermal and daylight (Chen, Yang, & Sun, 2016). Tools that rely on sensitivity analysis to screen out leading design parameters has to consider all interdependent objectives simultaneously to provide holistic DDS (Østergård, Maagaard, & Jensen, 2015). Sensitivity analysis for separate outputs e.g. a daylight optimized window strategy may fail to comply with other IEQ aspects such as glare, indoor temperatures, drafts, views and privacy.

Other early stage assessment tools are more comprehensive in their inclusion of considered aspects such as methods to access LCA (Basbagill, Flager, Lepech, & Fischer, 2013), LCC (Kovacic & Zoller, 2015) or green buildings (Kamari, Corrao, & Kirkegaard, 2017), but they suffer from a lack of detail level on IEQ topics. Some environmental assessment methods such as DGNB and WELL provide a good overview of IEQ criteria to consider, and have ambitions concerning early design inclusion, but provide no simple way to assess performance (Rohde, Larsen, Jensen, & Larsen, 2019a). Environmental assessment methods often require advanced simulations results as input, making them prone to the limitations mentioned above, including the need for expert knowledge to be available. Another approach to enable early IEQ simulation is to integrate assessments into CAD environments, for instance, using Rhino and Grasshopper in combination with different plugins (Energy+, Honeybee, Ladybug, Radiance). This approach has its challenges, however, including simplified assessments, lack of framework to compare results from different tools, and the requirement of a building model that may not be available at this stage (Andrade & Bragança, 2016).

The wide range of early stage DDS tools developed in the last two decades share two significant limitations, operationality (input availability, calculation speed, user interface) and the ability to guide designs holistically (assessment of all IEQ areas, simple overview, known trade-offs). Selected DDS tool-recommendations from existing literature are listed below to emphasize essential functionality of future tools. According to literature, early stage decision support tools should provide:

- early stage goal setting (Nielsen, Jensen, Larsen, & Nissen, 2016)
- a comprehensive overview of a variety of relevant criteria from project start (Markelj et al., 2014)
- dialogue and communication support between central parties of the project (Cole, 2005)
- early-stage DDS through timely performance feedback and design variation comparisons (Østergård et al., 2016)
- assistance to convince clients about early integration, by a clear presentation of advantages (Kanters et al., 2013)
- mechanics, intelligence and usability that make it effective and informative (rather than just evaluative) (S. G. Attia & De Herde, 2011)
- promotion of early-stage IEQ expertise integration and knowledge building within the design team (Cole, 1998)

The current situation calls for a framework that: (1) operationalize early stage IEQ assessment through fast and reliable input and calculations, (2) guide designs as a whole rather than optimize it for single parameters, and (3) provide a holistic IEQ assessment overview and design comparisons that enable known trade-offs. The tool should not optimize the design for IEQ performance, but rather contribute to the improvement of the overall design proposal by enabling IEQ considerations, as one of many vital design aspects.

In the present study, design teams were tasked to test a newly developed holistic IEQ assessment tool called **IEQ**Compass (beta version) (Larsen, Rohde, Knudsen, Jønsson, & Jensen, 2019) in different design processes. In previous publications the tool has been referred to as IV20, which was the national prototype name used during the tool development. The design teams applied the tool to aid IEQ considerations in the early design process. The tool is designed to accommodate integrating IEQ in the early design stages, addressing IEQ holistically, ensuring transparency (known trade-offs) and making informed design decisions. The tool use building geometry and simple information on context, constructions and components to assess the potential IE performance on 40 IE criteria split across four main IE areas: acoustics (ACO), indoor air quality (IAQ), thermal (THER) and visual (VIS). The tool automatically calculates the performance of all 40 criteria and score them on a 0-10 scale. Each score is assigned a relative weight and is visualized graphically on a performance overview Design Compass. The tool also generates combined scores in per cent with a matching IEQ label (letters 'A' to 'G') for each main area score (ACO, IAQ, THER, and VIS) and the overall potential IEQ performance.

This paper presents the results from two supplementary studies of IEQ integration in early design processes using the **IEQ**Compass tool, with the objective to: (1) demonstrate assessment speed, (2) observe whether tool feedback can influence decision making, (3) investigate the ability to compare design proposals, and (4) evaluate promotion of early-stage IEQ knowledge integration into designs. Results are based on qualitative data, through observations during design development and interviews with the participants combined with quantitative assessments of potential IEQ performance as assessed by **IEQ**Compass. This research provides valuable insights into how early-stage design processes can be influenced by the integration of technical performance aspects, in this case, particularly IEQ. Also, the results indicate that DDS tools such as **IEQ**Compass can support holistic design processes without compromising other crucial design topics.

Methods

The following section presents first the overall research design, followed by descriptions of the specifics of 'Setup', 'Case' and 'Data collection' for both the workshop and the project setups.

Research Design

In this study, the **IEQ**Compass was applied in two complementary setups (Table 1) designed to evaluate whether the tool can provide operational DDS and potentially overcome the obstacles summarized above. The first setup was a one-day workshop with a professional design team consisting of architects and constructing architects. In a condensed design process, the team made several iterations on renovation proposals for an apartment building with which the design team was already familiar. The second setup involved two groups of architect/engineer master students during two months of project work to create dense sustainable multifamily housing. The students had sufficient technical expertise to operate the software and interpret results, meaning that the design process could be studied with minimal influence from the tool developers. Also, as the tool was applied throughout the project from brief to validation it is possible to follow the process through all design stages with the same participants. A correspondingly continuous process would be difficult to achieve in practice where design teams often change throughout the process (e.g. from the competition stage to project detailing). Performance data was collected with **IEQ**Compass for different design iterations in both setups. Results will be presented as a simplified design process by grouping essential IEQ-related design changes into a manageable number of iterations.

Qualitative data were collected (by the first author) using observations and post-workshop interviews with participants on tool operationality and the potential influence on early stage DDS as interpreted by the participants. Semi-structured interviews were used as they allow a certain degree of freedom, both in the answers from participants and for exploring some responses further through probing, elaboration and paraphrasing techniques (Kvale & Brinkmann, 2009). An interview guide was developed to get participant feedback on whether the IEQCompass helps break down the identified barriers for integrating BPS tools and engineering expertise into early design or not. The interviews were designed to evaluate tool influence on the following workflow-related queries:

- how architects make design decisions and on what grounds these decisions are made (Kanters et al., 2013)
- structural challenges concerning the collaboration with engineers in architectural competitions (Kanters & Horvat, 2012)
- the necessity of using multiple tools during the design process (S. G. Attia & De Herde, 2011)

Interview data were analysed using the research method grounded theory (Glaser, Strauss, & Strutzel, 1968), which has been applied to analyse architectural design processes previously (Kanters et al., 2013). Interviews were broken into paragraphs and quotes that were coded using a list of categories from the interview guide and mapped into themes. Findings will be presented in the results section as a condensed narrative with supporting quotes. All interviews were conducted in Danish. Quotes given in the results section have been translated by the authors as closely as possible to the original statement.

The integration of qualitative and quantitative methods build on mixed methods techniques combine knowledge to provide a holistic perspective on the topics investigated. The arguments for applying a mixed methods approach include *Completeness*, *Explanation*, *Illustration* and *Utility* using Bryman's mixed methods rationale classification (Bryman, 2006). In this case, the **IEQ**Compass results provide evidence for potential IEQ performance improvements, but observations are required to explain when and how the tool was used. Interviews allow for further

Table 1. Overview of the how the two design process setups complement each other.

Topics tested	Design team workshop	Master student project
Project type	Deep renovation (of an existing apartment block)	New built housing complex and development of a site plan
Dwelling	Refurbishment	New apartment design
Time span	3x 45 minutes ('condensed design process')	Two months ('regular design process')
Project phases	Early design stage (renovation)	Preparation and Brief, Concept Design, Developed Design, Technical Design
Users	Multi-disciplinary professional design team	Architecture/Civil engineer master students
IEQ-Compass use	Operated by the Specialist team	Operated by the students
Interview focus	Creative processes, Design compromises, Collaboration, Tool functionality	Creative processes, Design compromises, Collaboration, Tool functionality

investigation into the participant's reflections on tool functionality and usability through their interpretation of the design process experiences.

While this research presents only the key design developments related to IEQ performance, many decisions taken during the design processes were not IEQ driven. The design teams had to balance a wide range of interests such as functionality, aesthetics, cost and energy efficiency (Table 2). The design teams were introduced to **IEQ**Compass before the design work was initiated, but measures were taken to monitor that the IEQ focus did not compromise other interests. For instance, all workshop design iterations were checked to comply with the energy performance requirements of the Danish building regulations. Also, the professional design team used their practice experience to ensure the integration of a sufficient level of functional and aesthetic qualities (self-assessed, through comparison to similar renovation projects), while keeping cost reasonable. The design proposals of the students were commented regularly during supervisor meetings, and also by a panel of opponents representing the architectural and engineering industry at a midterm seminar. The final proposal was evaluated as a whole (including aesthetics, function and buildability) at the project exams, which included both supervisors and an external censor (architect).

Workshop setup (condensed design process)

The design team was asked to generate design proposals while being presented with IEQ performance assessments to guide their design choices. The design team controlled the design process and made all decisions. The specialist team used the drawings and decisions made by the design team as **IEQ**Compass input. The specialist team presented the results to the design team before starting their next design iteration.

The workshop took place in a single room and lasted for five hours, including breaks and reflections. The design team were the main actors, with the specialist team acting as technical consultants (Table 2). The specialist team introduced the design team to the potentials of the **IEQ**Compass tool and the aim of the workshop. After that, a 3x 45 minutes design process began, opening with developing a preliminary renovation proposal (duration: 45 min). At this stage, there was no interference from the specialist team.

Table 2. Overview of design criteria and participant composition (facilitators, consultants and supervisors *in italic*) for the two setups.

	Design team workshop	Master student project
Design Criteria	From the original renovation brief: - more attractive neighbourhood - improved safety and security - modern style and aesthetics Additional workshop requirements: - improved overall IEQ (as assessed by the **IEQ**Compass tool)	From the semester description: (key topics from the project brief): - high-density sustainable dwellings - small-scale urban design - housing complex design (new built) - apartment layout design (families) - zero-energy building - high-level IEQ - DGNB design criteria - sustainable material use
Participants	One design team, 5 people (LINK Architecture): - architect x3 (representatives from both the competitions department and project development) - constructing architect x2 (both project managers, one specialized in dwellings, the other head of sustainability) *Specialist team, 4 people (academic and industry):* - *engineer consultant (workshop facilitator, linking Design team and Specialist team)* - *co-author (IEQ specialist,* ***IEQ****Compass operator)* - *student helper (energy performance evaluations)* - *first author (participant-observer, interviewer)*	Two design teams, 4 and 5 people (students): - architect/engineer profile, 2nd-semester master students, high level of training in integrated design processes *Supervision / critique (academic and industry):* - *architect supervisor (architect)* - *engineering supervisor, co-author (building energy and indoor environment engineer)* - *censors, midway and final critique (external censors from the industry)* - *first author (participant-observer, interviewer)*

During a short break, the specialist team used the preliminary design proposal to calculate the potential IEQ score and to evaluate energy performance. After the break, the design team was presented with the assessment results (15 min). Using this analysis as the point of departure, the design team revised the proposal while consulting the specialist team and receiving live **IEQ**Compass score feedback on different proposals (30 min). After a lunch break, the specialist team presented the results of the revised proposal assessment (15 min). The design team made final changes to the design proposal, including making detailed decisions on 'surface material', 'user influence' and 'component' level (30 min). The workshop closed with score comparisons between baseline, 'as built' (realised renovation, see 2.2.2 below) and the workshop proposal. Also, a semi-structured group interview was conducted with the design team concerning immediate reflections on the design process and workshop.

Workshop case

The design team was tasked to produce renovation proposals for a worn-down apartment building at Fyrkildevej in Aalborg, Denmark. Prior to the workshop the architectural firm had been charged with making a renovation proposal for one of these buildings, as part of the REBUS project. The architectural firm was invited to participate in the workshop as a design team consisting of members with a broad representation of skills and backgrounds, some of which were familiar with the project from either the competition or the project development stages. In the workshop, the design team was asked to generate a new design proposal with a focus on the indoor environment using the feedback provided by **IEQ**Compass. The proposals had to live up to the requirements for functionality, aesthetics, buildability and cost corresponding to the actual renovation proposal, which was finalized just before the workshop.

Workshop data collection

Several design proposals were scored using **IEQ**Compass, including a series of explorative performance comparisons between design proposal variations (e.g. different window areas). Results will present score developments between workshop iterations, and compare the scores of the three different designs; (1) 'baseline' (before renovation), (2) 'as-built' (realized renovation), and (3) 'workshop' (final workshop proposal (Figure 1). The workshop proposal score can be compared to the realized renovation score from 2017 ('as built'), which represents a renovation proposal of the baseline using a traditional design process (i.e. no particular IEQ focus and no use of IEQ DDS tools) (Figure 1).

Qualitative data were collected to evaluate the role of the tool in the design process, and to get feedback on the potential application of the tool in practice. Qualitative data were collected in three ways; (1) participant observations during the workshop, (2) a semi-structured group interview with the Design team right after the workshop, and (3) semi-structured individual interviews with two design team participants ten days after the workshop. Individual interviews included both an architect (competitions department) and a constructing architect (head of sustainability).

Project setup (regular design process)

To test the application of the **IEQ**Compass in a longer design process, the authors collaborated with two master student groups at the Architecture specialization

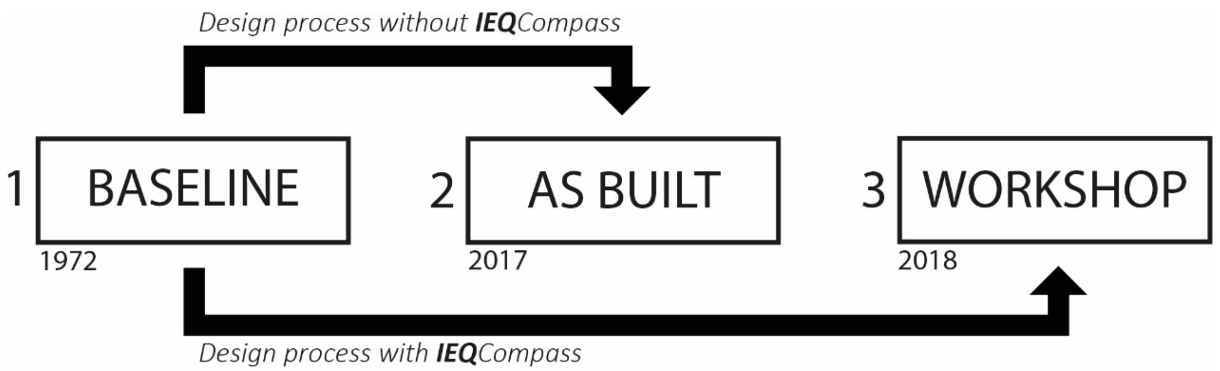

Figure 1. Diagrammatic overview of the two new renovation proposals generated for the apartment building ('baseline'), using different design process setups. 'As built' follows a traditional design process, while 'Workshop' is the result of the condensed design workshop.

of the Architecture and Design education at Aalborg University (Table 2). Aalborg University has a solid problem based learning platform, and the Architecture and Design students are schooled in applying IDP (Hansen & Knudstrup, 2005) to realistic building development tasks. The students work in small design teams from preparation and brief, to concept design, developed design, technical design and validation. The students are highly trained in integrating technical parameters such as energy efficiency, statics and IEQ. This setup provides a unique opportunity to study the influence of the tool from the earliest design stages to validation and communication of results.

The two groups consisted of 4 and 5 students on their 7th out of 10 semesters towards an engineering degree within architecture. The groups volunteered to use **IEQ**Compass on their main project and to provide feedback in a closing group interview. The authors introduced the tool to the students at the beginning of the project period spanning from October 24th to December 20th 2018. The students were supervised by an architectural supervisor (architect), and a technical supervisor on indoor environmental and energy efficiency topics (civil engineer), who also provided support on the use of the **IEQ**Compass tool. Design process observations were performed during select supervisor meetings and the project exam in January 2019.

Project case

Students were tasked to design a small housing complex for the project site Limfjordsværftet in Aalborg, Denmark (4350 m^2). The design task involved small scale urban design in an old industrial harbour area, as well as the design and layout of the apartments. Project proposals were to reinterpret the qualities of suburban living into a dense urban context. Excerpts from the design brief include: mixed user profile housing complex, family apartments of 115 m^2 with three bedrooms, access to private outdoor areas, plot ratio of 70% or higher, zero energy standard.

Project data collection

IEQCompass performance assessments were generated throughout the project, but results will be presented only for design iterations within the same conceptual direction. The use of the tool in the early conceptual design stages will be discussed qualitatively. Qualitative data were collected in three ways; (1) observations during selected supervisor meetings, (2) participation in group exams and (3) semi-structured group interviews two weeks after the exams.

Results

First, the results from the workshop with design professionals will be presented in two parts: (1) analysis of design proposals and a summary of the observations during the design process, and (2) main findings from the group interview and the two individual follow-up interviews. Similarly, the results of the student project work will be presented in two parts: (1) analysis of and comparison between design proposals, and (2) main findings from the exam observations and the follow-up group interviews.

Workshop design process and design proposals

In the first design phase, the design team was instructed to approach the renovation task as they usually would, without being constrained by the workshop focus on IEQ. A simplified version of the workshop design process concerning IEQ performance is presented in table 3. Numbers in brackets refer to iteration numbers listed in the table. The design team split into two sub-teams and started to generate renovation proposals to the case building that the design team was presented with at the beginning of the workshop [#1]. There was no interference from the specialist team during this phase. The design teams worked primarily with plan layout topics such as zoning, flow, spatial qualities, merging rooms, moving functions, access to private outdoor areas, efficient use of m^2 and flexible furnishing. They also considered IEQ aspects such as cross-ventilation, daylight access, daylight from two sides and the risk of overheating. One proposal suggested moving the façade two meters out to avoid an overhang from a balcony on the floor above. However, the design team decided to proceed with a proposal that kept this overhang as a measure against overheating, as it would allow for more glass in the façade below. The team also discussed envelope and construction topics such as suspended ceilings, loadbearing constructions, and elimination of panel walls below windows to improve thermal performance and reduce heat losses. The design team settled on a preliminary renovation proposal after improving apartment layout, functionality and flow. The specialist team updated the building model to match the design proposal and presented the resulting minor changes in IEQ performance [#2].

In the second design phase, the design team worked with envelope and façade design topics including external walls (materials, insulation), windows (G-, U- and Lt-values), balcony design and interior surface materials. The design team used a Design Compass (graphical scoring integrated into the tool, Figure 2) as the point of departure for a series of iterations to improve the IEQ performance [#3-#6]. The first step was adding mechanical ventilation to improve IAQ performance [#3]. After this, the design team discussed whether to replace panel walls with well-insulated wall sections or French windows. Topics considered include drafts, radiators vs other heating sources, view out, view in, daylight access and risk of excessive passive solar. The design team decided to increase glazing on the west façade (living room) by including full-height glazing despite the risk of overheating, using qualitative arguments: 'This is also about habitation quality: the sense of being connected to one's surroundings.'

The increased glazing positively impacted daylight performance but also resulted in minor setbacks in noise exposure from the surroundings and a higher risk of downdrafts [#4]. These setbacks were countered by opting for triple-pane windows with better noise insulation and U-values [#5]. Again the design team prioritized daylight, by also increasing glazing to the east (bedrooms and kitchen) [#6]. The positive change in daylight performance was offset by too high summer temperatures.

In the last design phase, the design team made final adjustments towards the workshop renovation proposal. At this stage, the design team discussed surface materials and IEQ robustness and were presented with a range of 'user influence' options on solar shading, window opening and mechanical

Table 3. Overview of **IEQ**Compass scoring of selected workshop design proposals. Numbers given in parenthesis show score changes compared to the previous iteration. Arrows indicate positive (up) and negative (down) criteria influence.

Iteration	IEQ-Compass score	Main area scores	Criteria changes
#1 'Baseline'	69%	ACO = 74% IAQ = 66% THER = 72% VIS = 66%	N/A
#2 'New plan layout'	70% (+1%)	ACO = 73% (-1%) IAQ = 70% (+4 %) THER = 71% (-1%) VIS = 66%	**ACO:** ↑ Fewer rooms with low absorption surfaces ↓ More exposure to noise in the main room **IAQ**: ↑ Option to dry clothes outside the envelope **THER:** ↓ Fewer rooms without radiators under the window (draft)
#3 'Mechanical ventilation'	76% (+6%)	ACO = 76% (+3%) IAQ = 89% (+19%) THER = 75% (+4%) VIS = 66%	**ACO:** ↑ Mechanical ventilation with sufficient sound dampening **IAQ**: ↑ Balanced mechanical ventilation ↑ Mechanical ventilation in the bathroom ↑ Filtration of the outdoor air **THER:** ↑ No drafts from intake air due to preheated air supply
#4 'Increased glazing: west'	78% (+2%)	ACO = 74% (-2%) IAQ = 89 THER = 74% (-1%) VIS = 74% (+8%)	**ACO:** ↓ Larger windows w. low sound insulation (compared to walls) **THER:** ↓ Increased risk of downdraft due to increased window heights **VIS:** ↑ Larger windows result in better daylight conditions
#5 'Tripple pane windows'	80% (+2%)	ACO = 78% (+4%) IAQ = 89% THER = 78% (+4%) VIS = 74%	**ACO:** ↑ Window components w. better noise reduction properties **THER:** ↑ Window components w. lower U-value: less risk of radiant temperature asymmetry and less risk of downdraft
#6 'Increased glazing: east'	80% (+0%)	ACO = 78% IAQ = 89% THER = 72% (-6%) VIS = 80% (+6%)	**THER:** ↓ Larger windows result in more hours w. too high temperatures **VIS:** ↑ Larger windows result in better daylight conditions
#7 'External solar shading' – Workshop final	85% (+5%)	ACO = 78% IAQ = 89% THER = 89% (+17%) VIS = 82% (+2%)	**THER:** ↑ External solar shading results in fewer hours w. too high temperatures **VIS:** ↑ Moveable external shading: separate for each window and with no view out interference when 'not active'

ventilation control. The specialist team directed attention to the thermal comfort issues, leading to one last iteration with external solar shading in the shape of movable shutters that eliminated issues with too high solar gains [#7].

The Design Compasses in Figure 2 compare the potential IEQ performance between three designs. The 'as built' assessment has an overall score of 72%, which is slightly better than the 'baseline' performance at 69%. As indicated by the black arrows on 'as built' in figure 2, the improvements in IAQ (mechanical ventilation), is almost offset by the setbacks in VIS (direct sunlight and daylight quality scores), and THER (summer comfort score). The workshop proposal, however, has managed to drastically improve both VIS and THER, by developing a design that maximizes scores for both direct sunlight, daylight and summer comfort through several iterative design steps (Table 3). When combined with the IAQ improvements, the 'Workshop proposal' score 85%. This brings the design proposal close to the realistic maximum score for the given renovation as some criteria are either: partly given by the context (such as airborne noise levels, air pollution levels and conditions for view in/out) or determined by conditions that are too expensive to remedy (e.g. airborne sound insulation to neighbours would require demolition of loadbearing walls).

Workshop interviews

The combined findings from the group-interview and the two follow-up interviews with design team members are presented categorized by themes and sub-themes.

Early-stage decision support

On the Concievement of design ideas. The design team expressed that while the first design stage was 'business as usual', the evaluation at the beginning of the second stage changed things. Several team members reflected that design choices were influenced by more aspects than usual and that the tool provided arguments to choose new solutions:

> Martin and I had many discussion about panels below the windows, both concerning exposure to views from the outside and too high temperatures. Usually, for a competition proposal, one would quickly select glazing all the way to the floor… and be more concerned about the façade-composition.

Using **IEQ**Compass gave the team ideas and arguments for prioritizing IE:

> Having IE in the back of your mind… it makes you come up with different solutions.

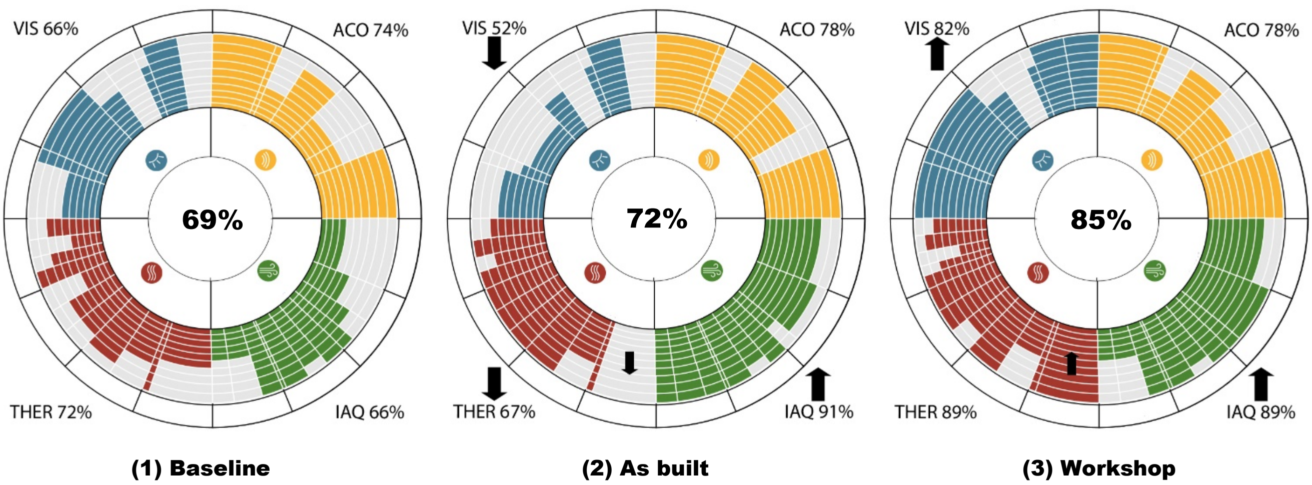

Figure 2. Design Compass. Graphical scoring of design proposals, from left to right: 'baseline', 'as built' and 'workshop' proposal. Arrows indicate significant differences in criteria (small arrow) and main area scores (large arrow), positively (up) or negatively (down) compared to the baseline score.

On the evaluation of the generated proposals. The team discussed IE topics such as simple ventilation strategies and daylight distribution in the first stage and expressed that they would have done this in any case (without a DDS tool). The design team described that they always form concepts within the constraints given by the project, whether that is technical aspects or the room programme – it is never merely about what they think looks good. In that sense, the team did not fear that early-stage technical evaluations would limit their creativity:

> It is very much about when you choose to activate which tools. When you draw the first few lines, you do not have to think about mechanical ventilation.

One design team member argued that a gradual activation of the tool would be useful, which could be guided by an IEQ consultant, a design team with IEQ expertise or even by the tool itself:

> It would be cool if you could tell which parameters influence decisions when designing on the site level – and which appear when you look at interiors etc.

Current and future work practice concerning early design processes

The design team has introduced parametric-based tools (grasshopper, ladybug and honeybee) to their daily practice to add simple evaluations of sun/shadow, wind/lee and daylight potential to their early site and volume studies. According to the head of sustainability, this is a consequence of crucial early-stage decisions taking place long before traditional simulations are available:

> This is something that we already focus on, as we realize that in the sketching phase, it is a challenge that we do not get the engineer calculations until the design is done.

He elaborates that as architect consultants, they are responsible for early decisions on building shape and façade designs, long before the calculations on energy, ventilation and thermal comfort are produced. Thus, they need early-stage technical tools, which can test the chosen building shape and façade design for robustness. A team member of the competition department adds that in the early stages they must be able to model a concept and test it in less than an hour for it to be operational and feasible. Looking back on the workshop, the design team express that they could see IEQ workshops as part of early design processes in their future practice:

> It is a significant advantage, whether it is renovation or new built, to get the technical parameters and the engineer introduced in the early stages and to do workshops with them… it is definitely a benefit to address the critical challenges from the various professions.

In competitions where there is a joint team with both architects and engineers, there is a potential to make robust designs by integrating technical requirements in the early concept proposals (Kanters et al., 2013). However, according to the competition department team member, the consultant engineers do not wish to participate in the early stages as it is too expensive for them to make calculations while the design is developing. This leaves the design team without an expert assessment of technical performance when selecting the concept with which to proceed. Afterwards, the engineers assess the performance of the concept and typically conclude that it fails to perform. If the team wins a competition with an 'all-glass building', then the client will get just that – with just expensive and inefficient half measures available to remedy lacking performance. Early multi-disciplinary workshops that apply low effort assessment tools could be a way to address this, as it provides operational DDS at a crucial stage while keeping costs low.

The design team was eager to see how the original renovation ('as-built') scored with **IEQ**Compass. The team was shocked to find that the renovated building did not perform very well on IEQ. The primary renovation goal was to re-establish social dimensions such as safety and security, while bringing the energy efficiency, building state and aesthetics up to speed. Thus, IEQ had not been a focal point in the renovation, yet everyone expected IEQ performance to have improved:

> It is frightening that score-wise, it gets the same value as before. In some areas, it actually performs worse.

Functionality and application

The design team emphasize that one of the strengths of the tool lies in the communication of results both internally, with other consultants and with clients. One team member expressed that because the tool calculates and visualizes the resulting IEQ when they change the window area, it becomes a very powerful design tool. Furthermore, it allows the team to document to clients why one proposal was chosen over another. The head of sustainability express that there is currently no shared language between the tools used by architects and engineers, and that they are trying to create one:

> A large part of the incitement to use "climate-tools" and put figures on our architecture, is a search for the good argument and the good basis for discussion. Often the architects draw the soft lines, and then the engineers enter with their hard figures (that always weight the most)... So the more numbers we can tie to our designs, the more we can argue or discuss with engineers about how the solution should be.

The head of sustainability adds that because **IEQ**Compass provides easy to read results, the tool can help create demand for high-performance IE:

> An operational tool like this will make a huge difference, as it means that you sell indoor environment because it can be communicated… Getting such a tool would be very good – if there are A/B/C/D (labels), then it becomes very simple for a client to set requirements.

Project results

Table 4 provides an overview of the project course by dividing it into eight weeks of project work, which corresponds to design processes common in practice. **IEQ**Compass assessments were made for the earliest design stages, in week three to five. As the project developed rapidly on both urban scale and apartment scale at this stage, the assessments were used in two different ways: (1) to evaluate the general performance of large-scale design options such as different massing and orientation options, or (2) to compare varying apartment layouts. After deciding on a concept to detail from week six to week eight, the assessments were used to test the influence of small-scale design suggestion such as façade designs and floor plan variations. **IEQ**Compass helped indicate how non-IEQ-related improvements to the design such as functionality, aesthetics and energy efficiency would influence IEQ performance. Also, the tool was explicitly used to show lacking IEQ performance so that the project groups could work on design suggestions that would improve IEQ performance. Thus, the **IEQ**Compass tool provided holistic IEQ assessment input to guide the project direction from the early design stages (brief, pre-conceptual design, conceptual design) to the later design stages (preliminary design, developed design, detailed design).

Table 5 present a simplified summary of how the tool was used to guide, test and document a series of IEQ improvements. As the earliest models wary considerably, the process presented is from the selection of a single concept to detail.

Both groups show considerable overall improvements over the three iterations, with a +17% point improvement compared to the baseline (iteration 1). The four area scores vary considerably between the two projects, showing that the search for overall IEQ improvements does not dictate priorities between areas. Despite the very similar overall performance, the variation between areas is as high as 16% points (IAQ). Overall Group 1 has very balanced scores (+/-8%points from the average) although choosing to prioritize THER at 90% slightly over VIS at 75%.

Table 4. Overview of Project phase, Tasks, **IEQ**Compass tool application and the Qualitative data collection over the eight project weeks (W1-W8) and the project exam.

	W1	W2	W3	W4	W5	W6	W7	W8	January 2019
Project phase	Problem	Analysis	Analysis/ Sketching	Sketching	Sketching	Sketching/ Synthesis	Sketching/ Synthesis	Synthesis/ Presentation	Presentation
Tasks	**Project startup** Problem statement and vision	**Analysis** Project program develop-ment*	**Site plan** Typology, volume, orientation	**Apartment layout** Function, Circulation, light and spatiality	**Materials** Tectonics and at-mosphere	**Midway critique** Final concept direction	**Concept iterations** Optimizatio n and detailing	**Final touches** Documen-tation and project hand in	**Exam** Preparation of posters, models and presentation
Application of IEQ-Compass	Initial under-standing of essential IEQ topics	Setting goals for IEQ perfor-mance	Assess: orientation studies	Assess: Apartment com-parisons	Assess: Finding the critical apartment	Assess: Basic model	Assess: Iteration 1 and 2	Assess: Iteration 3 (final)	Communicati on of the process and the result
Qualitative data collection			----------------------- Observation: Group meetings -----------------------						Observation: Exam (and follow-up interviews)

*(project vision, design criteria, room programme, analysis of; site, user group and technical aspects such as sustainability, LCA, DGNB, energy).

Table 5. Overview of **IEQ**Compass scoring of selected project proposals. Numbers given in parenthesis show score changes compared to the previous iteration. Arrows indicate positive (up) and negative (down) criteria influence.

	Iteration	IEQ-Compass score	Main area scores	Criteria changes
GROUP 1	1 'Basic Model'	65%	ACO = 76% IAQ = 50% THER = 69% VIS = 65%	N/A
	2 'External solar shading'	68% (+3%)	ACO = 76% IAQ = 50% THER = 78% (+9%) VIS = 67% (+2%)	**THER:** ↑ External solar shading results in fewer hours with too high temperatures **VIS:** ↑ New window layout improves access to daylight
	3 'Window properties and surfaces'	71% (+3%)	ACO = 80% (+4%) IAQ = 50% THER = 77% (-1%) VIS = 79% (+12%)	**ACO:** ↑ Lower reverberation time due to high absorption surfaces **THER:** ↓ Lower window U-values result in more hours with too high temperatures) **VIS:** ↑ Larger window area results in more daylight access, ↓ Less access to view out (because of changes in the master plan)
	4 'Mechanical ventilation'	82% (+11%)	ACO = 83% (+3%) IAQ = 82% (+32%) THER = 90% (+13%) VIS = 75% (-4%)	**ACO:** ↑ Mechanical ventilation with sound dampening **IAQ:** ↑ Balanced mechanical ventilation ↑ Particle filtration of outdoor air (fine or ultra-fine filter) ↑ Improved possibility to increase ventilation rates (cross ventilation, night flushing, openable windows in all rooms incl. bathrooms, temporary mechanical ventilation boost) **THER:** ↑ Fewer hours with too high temperatures due to reduced window area, and lowered window U- and g-values ↑ Possibility to improve thermal comfort through increased ventilation rates (see IAQ above) **VIS:** ↓ Less daylight access: less window area and a lower Lt-value ↑ View out improvements (window layout and orientation) ↑ Lower view in risk because of reduced window areas and attention to window placement ↑ Adjustable external solar shading (no view interference)

	Iteration	IEQCompass score	Main area scores	Criteria changes
GROUP 2	1 'Basic Model'	67%	ACO = 38% IAQ = 91% THER = 69% VIS = 71%	N/A
	2 'Added external shading, reduced glazed area, and improved acoustic performance'	74% (+7%)	ACO = 63% (+25%) IAQ = 97% (+6%) THER = 76% (+7%) VIS = 60% (-11%)	**ACO:** ↑ Improved sound insulation of apartment partition walls ↑ Lower reverberation time due to high absorption surfaces (acoustic ceiling panels)A **IAQ:** ↑ Demand-controlled ventilation ↑ Possibility to improve air quality by temporarily boosting ventilation rates (pushing a button) **TER:** ↑ Fewer hours with too high temperatures due to external solar shading, reduced window area, and reduced window g-value ↑ Possibility to improve thermal comfort by temporarily boosting ventilation rates (pushing a button) **VIS:** ↓ Less daylight access resulting from decreased window area and lowered Lt-value
	3 'Further acoustic improvements'	78% (+4%)	ACO = 79% (+16%) IAQ = 97% THER = 76% VIS = 61% (+1%)	**ACO:** ↑ Improved sound insulation of floor separation ↑ Sound dampening of staircase elevator **VIS:** ↑ Better daylight access from larger bathroom windows
	4 'Improved efficiency and functionality of external shading'	84% (+6%)	ACO = 79% IAQ = 98% (+1%) THER = 92% (+16%) VIS = 66% (+5%)	**IAQ:** ↑ Service agreement for kitchen exhaust hood **TER:** ↑ External shading factor increased on one façade (affects three bedrooms and two bathrooms) resulting in fewer hours with too high temperatures **VIS:** ↑ Adjustable external solar shading (no view interference)

Group 2 has almost perfected the potential IAQ with 98% and has also chosen to prioritize THER performance at 92%, over VIS performance at 66%. One of the reasons that THER performs higher than VIS is that both groups chose to reduce window areas in their latest iteration to avoid excessive solar gains: This compromise was made to prevent the need for mechanical cooling of the apartments, which impose a penalty in the Danish energy labelling system.

Project interviews and observations

Observations during supervision meetings, project evaluation and the follow-up interview revealed that the two student groups had different experiences with the tool, as they had used it in different ways. The following summarizes the most interesting reflections presented by topic for both groups combined.

Early-stage decision support

On the Concievement of design ideas. All participants had previous experience with IDP and managed to use the tool in the early design processes. One group used **IEQ**Compass mainly as verification of their design choices, and at the exams, they reflected that the tool was unfortunately not used in an explorative manner. They stated that the tool was used to identify a problem, which was then solved 'outside' the program. The other group first used **IEQ**Compass to test the relative influence of different parameters by adding and removing, e.g. mechanical ventilation and external shading. They created a simple apartment model with given input (such as site conditions and apartments sizes) and explored the design space through experimentation before developing their initial design concepts. Despite this exploration, they expressed that:

> **IEQ**Compass does not dictate the design - you need to have architectural considerations before you can use the tool.

Both groups stated that design decisions often were a compromise between IEQ and energy performance. Sometimes **IEQ**Compass pulled in one direction, while the energy compliance tool Be18 pulled in the other direction. The design teams had to prioritize one of the two, or even choose to prioritize aesthetics instead. Consulting the technical tools during the design development helped convince teams that their designs would perform well:

> If not - the early design discussions would be purely architectural and aesthetic, and you would lack the arguments for the other parts. It is nice to have some evidence to back your choices. You can say: it does work because **IEQ**Compass says so and you can see it right here.

On the evaluation of the generated proposals. Each group had a consensus on aesthetic priorities that allowed them to evaluate designs aesthetically while using **IEQ**Compass and Be18 assist in the evaluation of technical aspects. The students were not new to energy-efficient building design but said that:

> **IEQ**Compass helped us realize that as long as we meet the requirements of Be18, we did not have to strive for the lowest possible energy consumption because there were other qualities to consider.

Current and future work practice concerning early design processes

Both groups expressed that working with the tool has influenced their way of thinking about indoor environment:

> I have learned many things that I need to consider in future projects – already after using the tool once we have gained ballast to bring into future projects.

> I am working on a single-family house at the moment, and I can tell from my argumentation that I have brought some things with me.

Without **IEQ**Compass the early IEQ considerations were mainly concerning daylight and temperature, but now also includes acoustics, air quality, and view in/view out. The tool made the students consider some aspects in greater detail, such as how windows opened and whether the users could operate them easily. Particularly the ideas about user influence resonated with the students. One student stated that 'IEQ in design practice makes perfect sense because architecture is about people'. Another student said:

> **IEQ**Compass had a major impact on the design team member´s thoughts on the user as a new important aspect.

Functionality and application

Both groups expressed that the tool provided an excellent overview of the many IEQ parameters to consider. They reflected that without **IEQ**Compass, IEQ criteria were handled in an arbitrary order by a range of separate tools, but now it was united in a single tool. In that way, different parameters could be compared simultaneously. One group decided to use a supplementary tool (VELUX Daylight Visualizer) to simulate the daylight distribution in the apartment, which shifted focus away from the holistic overview provided by **IEQ**Compass:

> We had more focus on daylight in the VELUX visualizer, and at that time in the process, we forgot to look at the visual comfort in **IEQ**Compass… so maybe we forgot something because we used too many tools.

Both groups expressed a demand for **IEQ**Compass performance benchmarks – is the label 'C' good or bad? How much of a problem is a 'view in risk' score of 4? When relevant, the tool manual compares **IEQ**Compass scores to PD and PPD to provide relatable performance indication. Also, the tool has a built-in comparison with Danish building code minimum requirements, but requirements only exist for 8 of the 40 criteria assessed in tool. Another challenge is that project conditions differ, meaning that project-specific practical maximum scores may be much lower for external noise, outdoor air pollution, daylight, sunlight, view in and view out. Regardless of the design, one cannot score 10 in the external noise criterion if there is heavy traffic nearby. The authors recognize that this is a crucial communication task from both the **IEQ**Compass developers and the consultants using it. In a Danish context, many potential assessors would have experience with DGNB that has a similar structure, where some credits may be inaccessible for a given project, but which does not prevent the project from achieving a platinum rank.

The general impression is that 'It was very straightforward and pedagogical - and it makes perfect sense that you type in input and then you see what changes'. Several students highlighted that it was easy to see which parameters affected what, as the program highlights which criteria (output) are influenced by individual input (e.g. window areas influence THER1.1, THER1.2, ACO1.1 and VIS 1.1). The students appreciated the visual feedback provided by the Design Compass:

> It makes a difference that it is easy-to-read and looks good… it is a quality that it has a nice design.

> I think it is incredibly easy to work with the **IEQ**compass - compared to all the other tools we have had during our studies this is really, really easy.

Discussion

This study indicates that the **IEQ**Compass can act as an integrated platform for early stage IEQ integration. The design guidance features and architect friendly user interface were well received by the design teams, which is in line with findings from BPS tool surveys (S. Attia, Hensen, Beltrán, & De Herde, 2012). When combined with rapid simulations and graphical support for result interpretation, the tool provided a supportive environment for early stage DDS. Assessing 40 IEQ parameters for every possible design alternative in the early design stages may sound unfeasible for design teams, but the tool combines calculation and assessment of all 40 IEQ parameters simultaneously and provides weighting, scoring and dissemination of results. According to the interviewed participants, the **IEQ**Compass provides feedback they would usually need several tools to get, in a faster and effortless manner.

The right balance between precise simulation methods and appropriate model resolution levels, provides a much more efficient route to sufficient level IEQ assessments, compared to traditional BPS tools. For early-stage DDS there is no need for high-precision methods such as CFD or ray-tracing when sufficient accuracy can be obtained using simpler methods that fulfil the architect's requirements for responsiveness (Hensen, 2004). Instead, the **IEQ**Compass tool has been developed to provide the smartest path to the most accurate assessments possible (as described in international IEQ standards), without compromising assessment speed through advanced detail input requirements and highly labour consuming simulations and interpretation. However, as pointed out by Negendahl (Negendahl, 2015) it is vital not to sacrifice tool features and flexibility to end up with a fast and user-friendly tool that is too simplistic. This became evident when one design team used a supplementary tool to simulate daylight distribution, which the **IEQ**Compass does not provide (daylight quantity assessed according the Danish Building Regulation, BR18). As the design team ignored the daylight assessments of **IEQ**Compass in lieu of the separate tool, they lost the holistic overview when they forgot to update design changes in the separate tool. To avoid this, holistic DDS tools should not only provide the assessments prescribed in standards, but also assessments that offer useful information for design teams.

The workshop demonstrated the responsiveness of **IEQ**Compass by providing real-time assessments and comparisons between design proposal variations. Since the case was a renovation of an existing building registered before the workshop, there was little time spent changing input during the workshop. As with any renovation project, there were physical and practical constraints, but the design team was free to challenge these boundaries, e.g. by changing room dimensions and plan layout. For tools that rely on pre-simulated meta models with parameter variations on 'expected' parameters, such unpredicted changes could render the models useless. The model was operated by the **IEQ**Compass team, who also interpreted the results and presented them to the design team. Thus, although the design team led the design process, the indirect influence of the IEQ domain experts cannot be ignored. But for a half-day collaborative IEQ workshop the presence of domain experts is not a bias, but a prerequisite for multi-disciplinary IDP, or in the words of Busby et al. (Busby et al., 2007) 'In general, the integrated design process is an approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints. It relies upon a multidisciplinary and collaborative team whose members make decisions together based on a shared vision and a holistic understanding of the project'.

The IDP deliberately shift the traditional work peak towards the earlier stages, where increased influence and reduced cost of changes more than makes up for the extra investment of resources early in the project (Kanters & Horvat, 2012). This type of collaboration depends on two things: (1) that IEQ domain experts navigate between active IEQ guidance and no interference when required, and (2) that the architects are open to IEQ influence, without letting technical input dictate the design or inhibit the creative process. Architects have previously reflected that technically focused workshops can make the architects 'feel like a minority' (Kanters & Horvat, 2012), but the participants of this workshop showed a high level of acceptance towards both the process and the tool itself.

The student projects provided evidence for the applicability of the **IEQ**Compass tool in projects with fewer constraints (new built) and the support of design developments from design brief to validation. It is with some precaution that the authors generalize findings from student projects to be applicable for practice, but the students are trained in a practice oriented environment and projects are set up to mimic actual design work practice. Their architect/engineer profile and IDP schooling mean that they very closely represent a professional integrated design team with access to IEQ expert knowledge. In the early conceptual design stages, design teams used the tool with a combination of predetermined project site information, default component values and simple geometric information to investigate early stage decisions on orientation, building shape and room dimensions. This is an important finding because conceptual decisions are often taken based on rules of thumb and experience, while DDS tools and performance analysis will only be employed after those decisions are made (Reinhart & Fitz, 2006). Early application of **IEQ**Compass may solve the issue that simulation tools tend only to influence 'sizing and optimization' because fundamental design-strategic decisions have already been made (Pilgrim, Bouchlaghem, Loveday, & Holmes, 2003; Wilde, Voorden, Brouwer, Augenbroe, & Kaan, 2001). A participant suggested to support early explorations further, IEQ criteria could be sorted by project phase relevance. Such criteria grading could indicate that interior surface materials are not relevant when making decisions on a master plan level.

The approach to DDS presented in this research is meant to improve conditions for early integration of IEQ topics while improving the performance of the project as a whole. Thus, the intention is to promote IEQ inclusion alongside other crucial early stage design parameters by making IEQ assessments available much earlier than using existing methods. The design experiments presented indicate that the assessment of complex technical aspects can be operational in the early design stages. The findings are likely to apply outside the topic of IEQ, and the methodologies and approaches to holistic performance assessment should be relevant for the integration of other technical aspects such as energy performance, constructions, LCC and LCA.

Conclusion

The findings of this research demonstrate that early stage integration of IEQ aspects can be promoted through the use of assessment tools developed specifically to provide ongoing DDS. Observations and interviews reveal that fast-paced assessments with a graphical presentation of results allowed for IEQ considerations on a level far more in-depth than traditional design processes, without removing the focus on other vital design parameters. The visual interpretations of results provide a holistic overview of IEQ performance, resulting in known trade-offs between IEQ aspects, which led to gradually increasing overall IEQ performance between iterations in all the tested scenarios. The workshop results show that overall IEQ performance is not necessarily improved with a traditional energy-efficient renovation, even if it includes a new building envelope and top-level components. However, IEQ performance can be improved dramatically within the same project boundaries through the use of holistic assessment methods in a multidisciplinary design team setting, by shifting a very modest amount of resources to the early design stages.

The **IEQ**Compass tool provides feedback on the current design and potential design alternatives, which guides the design team, rather than providing a single locally optimized solution. This feedback allows the design team to take IEQ performance into account, alongside other performance parameters like energy performance and qualitative architectural disciplines. Project work findings demonstrate that top-level IEQ performance can be combined with zero-energy requirements without compromising other crucial design parameters, such as functionality and aesthetics. Also, interviews suggest that tool features such as goal setting, comparison and visualized results can help increase demand for good indoor environment and help communicate the advantages of well-integrated IEQ design solutions.

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Appendix A

Interview guide for the semi-structured interviews (both individual and group interviews). Participants were asked four open-ended questions and were given both information and detail level freedom. Follow-up questions *(in italic)* were used as probes only if necessary, and both positive, neutral and negative examples were provided when used.

Appendix A – Table 6. Interview guide.

	Main question *Sub-question* - *probe examples*
Conceiving design ideas	During the workshop, how did you experience the generation of ideas and concepts being influenced by IEQ considerations? *Did IEQ considerations* - *act as creative catalysts* - *emerge naturally as integrated parts of other ideas* - *get worked into the ideas during design development* - *not influence idea generation* - *appear only as a counterargument* - *disrupt the further development of ideas* During the workshop, how did you experience the creative process being influenced by IEQ considerations? *Did IEQ considerations* - limit the creativity/scope when generating ideas - expand the scope of original ideas (inspiration) - limit the solution field when choosing ideas? - strengthen confidence and belief in non-standard solutions?
Evaluating proposals	Looking back at the generated design proposal, how do you think working with **IEQ**Compass has influenced the results? *Evaluation of design proposal* - *Have you created (a good starting point for) good IEQ?* - *Was IEQ considered earlier/more in-depth than standard practice?* - *Is the concept more robust/resilient to later-stage IEQ compromises?* - *Are some IEQ considerations well integrated into the solutions?* - *Are some IEQ considerations put-on measures?* *Did the IEQ focus compromise other essential design criteria?* - *Function* - *Aesthetics* - *Cost* - *Energy efficiency* - *Buildability* - *Other*
Expected future work practice	In your future work, how do you see the role of IEQ in design processes? *Will it remain unaffected (business as usual)? - if so is this due to:* - *excessive time/cost* - *design philosophy: not the architect's field, responsibility, interest etc.* - *removing emphasis on 'architectural qualities'?* - *difficulty: missing specialist/generalist expertise?* - *lack of incitement (client demand, legislation)?* - *conflict of interest (contracts, legal responsibility)?* *Will it be affected slightly, noticeably or disruptively?* - *will this have a prolonged incubation (conservative industry, tradition, legal matters), relatively brief incubation time, or happen immediately?* *Will it affect your collaboration with in-house or external specialists within IE? – if yes:* - *positively? (working towards the same goal, speaking the same language, more robust proposals, less 'wrongs' to wright in the end, other)* - *negatively? (conflicts of interest, legal responsibilities, other)*
IEQC – tool functionality	How do you expect the different **IEQ**Compass modules will affect your future design process? *Will the possibility to **set specific ambition levels** for IE make it more likely to be a design driver?* *Will the **criteria overview** allow natural integration of IE in future proposals (knowing what affects what)?* *Will the **design proposal comparison** module enable you to make informed decisions on IEQ aspects?* *Will the **visual communication** promote communications with colleagues, clients and end users?*

CHAPTER 6. REFLECTIONS, DISCUSSION AND CONCLUSION

6.1. REFLECTIONS – PAVING THE WAY FOR HIGH-QUALITY IEQ

Improving IEQ has proven to have several advantages, yet it remains a challenge to increase the demand for high-performance IEQ. The author suggest to approach this challenge from three angles: (1) informing the public that IEQ is not necessarily expensive, (2) informing occupants of IE consequences and potentials, and (3) increasing political focus.

6.1.1. ARE IEQ IMPROVEMENTS EXPENSIVE?

The most widespread comprehensive sustainability assessment methods are very resource demanding, from additional expenses for consultancy (or in-house specialists), and resources spent on planning and following up. As third party (commercial) certification systems, also charge building owners for receiving the label, the process quickly becomes too expensive and time-consuming to be attractive for small-scale projects. Since assessment methods for IEQ (and green rating schemes that include IEQ) are voluntary, only the building owners who already prioritise these topics are likely to use them. Furthermore, only high-quality buildings that are certain to achieve a given label will apply the necessary effort and resources to get it (Haapio & Viitaniemi, 2008). Thus, the projects with the largest potential for improvements (i.e. low-quality projects with building owners who do not prioritise IEQ) are unlikely to apply such an assessment method.

Despite the strong case to invest in IEQ, for both society, professional building owners and private homeowners, demand does not directly follow. Unlike for energy-saving initiatives, or productivity boosts from improved IEQ in offices, the benefits for IEQ in dwellings are harder for building owners to translate into ‘investment payback time’. The willingness to invest is likely to be inhibited by both investment costs and running costs of IEQ, as building owners have financial constraints, and there are many competing investment options. According to a report on the state of housing in the EU, housing is the single highest expense amounting to 25% of Europeans’ monthly budget in 2015 (Pittini, Koessl, Dijol, Lakatos, & Ghekiere, 2017). Although concerns on implementation costs of high IEQ is outside the scope of this dissertation, the two paragraphs below will provide some perspectives on cost assumptions.

Investments costs

Investing in IEQ improvements may include some or more of the following expenses: IEQ consultancy, IEQ assessment, purchase of new (or more expensive) products and components. The first two expenses could be significantly reduced using the **IEQ**Compass tool in the early design stages, as it provides inexpensive assessments that use much of the same input required for the already mandatory energy compliance calculations. Also, the tool supports planning, dialogue and result dissemination, which may reduce demands for additional IEQ consultancy. The design process analysed in Paper D, provide examples of a shifted workload rather than an increased workload (e.g. from detailed design to conceptual design). If successful, this extra investment of time in the early design stages will be offset by savings in the later stages, as the IEQ design strategies are more developed and the overall IEQ performance is more robust than it would otherwise be. Also, IEQ strategies implemented in the early stages are generally more effective and less expensive (Brager, 2013). For instance, a design concept that limits passive solar gains can prevent the need for expensive external solar shading to pass regulation compliance checks in the detailed design stage.

Running costs

The additional running costs of high-quality IEQ depends very much on the nature of the improvements, but may include increased energy consumption, such as from increased ventilation rates or changed setpoints for heating. Contributors to increased electricity consumption include mechanical ventilation, increased artificial lighting, cooling systems and motorisation windows and shading systems. Many other IEQ improvements are, however, of a passive nature, and such initiatives could result in a more robust indoor environment with no additional running costs. Some may even reduce running costs, such as improved access to daylight. Energy-related performance gaps have shown to be highly affected user behaviour, such as from the 'Rebound effect' when energy consumption after a renovation is higher than expected due to changed IEQ expectations (Booth & Choudhary, 2013). If holistic IEQ design can generate robust and user-friendly IEQ solutions, this may help realise economic and environmental sustainability through reduced actual energy consumption.

Improvements for free

Some IEQ improvements may be implemented without additional expenses, by balancing IEQ aspects holistically in the early design stages. For instance, window openings with several orientations may increase daylight and sunlight access, enable cross-ventilation, and provide access to fresh air from the direction with the least exposure to outdoor noise and air pollution. Window layouts can combine glass area and orientation to obtain the right balance between passive solar gains and access to daylight. Façade designs can provide a good compromise between limiting exposure to view in and providing access to view out. If we assume that the efforts of the design team and consultants are shifted from late to early design stages, the above improvements do not result in any additional investment or running costs - and may even reduce the final costs, by eliminating the need for expensive add-ons in later stages.

Technological advances have led to increased comfort expectations. To some extent, the indoor environment is controlled to approach homogenous conditions irrespective of dynamic parameters such as weather conditions or people loads. Controlling the indoor environment has a price, both economically and environmentally. Particularly so, if it is tackled using active technical solutions in the later design stages. Instead, the evidence presented in Paper A for occupants preferring dynamic and varied environments (for some IE aspects) could be used to identify both low-cost and no-cost improvements of IEQ, which may also save energy. Similarly, many of the examples of positive stimuli presented in Paper A could be implemented in early design concepts without any additional investment. The evidence presented for positive stimuli that increase IE acceptance and promote positive subjective evaluation of the overall IE means that integration of qualitative aspects could help close the gap between predicted and realised IE satisfaction.

6.1.2. MOTIVATING PRACTITIONERS AND OCCUPANTS

In the absence of mandatory IEQ labelling, the best option for promoting the use of IEQ assessment tools is to make them attractive for all stakeholders. With **IEQ**Compass design teams get access to IEQ decision support, engineer consultants get the opportunity to influence projects before the design is fixed, and building owners receive goal-setting and dialogue supporting functionalities. Addressing the needs of different stakeholders helps generate demand for the use of the tool on as many levels as possible. The research presented has already described this through recommendations for assessment method modules (Paper B), implementation of functionalities in the **IEQ**Compass tool (Paper F), and tested the value of such in actual design processes (Paper D).

The research presented has primarily focused on creating a demand for professional stakeholders, but as mentioned in Chapter 1, the motivation of occupants present another opportunity to increase demand. Homeowner investments have many different drivers such as improvements in home size, energy efficiency, and the state of renovation (A. Mortensen et al., 2016). Some drivers are more attention-demanding than others, such as poor building conditions from, e.g. mould, wear and tear, or structural damage. Energy-efficiency improvements receive attention for a range of reasons including from legislation, expected investment payback times, and a general environmental sustainability trend. If we intend to motivate investments in IEQ above the minimum national requirements, IE investments have to be made attractive in order to compete with other investment options that are currently easier to communicate than IE upgrades.

Surveys show that occupants in dwellings value wellbeing (A Mortensen et al., 2014; VELUX, 2016), which is convergent with the positive occupant well-being perspective presented in Paper A - as opposed to the predominant focus on avoiding poor or unhealthy conditions. The current trends of investing in, and displaying, a lifestyle that is both sustainable (energy and water consumption, CO_2-footprint, material use and reuse) and healthy (food, exercise, consumer products), should be transferable to IEQ investments. In fact, a survey on the relative importance of different health factors on healthy living revealed that European citizens in general valued factors related to the home (sleep quality, ventilation, daylight, avoiding chemicals) above those related to activity and intake (being outdoors, exercise, avoiding tobacco, eating fruit/vegetables and dietary supplements) (Beranova et al., 2017). The challenge is to direct this concern about healthy indoor environment into both renovation action and behavioural action, such as airing out, drying clothes outside and not lighting candles.

Already two decades ago, research indicated that building owners preferred building product labels as they facilitate decision-making when choosing a dwelling (Kohler, 1999). Building owners know ‘green labels’ from various consumer products, and similar labels exist for building materials such as the Health Product Declaration, Declare, Cradle to Cradle Material Health Certificate and Nordic Swan. In the same way, well-known labels from household appliances and vehicles apply the same scale as mandatory building energy labels. Previous studies indicate that building owners can easily relate to smileys (happy to sad), colours (green to red) and letters (A to G) used in such labels (Galiotto, Heiselberg, & Knudstrup, 2015). This means that future IEQ labelling is likely to benefit from using the same 7-letter scale, rather than continuing the current trend of inventing new IEQ labels for individual ranking systems (‘platinum’, ‘outstanding’, ‘category I’, ‘class A’ etc.).

Private homeowners could also be motivated indirectly through exposure to IEQ labels such as the implementation of mandatory IEQ labelling of schools. Similarly, if the socio-economic incentives presented lead to IEQ labelling for social housing, this could become a driver for private homeowners. Also, investments rates are advanced if IEQ labels turn out to influence market prices as has been the case for energy labels, where each step of label improvement is worth around DKK 50,000 for a $100m^2$ house (Energistyrelsen, 2015). Although positive IEQ labels do not come with expected energy savings, they are likely to affect the market value of dwellings, particularly if followed by the dissemination of positive IEQ impacts.

6.1.3. POLITICAL DEMAND AND SOCIETY

To realise the full potential of IEQ assessment methods, we need not only to overcome the listed barriers of operationality in the tool design (such as ease of use, low-cost, fast-paced), as addressed in the presented papers. We also need political support for improved IEQ at a national level, such as an IEQ labelling legislation similar to the mandatory energy labels.

Balancing IEQ and energy

Climate change has resulted in increasing demands for energy efficiency, which in 2002 made the European Union adopt to the Energy Performance of Buildings Directive (EPBD) forcing EU member states to implement this into their regulatory requirements. The revised EPBD-recast from 2010 required all new buildings to be nearly zero-energy after 2020, while clearly stating that this should not be achieved by compromising the indoor environment (European Parliament, 2010). This is vital, as the narrow focus on energy-efficiency often comes at the expense of aesthetics, functionality or indoor environment, with a negative impact on the user experience (C. Brunsgaard, Heiselberg, Knudstrup, & Larsen, 2012). Although recent versions of the directive recommend promoting comfort, health and well-being for occupants (European Union, 2019) it is not followed through by demanding additional compliance checks, requiring IEQ labelling, or setting targets levels for improvements.

A series of case studies of Danish multifamily dwellings have been made to investigate (1) how the energy requirements of Danish building codes have influenced the calculated energy consumption, and (2) how this has affected IEQ developments over time. The study is presented in Paper E – Appendix D:

"*Historical development of IEQ in Danish dwellings*

- has energy efficiency requirements inhibited positive IEQ developments?"

The study provides a historical overview of the development of overall IEQ in the last 150 years, by mapping the potential IEQ performance of 63 case buildings using the **IEQ**Compass. This IEQ overview is compared to developments within energy efficiency in the same period by investigating calculated energy consumption figures from the Danish energy label database. Findings indicate that advances in ventilation strategies, heating systems, building materials and components (particularly windows) has (1) successfully prevented most issues related to drafts and low operative temperatures in the heating season, and (2) improved conditions for a range of IE aspects including air filtration, air change rates, sources of indoor pollution, daylight access, and noise from neighbouring apartments and outdoors. However, many of the advances are limited, and new issues have been introduced such as noise from installations, reduced privacy from exposure to view in, and particularly issues concerning too high temperatures outside the heating season. The case studies scored with the **IEQ**Compass show very modest improvements over the last 150 years, which is in contrast to the drastic improvements within calculated energy consumption. This indicates that although building code requirements have set higher demands for overall building quality, particularly for energy performance, we cannot assume that IEQ improvements will automatically follow. However, cost-efficient IEQ improvements are possible with a correct implementation of the combined ambitions for IEQ and energy described in recent versions of the EPBD (European Union, 2019). In addition to providing incentives by requirement (such as IE legislation), incentives by reward (e.g. subsidies) could be a powerful tool for promoting IEQ improvements.

The study presented in Paper E also shows an example of systematic IEQ labelling being used to collect building data to support researchers, legislators and authorities. A database of IEQ labels could be used to compare performance between and among different building types to inform building owners how to prioritise renovation activities or by policy officials inform future building code initiatives. Results could also be used to inform urban planning, e.g. by comparing the potential visual IE performance between different types of city districts, where building density and height are crucial to visual IE performance.

IEQ labelling in building codes?

Arguments have been provided for large scale IEQ investments in dwellings (Chapter 1.2 and 2.4), including economic incentives such as reduced health care costs, and social incentives such as improvements in physical health, mental health and health equity. By providing an assessment method that creates value for all stakeholders and enables low-cost, non-invasive

IEQ labelling is a big step towards possible building code inclusion. National initiatives to strategically improve IEQ in dwellings have previously been implemented in the building code in the UK when the Code for Sustainable Homes was introduced in 2007 as a voluntary national standard to improve home sustainability. In Sweden different systems were developed for voluntary evaluation and labelling of IEQ in existing buildings such as P-labelling, and MIBB which was promoted actively by the Swedish tenant's organisation (Malmqvist, 2008).

In Denmark political action has been taken to ensure better IEQ in the school system in a recent proposal for legislation (Folketinget B22, 2019) based on an inspections-report by Danish Centre for Educational Environments that showed significant room for improvement of IEQ (DCUM, 2019). This action could be the first step towards IEQ labelling in Danish building legislation. Other initiatives to improve IEQ in dwellings include requiring low-emission documentation of all materials (such as the Nordic Swan Ecolabel) as set by the DGNB system Denmark and some professional building owners, such as Danish pension funds (who own large building portfolios).

6.2. DISCUSSION

Holistic IEQ: a part of sustainable design

The work presented supports the design and assessment of holistic IEQ. It points to the issues of making ill-informed design decisions, particularly ones made due to a too narrow perspective when performing assessments or optimising design proposals. As discussed in the above, the DDS provided by the **IEQ**Compass tool assesses IEQ performance exclusively, and it is up to the design team to use this to inform the design direction while also considering a range of other crucial aspects.

Unlike green building rating systems (such as LEED and BREEAM) the assessment method presented in the current work is not a comprehensible sustainability assessment, but rather a method for assessment of holistic IEQ. However, holistic IEQ assessments could be used in combination with existing comprehensive sustainable assessment methods to strengthen the social sustainability dimension of such, similar to what has been suggested with the WELL Certification system. In a Danish context, this could mean using the tool for early-stage DDS on holistic IEQ while providing input for a DGNB certification that provides a holistic perspective on both economic, environmental and (the remaining parts of the) social sustainability dimensions.

Assessment tools have been developed to assess the combined impacts of both economic sustainability (LCC) and environmental sustainability (LCA, energy consumption). Until now, no assessment tool or method exists to quantify the combined impacts of social sustainability, presumably due to the challenges of combining the results of dissimilar assessments types (thermal/visual/acoustic/IAQ, comfort/health/well-being, qualitative/quantitative). This is made possible with the developed methodology to assign relative inter-area weights as it allows pre-weighted IEQ criteria for which the relative contribution to overall IEQ is known.

Developing a holistic IEQ assessment method with pre-selected and pre-weighting criteria is a significant responsibility as it represents both the authority to emphasise some criteria and to exclude others. Some criteria were excluded during tool development because of a very low potential influence for the given context, or because insufficient knowledge exists on how to tackle them. Conditions may change with new developments building practice and IE research meaning that criteria selection needs periodic reevaluation. Other criteria were discarded because they were impossible to assess accurately without measurements, such as PCB, mould and radon. Although the prevention of such issues are covered by the Danish building code, the exclusion of those criteria could be a risk if the tool is applied for other contexts or in ways it was not intended. As for any tool that provides assessment of a combination of contributions, there is a risk that everything not included in the tool is potentially neglected.

A challenging new perspective

The positive well-being dimension of the proposed holistic IEQ framework challenges our way of thinking about the indoor environment. Multi-disciplinary collaborations will be required for researchers to integrate qualitative IE aspects, possibly by borrowing theories and methods from other fields of science. Such a shift of perspective requires support from both research and practice, and the willingness to invest resources. Even with support and willingness, it may take time to adapt practice, and gradual implementation is to be expected in any case. For instance, the well-being domain is underrepresented in the **IEQ**Compass tool, which only includes a limited amount of positive IE aspects (particularly within visual IE) as well as opportunities for user control.

Although the feedback from design experiments with the **IEQ**Compass was very positive, the test subjects may not be representative of the industry in general. The professional design team were not new to applying performance software to inform their early-stage design decisions, and they were generally positive towards participation in a workshop to test IE as a potential design driver. However, the building industry, as a whole, is known for being conservative. They rely on field-proven solutions and previous experiences. In many countries, the business is under pressure to deliver on time, low-cost, high-performance solutions, which leaves little room for innovation and experiments. As a result, engineers may not be enthusiastic about implementing new qualitative parameters to their field and adapting to a positive IE perspective. Also, they may not be inclined to get involved in the early design processes, which is usually the domain of architects, and where the project develops continuously. Architects, on the other hand, may not be eager to adopt highly technical IE parameters, for which engineers would usually be responsible. Also, Architects may fear that the current design complexity will be increased further by introducing more performance parameters to early design stages.

Holistic IEQ makes a difference

Unlike most compliance tools and green building certifications, the **IEQ**Compass has been developed to also perform as a design tool. This may be vital for the inclusion into architectural practice as it combines fast-paced DDS with graphical dissemination of results, from a very modest effort. Architects are expected to find that early stage IEQ considerations improve the robustness of their designs, which minimise compromises in the later stages. Also, it allows architects to argue for their designs to both engineers, building owners and competition jury panels. Engineers should find that resources spent integrating early IEQ considerations are well spent, as they will experience fewer major challenges during detailed design. As the building industry faces growing complexity and increasing performance demands, the application of tools that support multi-disciplinary collaboration and DDS from a holistic perspective may be a necessity in the future of the profession.

Non-specialists may at first perceive IEQ to be a complicated engineering discipline that is of little interest to them. However, holistic IEQ has the potential to be relevant for all built environment stakeholders by carefully targeting the nature of arguments and the level of detail provided to match different interests. DDS tools can help create demand within the profession by creating value for architects, engineers and professional building owners, but demand can also grow outside the profession. Holistic IEQ can appeal to end-users through the positive dimension of IE as multi-sensorial experiences that supports both physical and mental health for occupants. In addition, arguments for political support for holistic IEQ improvements have been presented from both a social equity perspective and a socio-economic perspective.

6.3. CONCLUSION

The dissertation has presented research contributing to indoor environmental research from both theoretical and practice-oriented perspectives.

The framework suggested for expanding holistic indoor environment to be a trinity of comfort, health and well-being is a step towards systematically introducing a positive well-being dimension to IEQ. The proposed framework argues for a multi-disciplinary research effort and broader inclusion of aspects, particularly new qualitative aspects within the well-being domain. The potential implications of positive well-being for occupants include environments that promote mental and cognitive restitution, varied and dynamic environments leading to increased satisfaction, and positive sensory stimuli to further mental well-being. The suggested definitions of comfort, health and well-being provide the foundation for a more precise (un-ambiguous) discourse on holistic IEQ impacts.

A direction has been proposed for the development of future design decision support (DDS) tools and holistic IEQ assessment tools, based on the investigation of limitations and potentials in current tools. A holistic IEQ assessment method has been developed to provide early-stage DDS and enable inexpensive IEQ labelling. Design experiments have tested the assessment method to live up to requirements for early-stage DDS and have shown potential for IEQ aspects of becoming active design parameters. The experiments showed that applying holistic IEQ DDS furthered integration of IE aspects in early design, and resulted in design proposals with significantly improved potential overall IEQ. In addition, the assessment method provides visual dissemination of results on several levels to provide meaningful communication of incentives for individual stakeholder interests based on a simple colour-coded A-G letter scale known from energy performance certificates.

A methodology has been developed to determine context-specific IEQ weights that combine the relative impacts on occupant comfort, health and well-being within indoor air quality, acoustic, thermal and visual IE. The methodology enables holistically established weights that combines diverse evidence such as objective/subjective and quantitative/qualitative, from both theory and practice. The methodology has been applied to derive a set of pre-weighted categories and criteria which is a prerequisite for combining the contributions of the many diverse aspects into an overall IEQ label.

The author of the presented research acknowledges that no final optimal IEQ solution exists, but believe in supporting the pursuit of a great holistic indoor environment. This pursuit is hypothesised to be best supported through a series of deliberate compromises between IE parameters, as opposed to the predominant sequential single-parameter symptom treatment of current practice. For this to be possible, IEQ assessment tools should guide dynamic and iterative design processes, rather than merely offering post-design compliance checks.

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LIST OF APPENDICES

Appendix A.

Paper F – IEQCompass

Paper F

*"**IEQ**Compass – A Tool for Holistic Evaluation of*

Potential Indoor Environmental Quality"

Larsen, T. S., Rohde, L., Jønsson, K. T., Rasmussen, B., Jensen, R. L., Knudsen, H. N., Witterseh, T., Bekö, G., IEQCompass – A Tool for Holistic Evaluation of Potential Indoor Environmental Quality, Building and Environment (under review).

IEQCompass **– A Tool for Holistic Evaluation of Potential Indoor Environmental Quality**

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Highlights:

- A tool named **IEQ**Compass was developed to evaluate the potential indoor environmental quality (IEQ)
- It evaluates indoor air quality (IAQ), thermal, visual and acoustic IEQ
- It provides an overall "IEQ label" using a letter and colour code for ranking IEQ similar to energy labels for buildings
- The four areas are also labelled individually
- The "IEQ Design Compass" visualises the results in detail and provides an overview that aids indoor environmental design

Abstract

The development of a new tool (**IEQ**Compass) for holistic evaluation of indoor environmental quality (IEQ) is presented. The purpose of the new tool is to facilitate a broader understanding of IEQ, its importance for comfort, health and well-being, and to help and guide the building design process regarding IEQ. The tool evaluates the potential indoor air quality (IAQ), thermal, visual and acoustic IEQ, without considering user influence. The evaluation uses 16 parameters, four for each of the four areas of IEQ. These are evaluated based on relevant criteria assessed from blueprints, existing building information modelling data or observations during building inspection. The criteria and parameters are weighted to obtain an overall IEQ label for the building, as well as partial labels for the four areas. The labelling scheme uses letter ranking and colour code similar to that used in energy performance certification. The results are also communicated through the newly developed "IEQ Design Compass*",* which is a detailed graphical visualisation at criteria level and helps identify potential IEQ problems that warrant attention.

Key Words: building certification, residential buildings, building renovation, indoor air quality, thermal environment, acoustic environment, visual environment

1. Introduction

The indoor environmental quality (IEQ) of buildings has for many years been considered second to energy efficiency and at best a potential co-benefit when designing new buildings or renovating existing ones. This design strategy has often led to problems with e.g. overheating, glare due to large window areas, or poor air quality due to insufficient ventilation rates optimized towards low energy consumption [1–3]. The European Union's Energy Performance of Buildings Directive (EPBD) has increased the public's awareness of the importance of energy efficiency in the building sector through the use of the Energy Performance Certificates (EPC) [4]. Increasing public awareness of the importance of the indoor environment in the same manner would be a game-changer in the way the indoor environment is prioritized in buildings. The benefits would include increased comfort, improved health and well-being of building occupants, as well as economic consequences reflected in lower health care expenditures and increased productivity [5–10].

In order to increase the attention to IEQ, evaluation and labelling of IEQ should become available to both building users and building designers in an easily understandable and affordable manner, as has been the case for energy performance through EPC. Sustainability and building performance certification programs include the evaluation of the IEQ to a various degree [11]. Although there is a growing recognition of the importance of IEQ in these programs, there are opportunities for significant improvements [12]. In a study comparing the IEQ related content of major building certification schemes applicable for dwellings (DGNB, BREEAM, LEED, WELL and LBC - Living Building Challenge), Rohde et. al. found that the overall weight of IEQ (defined as indoor air quality (IAQ), thermal IEQ, visual IEQ, acoustic IEQ and user's influence on these parameters) ranged from 10% to 31% of the total scheme [13]. The study also showed large variations in the relative weights of the five IE areas. For example, LEED only includes IAQ and user's influence, LBC includes all except acoustics, whereas DGNB, BREEAM and WELL include all areas. DGNB was found to have the most balanced weights between the areas.

Other tools and evaluation schemes aim to more directly asses the IEQ [14,15]. These tend to assess the IAQ, thermal, visual and acoustic IEQ individually. However, not all tools include all four elements of IEQ. One reason for this may be that IAQ and thermal IEQ receive the most attention in the literature, whereas visual and acoustic IEQ are insufficiently understood and characterized [16]. Few studies investigated the combined effects of the different parameters on the perception of IEQ [17][18],[19]. ASHRAE guideline *10-2016* [20] provides an overview of the combined effects by a systematic comparison of the parameters. The combined effects of the indoor environmental quality parameters are poorly understood and they have not been considered in earlier IEQ evaluation tools due to their complexity.

The inclusion of multiple indoor environmental areas in a single IEQ indicator requires their weighting. One of the challenges of this approach is to identify reasonable weights for the individual areas. Heinzerling et al. [21] compared several tools and evaluation methods that combined IAQ, thermal, visual and acoustic IEQ. The weights of the four areas varied between studies. Residovic [22] has developed the NABERS Indoor Environment tool for offices, which included thermal comfort, acoustic comfort, indoor air quality, lighting and office layout. Thermal IEQ and IAQ were found to be the most important parameters. The same prioritization was found by Ncube et al. [15]. In a study in residential buildings, Lai et al. [23] found the thermal and acoustic IEQ to be most important, while IAQ contributed the least to the overall IEQ. Humphreys [24] discussed the difficulties of establishing weights and suggested that instead of relying on a combined index, assessments should also include evaluations of the individual areas. Andargie et al. [16] suggested to establish the weights on a case-by-case basis, in order to address the large variability in buildings and their users.

The current study developed the **IEQ**Compass, a tool with the purpose to holistically evaluate and effectively communicate the potential IEQ in multifamily residential buildings at a national level in Denmark. However, the overall framework is versatile; the tool can be adapted for other building types, such as offices, schools and single-family homes, as well as for different regions. The tool is a product of the Danish REBUS project [25], which develops solutions for deep renovations in the social housing sector. However, the tool is applicable both in new and renovated buildings. It aims to facilitate a broader understanding of IEQ and its importance for comfort, health and well-being, and to promote IEQ considerations in renovation strategies in response to the growing need for deep renovations at a European level [26]. The project relies on a partnership between IEQ scientists, practitioners, developers and end-users. This paper describes the tool, its development and an example of its application.

2. Methodology

The described methodology addresses the approach applied to select the appropriate content and corresponding weighting for the tool that is intended to holistically evaluate the IEQ in multi-unit residential buildings.

2.1 Overall considerations

Assessment of the IEQ in multi-family buildings is often done through short-term measurements or surveys. Short-term measurements reflect the IEQ at the time of the measurements, while surveys rely on real-time subjective evaluations or the occupants' recall of their dwellings' IEQ. The application of these approaches in a nation-wide IEQ assessment program is not feasible. Moreover, the results of both methods are strongly influenced by occupant behaviour and thus do not reflect the *IEQ potential* of a building as such. For example, earlier works have identified IAQ problems as a result of insufficient window opening, overheating due to inappropriate use of existing solar shadings and a strong effect of kitchen exhaust fan use on air pollution after cooking [27–30]. Therefore, the present tool aims to assess the building's *potential* to provide good IEQ through building design and available technical solutions, without considering occupant influence.

The following seven fundamental criteria were set for the tool:

- It must evaluate the building's potential to provide good IEQ, without being biased by occupant behaviour or taking it into consideration
- It must evaluate the occupants' possibilities to adjust and interact with the IEQ in their dwelling
- It must include the assessment of IAQ, thermal, visual and acoustic IEQ in relation to comfort, health and well-being
- It must be independent of physical measurements
- It must be based on existing regulations and standards whenever possible

- The assessment by the tool must be sufficiently detailed but should be easy and fast to use both regarding input data and output results
- The tool must be applicable for existing buildings (to evaluate present status), renovation projects (to evaluate before and after renovation) and new buildings (to be used for design and benchmarking).

2.2 Selection of parameters and criteria

In order to define the parameters included in the tool, gross lists of parameters relevant for acoustic IEQ (ACOU), Indoor Air Quality (IAQ), thermal IEQ (THER) and visual IEQ (VIS) were made. The lists were developed based on a literature survey and consultation with experts in each of the four areas. For each parameter included on the list, the sources (where applicable), the recommended or mandated limit values in Denmark and in the EU, impact on humans (comfort, symptoms, performance, health effects), occurrence including typical levels and variation over time, measurability/documentation and its challenges, and other issues relevant for inclusion in the tool, were described.

The extensive gross lists were then reduced to a number of parameters reasonable for an operational tool. For this purpose a set of rules was established:

- Each of the four main areas (ACOU, IAQ, THER, VIS) were considered equally important
- Obtaining evaluation data for the parameters should not require measurements
- The final parameters should be selected based on their impact on building occupants' comfort and health. This was done by subjectively assigning them a value from 1 (lowest impact) to 5 (highest impact) for both comfort and health individually. The values were assigned by an appointed panel of 12 experts. The final selection of criteria followed a consensus-based approach within this panel, as suggested by Chew & Das [31], through several successive rounds of agreement, similar to the DELPHI technique [32].

Three quantitative parameters were selected for each of the four main areas (12 parameters in total). For each main area a fourth parameter describing the users' possibility to influence it, was added. Thus, 16 parameters were included in the tool (the parameters are listed in section 3.1). Even though the tool disregards specific impact of occupant behaviour, the users' possibilities to influence the indoor environment, as given by the building design and operation (e.g. individual control), was judged to be an essential part of the evaluation. This is supported by the literature indicating a clear relationship between individual control of the indoor environment and occupant satisfaction [30,33].

In order to assess the parameters in the tool, between one and six relevant descriptive criteria were defined for each parameter. Each criterion can obtain a score between 0 (worst) and 10 (best). The assessment of the criteria is based on blueprints and existing Building Information Modelling (BIM) data, or observations during building inspection in existing buildings. Blueprints and BIM data are used when available. This is the case for most new buildings. Lack of documentation is common however in the case of old buildings and renovation projects. The criteria scores are assessed with the help of either checklists (e.g. questions with yes/no answers, as well as more detailed observations) or calculations (e.g. indoor sound levels calculated based on traffic-related outdoor sound levels provided by the national noise map [34], type of wall construction, windows and vents).

For checklists, the maximum score of 10 per criterion is distributed across the corresponding checklist entries (observations) (see example in Table 2). The relative importance of each observation (score corresponding to an observation) was subjectively decided by a group of experts in each of the four areas [35]. The required calculations are performed automatically by the tool, upon entering the necessary input data. The calculated criteria (continuous variables) are assigned a score between 0 and 10 in a linear fashion, as illustrated in Figure 1. Linear interpolation was selected over a stepwise approach in order to prevent users from aiming to achieve the poorest condition within a specific step. For example, an identical score for CO_2 levels between 1000 ppm and 1499 ppm does not motivate to improve ventilation and reduce CO_2 concentration below 1499 ppm, which is easier to obtain. The calculations are made at “room level” or “apartment level”. Data obtained at room level are combined into a single score for the apartment. These calculations aim to determine either the worst-case scenario (e.g. time with overheating), best-case scenario (e.g. direct sunlight hours) or average conditions (e.g. daylight across the apartment). Criteria calculated at “apartment level” are those anticipated not to vary significantly between rooms (e.g. ventilation/infiltration).

2.3 Weighting of criteria and parameters

Weighting the parameters and criteria is necessary in order to make a holistic evaluation of IEQ. The weights can either be adjustable based on values from occupants or building owners, as suggested by Gade et al. [36], or they can be a fixed set of values. The latter approach was selected for the **IEQ**Compass, in order to allow for benchmarking of multi-family residential buildings at a national level. The weights in the **IEQ**Compass are those described in Rohde et al. [35]. They were determined based on a questionnaire answered by 67 Danish professionals and experts, in combination with subjective judgments of the scientists and experts developing the tool.

3. Results

The evaluation of the 16 selected parameters and their corresponding criteria are described in the following sections. The communication of the results and an illustration of the tool using a case study, are presented.

3.1 Parameters and criteria in the tool

Acoustic Indoor Environment (ACOU)

The evaluation of the acoustic IEQ considers the effect of sound from outdoors, from neighbours, from technical installations within the dwelling and the occupants’ possibilities to alter these (Table 1).

The potential noise levels in parameters ACOU1 and ACOU2 are evaluated based on information on the wall construction, type of windows and load-carrying structure. ACOU1 evaluates the level of noise indoors originating from outdoor noise caused by traffic or industry. The average outdoor noise level from traffic can be found, for any given address in the noise exposed areas of Denmark, in the Danish national noise map. The average noise level from industrial sources is calculated separately and added when relevant. The score is then calculated from the calculated indoor noise level, where the maximum score (10 points) is obtained for a day–evening–night equivalent sound level, $L_{den} \leq 23dB(A)$, corresponding to sound class A in the Danish standard for sound classification of dwellings [37]. The lowest score (0 points) corresponds to class D in the standard ($L_{den} \geq 38dB(A)$). L_{den} between these values are scored linearly between 10 and 0 points (Figure 1). ACOU2 estimates the level of airborne noise (ACOU2.1) and impact noise (ACOU2.2). Class A defined in the standard on sound classification corresponds again to the maximum score. For ACOU2.1 this corresponds to an airborne sound insulation, R'w, of minimum 63dB between apartments, while for ACOU2.2 the impact noise, $L'_{n,w}$, must be below 43dB.

Table 1.
Parameters, criteria and their weights for the assessment of acoustic IEQ (ACOU).

Parameter		*Parameter weights*	*Criteria*		*Criterion weights*
ACOU1	Noise from surroundings	35%	1.1	Low impact of external noise (e.g. traffic noise, industry)	80%
			1.2	Possibility to open windows towards a silent side	20%
ACOU2	Noise from neighbouring dwellings	35%	2.1	Low impact of noise from other dwellings - airborne noise	50%
			2.2	Low impact of noise from other dwellings - impact noise	50%
ACOU3	Noise from within the dwelling	25%	3.1	Technical installations	60%
			3.2	Reverberation time	40%
ACOU4	Occupants' possibilities to influence the acoustic IEQ	5%	4.1	Possibility to open windows in multiple directions	100%

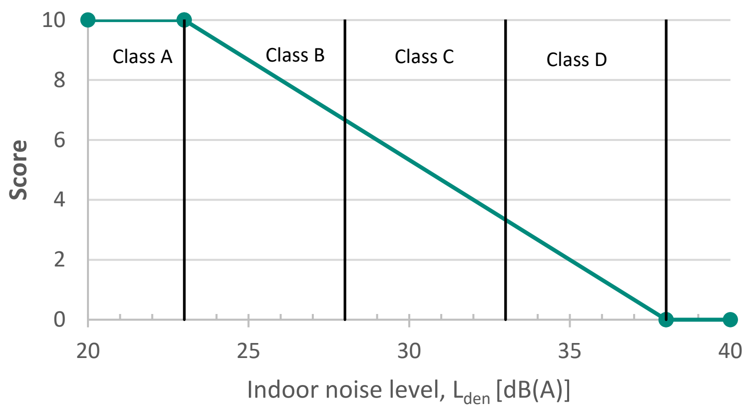

Figure 1. Score chart for criterion ACOU1.1 (impact of external noise) as a function of day–evening–night equivalent sound level (L_{den}). Classes A-D indicate sound classes in the Danish standard for sound classification of dwellings [37].

ACOU3 is evaluated based on noise from technical installations and reverberation time. The noise from technical installations (ACOU3.1) is evaluated using the checklist in Table 2, which serves as an example of score distribution across the respective checklist entries. The reverberation time (ACOU3.2) is estimated using Sabine's formula [37], which considers the presence of standard sound absorbents (table, two chairs, a desk and a closet) in a standard lightly furnished room (floor area of $12m^2$ and height of 2.5 m). The assumed light furnishing corresponds to an absorptions area of $2m^2$ (17% of the floor area) [38]. The actual furnishing in a dwelling is not considered in order to avoid penalization for the occupants' furnishing preferences. In order to apply this calculation for all room sizes, the absorptions area in the tool is fixed at 17% of the floor area. Evaluation of reverberation time is not a requirement for Danish dwellings and no standard values therefore exist. A reverberation time of 0.4 s was chosen to obtain the highest score (10), 0.8 s gives the lowest score (0).

Table 2.
Score table for criterion ACOU3.1 – noise from the building's technical installations. Conditions promoting a low noise level result in a high score. The final score is the sum of scores for three sub-criteria (maximum score is 10).

Score	*0*	*1*	*2*	*3*	*4*	*6*
Ventilation	Mechanical ventilation without silencing		No mechanical ventilation, only natural ventilation		Silencers are present, one central ventilation unit	Silencers are implemented locally for all rooms
Elevator in staircases	Yes		Yes, with silencing measures taken into account	No		
Visible drains	Yes	No				

The occupants' possibilities to influence the acoustic IEQ (ACOU4) are limited, since it largely depends on the building design. This is reflected in the weight of this parameter, which constitutes only 5% of the total score for the acoustic IEQ.

Indoor Air Quality (IAQ)

The evaluation of the indoor air quality (IAQ) considers the effect of outdoor air quality, building ventilation and building materials, household activities and the occupants' possibilities to influence these (Table 3).

Table 3.
Parameters, criteria and their weights for the assessment of indoor air quality (IAQ).

Parameter		Parameter weights	Criteria		Criterion weights
IAQ1	Impact of outdoor air	15%	1.1	Outdoor air quality and filtration	100%
IAQ2	Building ventilation and materials	35%	2.1a	Mechanical ventilation (and commissioning)	70%
			2.3	Emission from materials	30%
			2.1b	Natural ventilation (potential ACR)	35%
			2.2	Bathroom exhaust fan	35%
			2.3	Emission from materials	30%
IAQ3	Impact of household activities	30%	3.1	Options for drying clothes	30%
			3.2	Stove exhaust hood	50%
			3.3	Stove type (electricity or gas)	20%
IAQ4	Occupants' possibilities to influence the IAQ	20%	4.1	Ventilation boost, natural ventilation	35%
			4.2	Ventilation boost, mechanical ventilation	30%
			4.3	Automatic control of ventilation rate	35%

The evaluation of the impact of outdoor air (IAQ1) is based on the annual average concentration of $PM_{2.5}$ at a given address, reported by the Danish national particle map [39]. The final score is obtained after adjustment for the presence of air filtration in the ventilation system and its efficiency. IAQ2 is evaluated differently for mechanically ventilated buildings and naturally ventilated buildings, acknowledging the fact that mechanical ventilation can ensure a more stable minimum air change rate (ACR) across the dwelling compared to natural ventilation [40,41]. For the same reason, the presence of a bathroom exhaust fan (IAQ2.2) is scored in addition to the potential natural ventilation (infiltration) rate (IAQ2.1b), which is estimated using the method described by ASHRAE [42]. IAQ2 also considers emissions from materials. Scores are given if documentation is provided that no changes to surface materials have been made during the past two years or certified low emitting materials have been applied to at least 75% of all surfaces. A list of approved certifications and labels are included in the tool manual.

IAQ3 scores source control solutions related to occupant activities (clothes drying, stove and exhaust hood). Although occupant behaviour and furnishing are not considered in the tool, these technical solutions, which influence moisture and pollutant levels in the dwelling, are considered an integral part of the building. The users' possibilities to influence the indoor air quality (IAQ4) include the options to manually boost the ACR by i) opening windows (single-sided or cross ventilation) (IAQ4.1), ii) boosting the mechanical ventilation system (IAQ4.2), or iii) turning on automatic control of the ACR based on measurements of CO_2 and humidity (IAQ4.3).

Thermal Indoor Environment (THER)

The thermal IEQ is evaluated based on the summer and winter indoor temperature conditions, draught in the dwelling and the occupants' possibilities to influence these conditions (Table 4).

Table 4.
Parameters, criteria and their weights for the assessment of thermal IEQ (THER).

Parameter		*Parameter weights*	*Criteria*		*Criterion weights*
THER1	Temperature, summer	30%	1.1	Overheating of critical rooms	90%
			1.2	Discomfort due to cold surfaces	10%
THER2	Temperature, winter	25%	2.1	Heat source controls	50%
			2.2	Surface temperatures	50%
THER3	Draught risk	20%	3.1	Draught from leaky openings	40%
			3.2	Downdraught from surfaces	25%
			3.3	Draught from ventilation	35%
THER4	Occupants' possibilities to influence the thermal IEQ	25%	4.1	Ventilation boost, natural ventilation	25%
			4.2	Ventilation boost, mechanical ventilation	10%
			4.3	Automatic control of ventilation rate	15%
			4.4	External shading	20%
			4.5	Cooling system	5%
			4.6	Temperature regulation at room level	25%

The indoor temperature conditions in the summer and winter (THER1 and THER2) are scored based on the results of detailed calculations performed by the tool with the relevant input parameters set for Danish climate conditions. Thus, the tool requires adjustments before its application for different climates. The parameter THER1 evaluates the summer conditions. The criterion THER1.1 scores the number of hours above 27 °C in the dwelling during a standard year. A maximum of 30 hours per year results in maximum score. THER1.2 scores the availability of technical solutions used to avoid discomfort from cold surfaces during cooling (e.g. cooling by ceiling elements combined with mechanical ventilation). THER2 evaluates the winter conditions. THER2.1 scores the type of temperature control, where the presence of thermostats in each room yields the highest score. THER2.2 evaluates possible discomfort due to low radiant temperatures caused by window and wall constructions. The given score decreases with the increasing number of hours where the radiant temperature asymmetry is above 10.5°C. This is rarely the case in new buildings, where the maximum score will often be achieved. The criterion may, however, identify construction problems in older buildings.

THER3 evaluates the risk of draught caused by leaky windows and external doors (THER3.1, based on visual inspection), downdraught (THER3.2 based on thermal transmittance and U-values of window surfaces) and mechanical ventilation and air supply (THER3.3, based on e.g. type of mechanical ventilation, presence of preheating, type of inlet).

The first three criteria scoring the occupants' possibilities to influence the thermal IEQ (THER4.1-THER4.3) are related to ventilation and thus similar to those used for indoor air quality (IAQ4.1-IAQ4.3). However, in THER4.1-THER4.3, the evaluation is entirely related to the thermal conditions in the dwelling. The strict focus on thermal IEQ is also applied in THER4.4, where the possibility to control external shading is considered positive regardless of the potential visual discomfort (reduced view), which is addressed under the visual IEQ. Similarly, the possibility of personal control of mechanical cooling (THER4.5) results in additional scores despite the possible increase in energy consumption. When external shading and cooling (THER4.4 and THER4.5) are not present, these are removed from the evaluation and the criterion weights under THER4 are changed, while maintaining the relative weights of the remaining criteria (THER4.1 33.33%; THER4.2 13.33%; THER4.3 20.00%; THER4.6 33.33%). The same adjustment is made when only one of the two criteria is absent. THER4.6 scores the possibility to control the temperature at room level, in combination with the speed of the system's response to a change. The thermal indoor environment is the area with the most possibilities for occupant influence (THER4), which is reflected in the parameter weight of 25%.

Visual Indoor Environment (VIS)

The evaluation of the visual IEQ (VIS) considers the supply of daylight (amount and quality), direct sunlight, view (in and out) and the occupants' options to influence some of these (Table 5).

Table 5.
Parameters, criteria and their weights for the assessment of visual IE.

Parameter		*Parameter weights*	*Criteria*		*Criterion weights*
VIS1	Daylight	35%	1.1	Daylight intensity and distribution	80%
			1.2	Colour rendering of windows	20%
VIS2	Direct sunlight	25%	2.1	Sunlight exposure (hours/day)	100%
VIS3	View	30%	3.1	View out (access and quality)	40%
			3.2	View-in (exposure to passers-by)	35%
			3.3	Influence of view by external shading	25%
VIS4	Occupants' possibilities to influence the visual IEQ	10%	4.1	External solar shading, adjustment	50%
			4.2	External solar shading, window-by-window activation	50%

The amount and quality of daylight and direct sunlight (VIS1 and VIS2) are assessed through calculations performed by the tool on a 3D model of the building, upon providing the window area, glass type, direction, position and other relevant input parameters. VIS1 also scores the colour rendering caused by the selected type of glass (VIS1.2). Colour-neutral glass with a colour rendering index above 97 yields maximum score. VIS2 calculates the number of direct sunlight hours per day in the dwelling for 1 February, according to standard EN 17037 [43]. More direct sunlight results in a higher score in Danish dwellings. This parameter should, however, be adapted to other climates and building typologies. It should be noted that the tool only evaluates natural daylight conditions, since light fixtures are not an integral part of the residential building design. Adoption of the tool for other building types (e.g. office buildings) may require the inclusion of the effects of lighting installations.

The parameter scoring the view in and view out (VIS3) takes into consideration the positive effects of a good view from the dwelling and the negative effects of compromised privacy (view-in) [44]. VIS3 thus scores qualitative elements of the visual IEQ and supports the equal role of comfort, health and well-being in the consideration of IEQ, as defined by Rohde et al. [45]. VIS3 is aimed to promote the design of buildings that ensures a balance between providing a pleasant view for the occupants and protecting their privacy (limited view-in from passers-by). A model for the evaluation of view-in and privacy was therefore developed and incorporated in the tool.

VIS4.1 evaluates the occupants' possibility to adjust the solar shading (no possibility (lowest score), manual or by remote control (highest score)). VIS4.2 scores whether the shading can be activated and adjusted for each window individually. As is the case for the acoustic IEQ, the potential occupant influence is limited, because the solutions responsible for the visual IEQ are often decided during the design process. This is reflected in the relatively low weight of the parameter VIS4 (10%).

3.2 Criteria and parameters weights

Three levels of weighting are applied in the tool (Figure 2). The weighting between all criteria within a given parameter provides a parameter score (first level of weighting). The four parameters in each area are weighted to obtain an overall area score (second level of weighting). Finally, the overall IEQ score is obtained after weighting the four areas (ACOU, IAQ, THER, VIS) equally (25% each; third level of weighting).

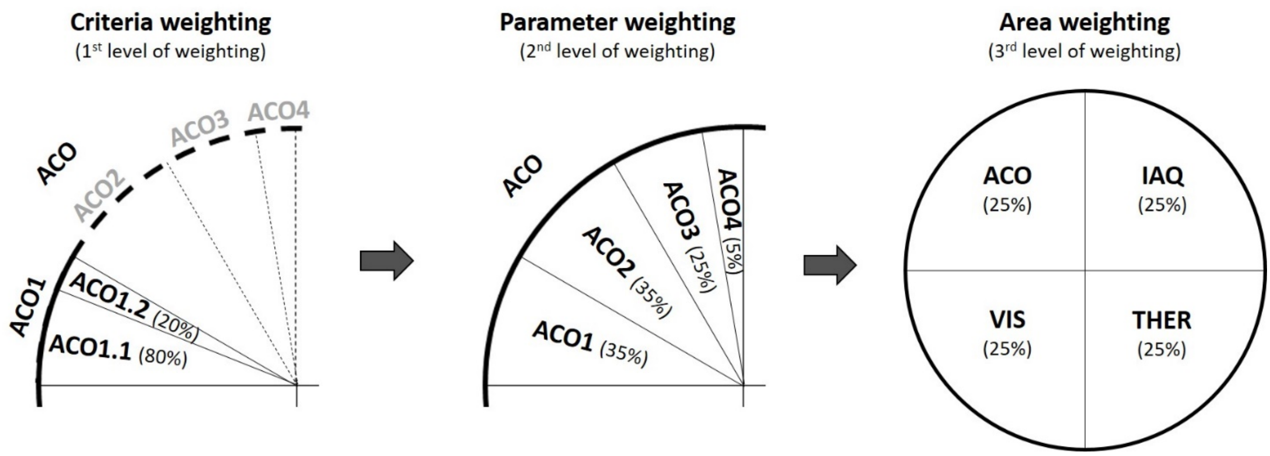

Figure 2. 1st, 2nd and 3rd level of weightings applied in the **IEQ**Compass.

The first and second level weightings are based on the weights identified by Rohde et al. [35]. These are included in Table 1, Table 3, Table 4 and Table 5. The four main areas are equally weighted because of the lack of sufficient data on their relative perceived importance.

3.3 Communication of results

One of the objectives of the **IEQ**Compass tool is to provide an intuitive communication of a dwelling's potential IEQ to both professionals and a broader audience. The results are communicated in two ways. The tool provides an overall "IEQ label", as well as a deeper insight into the criteria scores through the "IEQ Design Compass". Both use labelling by a letter ranking and colour code, similar to energy labels for buildings used in European energy performance certificates [46] (Table 6). The tool labels the building with an overall class, but partial classes for the four individual IEQ areas are also reported. This allows the identification of the most critical areas that should be addressed during the design process of new buildings, in existing buildings or in renovation projects.

The "IEQ label" must be applicable for all buildings. Class C, therefore, corresponds to the minimum IEQ conditions set for new buildings by the 2018 Danish Building Regulation. In order to obtain classes A and B, the building must perform, at least under some parameters, better than the building regulation's minimum requirements for IEQ. The overall class is obtained based on a (weighted) average of the scores for the four areas (ACOU, IAQ, VIS, THER). However, the overall class cannot be more than two classes above the lowest class obtained for the four individual areas. For example, class B can only be obtained if all individual area classes are D or higher. Table 6 shows the ranges of scores corresponding to the seven classes. These scores are applicable both for the individual classes and for the overall class based on the average of the four area scores.

Table 6.
Scores corresponding to the letter ranking and colour codes on the **IEQ**Compass labels.

Letter rank on the IEQCompass labels	**Scores** (fraction of the maximum achievable score)
A	85% ≤ score ≤ 100%
B	75% ≤ score < 85%
C	65% ≤ score < 75%
D	55% ≤ score < 65%
E	45% ≤ score < 55%
F	35% ≤ score < 45%
G	0% ≤ score < 35%

The “IEQ Design Compass” (see next section for example) provides the results with an additional level of detail by illustrating the scores (0-10) for all criteria under each parameter. The purpose of the “IEQ Design Compass” is to help identify potential IEQ problems and aid designers in decision making regarding the IEQ in an early stage of the design process. It can be used both for new buildings and for renovations. In the latter case, the Compass illustrates how the different parameters may change under different renovation scenarios and where the largest improvements can be found. The tool allows specific criteria in the Compass to be locked, in order to illustrate that these criteria cannot be changed during renovation (e.g. the quality of view out will often be unchanged after renovation).

3.4 Example of application

To illustrate the application of the tool, a case study is presented. An apartment to be renovated is used for this purpose. It is situated on the first floor of a 2-storey apartment building and has an area of $92m^2$ (Figure 3). Three rooms are facing south and do not have solar shading. The common room and the kitchen face north and have overhangs above the window (balcony above).

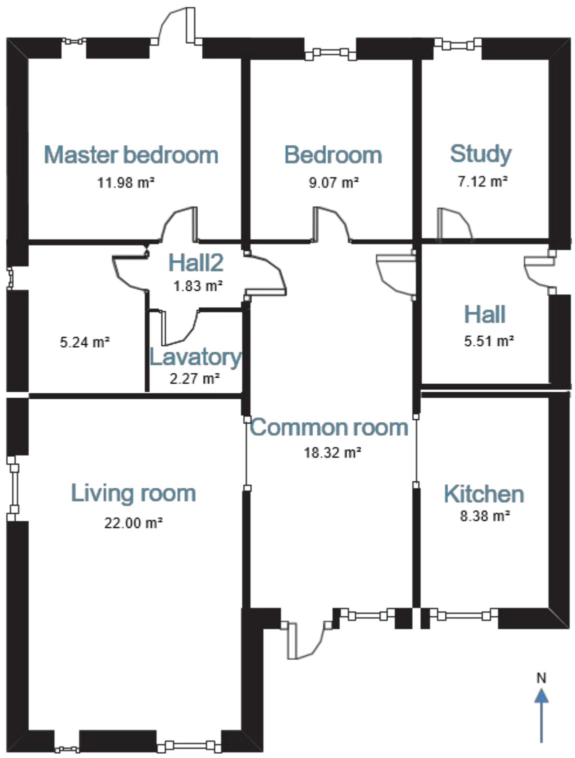

Figure 3. Floor plan of the apartment used in the case-study.

The apartment was constructed in 1972, which is reflected in the insulation levels and type of ventilation. The U-value for the external walls is 0.4 W/m^2K, the U-value for the windows is 1.5 W/m^2K (solar heat gain transfer coefficient, g-value = 0.63; light transmittance, LT-value = 0.7). The hybrid ventilation includes mechanical exhaust in the kitchen, lavatory and bathroom and natural ventilation (outdoor air inlet through vents in the windows, lack of heat recovery or preheating).

Figure 4 shows the "IEQ label" with the overall class and the four partial classes generated by the tool for the apartment. The potential IEQ in the apartment is classified as class E. The thermal IEQ, indoor air quality and visual IEQ are rated as class E, the acoustic IEQ obtained class D. The classification indicates a potential for improvements in all areas. The "IEQ Design Compass" for the apartment is shown in Figure 5.

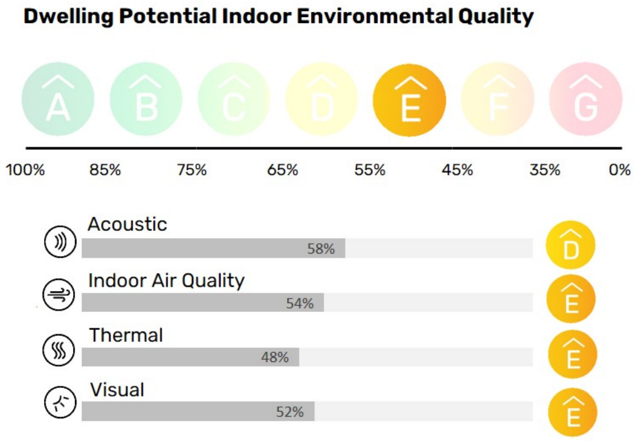

Figure 4. "IEQ label" for the apartment before renovation.

The acoustic IEQ obtained 58% of the maximum score. Relatively low scores were obtained for ACOU2.1 and ACOU2.2, which evaluate airborne noise and impact noise from neighbours, respectively. ACOU3.2 has a very low score due to long reverberation time and thus acoustic discomfort. Improvements of the acoustic indoor environment often require extensive constructional changes.

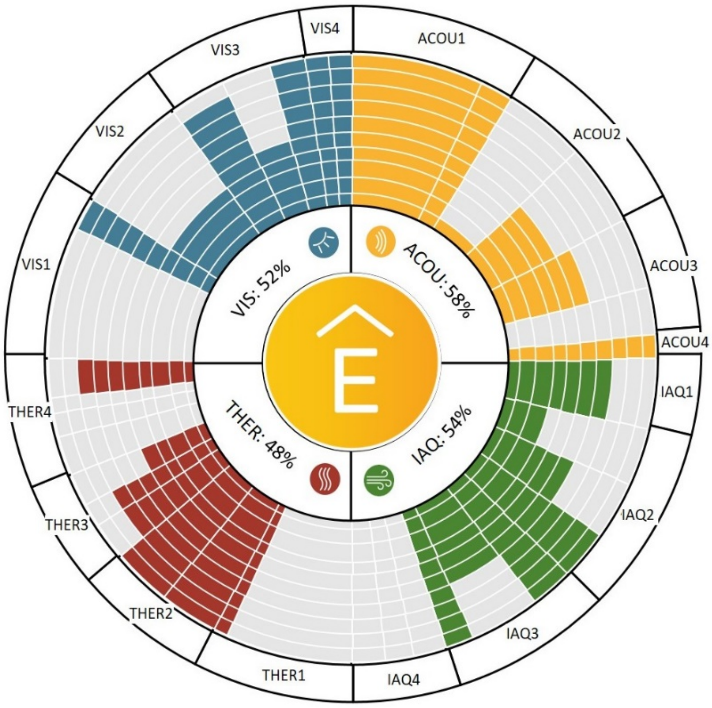

Figure 5. The "IEQ Design Compass" before renovation of the apartment.

The indoor air quality obtained 54% of the possible top score. The lack of filtration of the outdoor air resulted in a reduced score for IAQ1. Low air change rates achieved by natural ventilation resulted in a low score for IAQ2.1. Installing mechanical ventilation would substantially improve these scores. IAQ3.2 revealed the need for an upgrade of the kitchen exhaust hood (from recirculation unit to one that exhausts to the outdoor). The lack of user control of ventilation (IAQ4) further reduces the score and the corresponding class for indoor air quality.

The rating of the thermal IEQ (48% of maximum score) identifies problems during summer conditions when high indoor temperatures can be reached (THER1.1). During winter, the natural ventilation causes risk of draught (THER3.3). The apartment doesn't have external shading or any cooling system, which reduces THER4 into 4 criteria in this evaluation. Here, the lack of possibilities for the occupants to manually increase ventilation lead to a low score for THER4.

The visual IEQ obtained 52%, especially due to the low amount of daylight caused by deep rooms with small windows (VIS1.1) and lack of direct sunlight (VIS2). Additionally, discomfort caused by the risk of view-in by passers-by requires attention (VIS3.2).

The tool has revealed that the renovation of this apartment should focus on improving ventilation (including personal control), façade (including shading) and windows (size and quality). During the renovation, balanced mechanical ventilation with heat recovery and preheating was installed. This caused the parameter IAQ2 to be re-evaluated through three criteria (IAQ2b) instead of two (IAQ2a)). The U-value of the external walls was improved to 0.16 W/m^{2}K, the U-value of the windows to 0.52 W/m^{2}K (g-value = 0.53, LT-value = 0.74). The window area was increased. Following renovation, the potential IEQ in the apartment improved to class C, with the four individual area classes being D (ACOU), D (IAQ), B (THER), and B (VIS) (Figure 6).

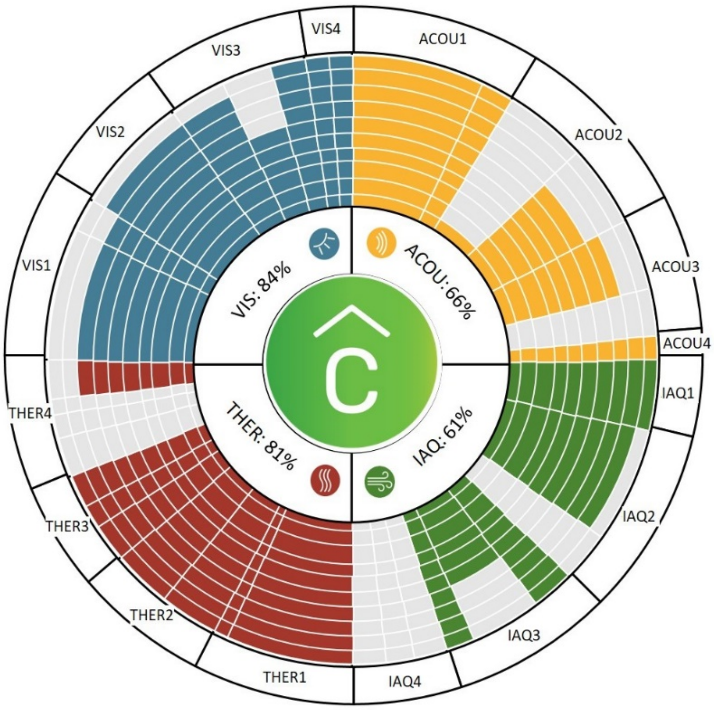

Figure 6. The "IEQ Design Compass" after renovation of the apartment.

4. Discussion

The ambition behind developing the **IEQ**Compass was to increase the overall focus on indoor environmental quality when designing new buildings or renovating existing ones, and thereby guiding designers towards designing healthier and more comfortable buildings. The tool is easy and fast to apply already in the early stages of a design process. It provides an IEQ labelling system, which can be implemented at a national level to complement the existing building energy certification program.

4.1 Limitations of the tool and its applicability

The **IEQ**Compass evaluates the *building's potential* to provide a comfortable and healthy indoor environment, without considering occupant influence. Although occupant behaviour is a strong driver of indoor environmental quality, the individual differences can be difficult to measure or predict. Measurements and surveys are often an important and trusted part of IEQ evaluations, but they also pose substantial practical and economic challenges. The labelling system needs to be widely affordable. Measurements and surveys are therefore not part of the tool.

The labelling system is based on a holistic approach, which includes the evaluation of IAQ, thermal, visual and acoustic IEQ. While this is considered an improvement compared to earlier efforts to create an evaluation system for the indoor environmental quality in buildings [14,15,22], it has its weaknesses. Classifying the IEQ of a dwelling or building into a single overall label requires weighting of parameters within the four areas. Individual classification of each parameter also relies on the weighting of the respective criteria. The weights at both levels have been determined based on subjective judgments of a group of experts. This approach may challenge the objectivity and reliability of the tool and its applicability for a national labelling system. However, great effort has been made to determine the weights that would produce a robust tool. This procedure was described in detail by Rohde et al. [35]. The four areas have been weighted equally, which may not reflect the occupant's true preferences between them [16,21,24]. Prioritization of the four areas is subjective and the scientific literature supporting a specific weighting between the areas is insufficient. As such data becomes available, the weighting in the tool may be updated.

The tool has been developed, and the applied weights have been determined, with the Danish climate and building conditions in mind. For application outside this region, the tool with its weights needs to be adapted to the local climate, buildings and perhaps even cultural conditions. Moreover, the **IEQ**Compass was developed for dwellings. Application in other building types, such as schools or offices, is relatively easily achievable after minor modifications of the criteria and weights. Thereby, the tool is versatile regarding content, while its framework and structure (four areas, each consisting of three building-related parameters and one user-related parameter) are independent of building typology.

The tool does not differentiate between urban and rural areas. Dwellings in urban areas are often exposed to noise, air pollution and view-in from passers-by to a larger extent than dwellings in rural areas. Therefore the **IEQ**Compass may on average indicate poorer conditions and a larger need for improvement in urban areas, where better solutions may be necessary in order to provide a good IEQ for occupants.

4.2 Target groups

The **IEQ**Compass was developed to address two different target groups, which is reflected in the two different methods to display and communicate the results ("IEQ label" and "IEQ Design Compass"*)*. The "IEQ label" targets a broad audience familiar with similar labelling schemes used for building energy consumption as well as for certain consumer products. This should facilitate a nationwide adoption, application along with the existing energy certification, and consequently a potentially large societal impact.

The "IEQ Design Compass" addresses practitioners in the construction sector. Its purpose is to promote dialogue between consultants and building owners/developers, set targets for good indoor environments and thus facilitate the implementation of solutions that ensure them. This should ideally occur already in the early design phase, where the tool is applicable due to its simple input structure. Poor indoor environment can often be traced to decisions taken too late, when substantial changes are difficult and expensive to make. The "IEQ Design Compass" can also be useful during building renovation, where it helps identify problems that deserve attention in order to achieve an improved IEQ.

4.3 Role of the building industry in development and implementation

In order to make the tool viable for the building industry, leading companies in the Danish building industry and key stakeholders from relevant industrial organizations were consulted during the development of the tool. Several workshops with industrial participation were organized to obtain feedback on the tool's contents, user interface, presentation of results and application strategy. All participants of the workshops were invited to test the tool, which helped identify errors and ambiguities. Two test rounds were conducted during the development of the tool. Experts and practitioners from the industry were also asked to fill in the questionnaire, which was used to determine the weighting factors for the different criteria and parameters in the tool. The active involvement of the industry in the development of the tool is anticipated to facilitate the tool's adoption by the intended end-users. The implementation of the tool will start on a voluntary basis, but it is envisioned to contribute to the Danish building regulation in the future.

5. Conclusion

The **IEQ**Compass demonstrates that developing a holistic tool for the evaluation of the indoor environmental quality, which considers indoor air quality, thermal, visual and acoustic indoor environmental quality, is feasible. Weighting of the parameters used for the evaluation of the four areas (IAQ, thermal, visual and acoustic IEQ) and their underlying criteria has been established. This has been done for dwellings only and the tool is therefore currently not applicable for other building typologies. The tool can however be relatively easily adapted to other types of building. Moreover, the four areas are currently weighted equally, due to the lack of data on their relative importance for the overall IEQ. If such data becomes available, the weighting may be updated in the tool.

The tool performs all simulations and calculations required for the evaluation of the IEQ. Its application is relatively straightforward; the typical time required to perform an evaluation for an apartment is under 3 hours. The results from the tool target two different user groups, building professionals and a broader audience, including building users. The results are therefore presented at two different levels of detail. The “IEQ label” indicates the overall IEQ label for a dwelling, together with the partial labels obtained for the four individual areas. A 7-step letter ranking labelling system was developed for this purpose. This level informs building owners and occupants in a fashion similar to the building energy performance certification programs. The “IEQ Design Compass” is a more detailed graphical presentation of the results. It is intended to help designers and building professionals identify potential causes of IEQ problems and appropriate solutions during the design process.

Acknowledgement

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Appendix B.

Input data examples for **IEQ**Compass

Input Category	Sub-category	Input example
Built environment data		geographical location, elevation (sea level), surroundings (obstruction height, density and distance from the building), pollution from local environment (combustion pollution levels, traffic and industry noise levels)
Building properties	Building description	year of construction (possible year of renovation), number of stories, number of apartments
	Structural systems	construction of external walls/neighbouring walls/interior walls, floors/ceilings/roofs
	Building services and systems	HVAC system and controls, heat recovery, heating system and controls, cooling system, external shading and controls, presence of lift in the staircase, presence of visible piping
	Building geometry derivatives	number of rooms, room types, floor areas, façade areas, window areas, window orientation, the possibility for cross ventilation, window/exterior door data, shading from own building, surface material type
Maintenance and operation data		protocols for particle filter change and duct cleaning, maintenance commissioning

*Table 1 – Input data examples used for **IEQ**Compass assessments*

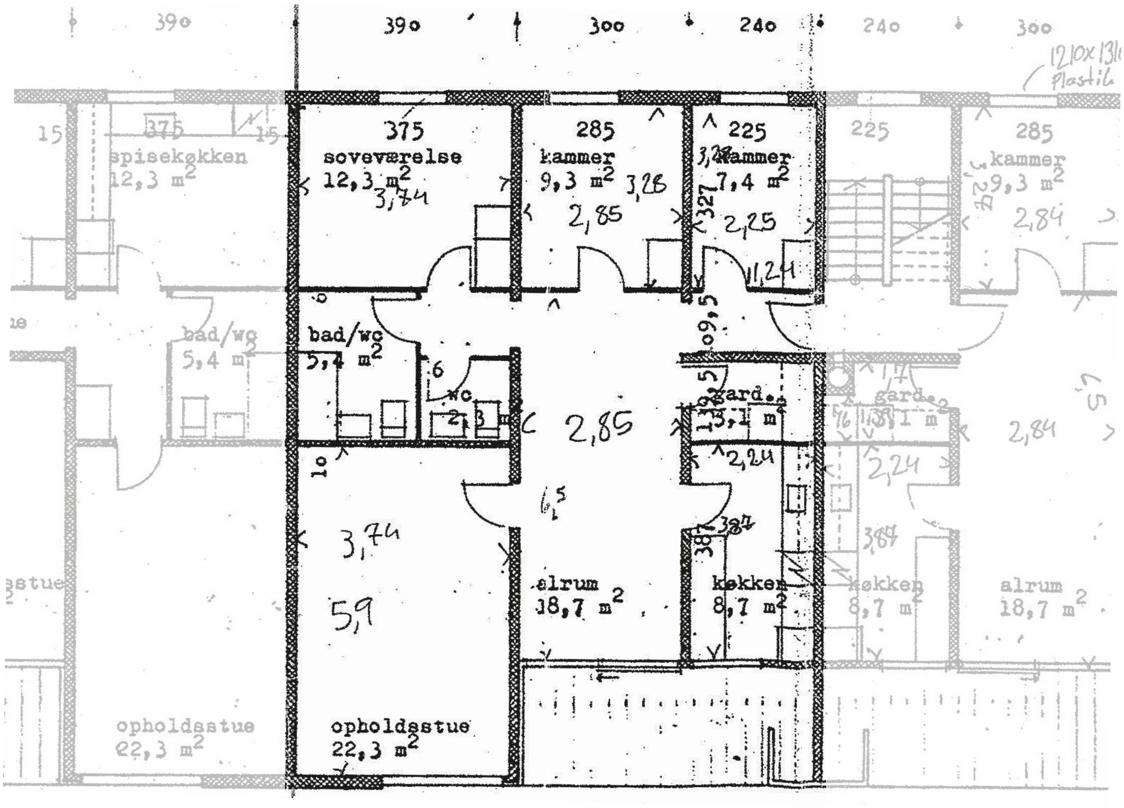
Appendix C.

Illustrations from workshop and project work presented in Paper D

Design team workshop – Photograph 1

Design team workshop – Photograph 2

Design team workshop – Photograph 3



Design team workshop – Plan drawing of workshop case

Design team workshop – Photograph 1 of workshop case

Design team workshop – Photograph 2 of workshop case

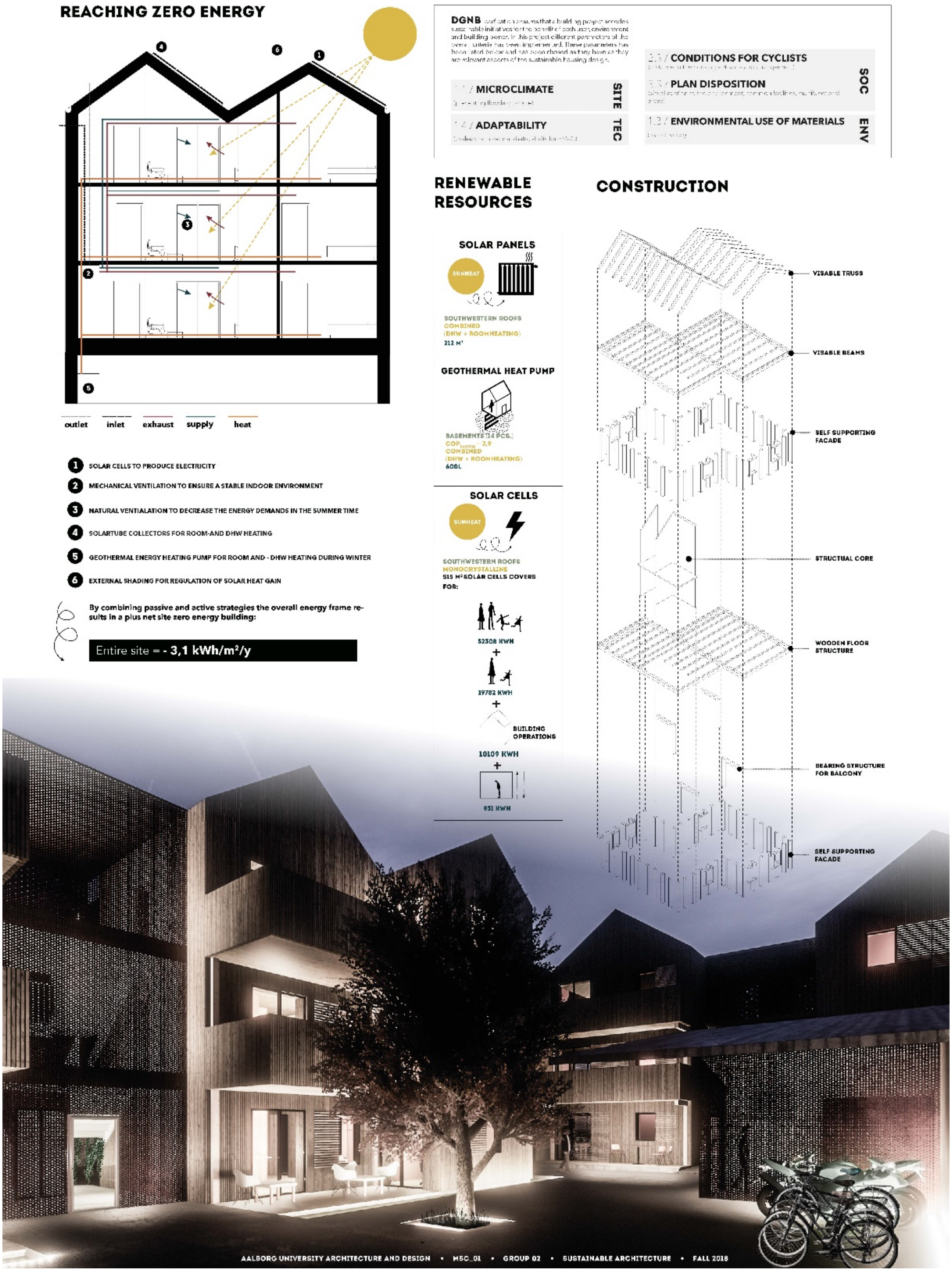
Design team workshop – Photograph 3 of workshop case

Design team workshop – Photograph 4 of workshop case

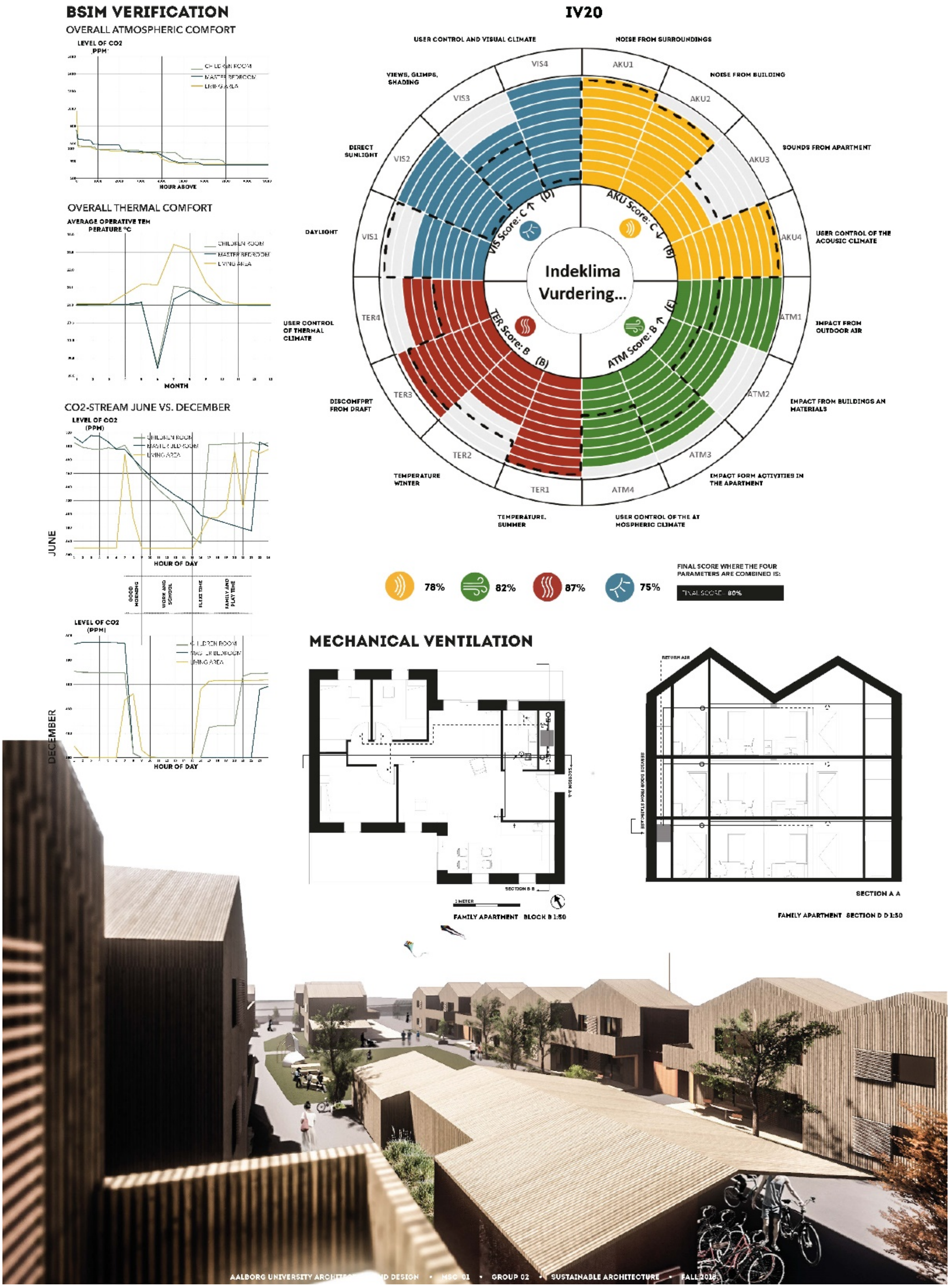
Student project work – Presentation material: Poster #1 (reused with permission from the students)

Student project work – Presentation material: Poster #2 (reused with permission from the students)

Student project work – Presentation material: Poster #3 (reused with permission from the students)



Student project work – Presentation material: Poster #4 (reused with permission from the students)



Student project work – Presentation material: Poster #5 (reused with permission from the students)

Appendix D.

Paper E – Historical developments of IEQ in Danish dwellings

<u>Paper E</u>

"Historical development of IEQ in Danish dwellings

- has energy efficiency requirements inhibited positive IEQ developments?"

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Historical development of IEQ in Danish dwellings
- has energy efficiency requirements inhibited positive IEQ developments?

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Abstract
This paper investigates developments in indoor environmental quality (IEQ) and energy efficiency over the last 150 years. Sixty-one Danish multistory dwellings were registered and scored using a newly developed IEQ assessment tool called IV20. An overview of this scoring is presented, indicating which IEQ issues have been solved, which remain unsolved, and which new ones have arisen. IEQ developments are compared to developments in energy consumption, to test the hypothesis that some initiatives to reduce energy consumption comes at the expense of occupant comfort and health. An overview of energy efficiency developments for Danish multistory dwellings is given through analysis of data from the Danish energy labelling database. The results show a solid positive development in energy efficiency and a very modest improvement in potential IEQ. Results suggest that positive IEQ developments may have been inhibited by energy efficiency initiatives and that further IEQ advances may depend on a change of political priorities.

Introduction
The European Union's 2020 and 2050 targets for the reduction of energy consumption and CO_2 emissions (European Commission, 2011) signal significant changes for the building sector responsible for almost 40% of the global final energy consumption and total greenhouse gas emissions (International Energy Agency, n.d.). This political agenda has enforced energy-saving practices into national building codes in the developed world heavily influencing how we build and renovate. In some cases, this focus on energy efficiency has been at the expense of healthy and comfortable indoor environments (IE) (Roulet et al., 2006). Increasing insulation values, air tightness, and passive solar gains often result in extensive overheating in cold climates (Brunsgaard, Heiselberg, Knudstrup, & Larsen, 2012; Larsen, Daniels, Jensen, & Andersen, 2012; Morgan, Foster, Sharpe, & Poston, 2015).

In many parts of the world, people spend 90% of their time indoors (Klepeis et al., 2001). Most of this time is spent at home, meaning that IEQ in dwellings has an enormous impact on the comfort, health and well-being of people. The social sustainability potential of good indoor environmental quality (IEQ) in dwellings is huge from perspectives such as work absenteeism, productivity, healthcare costs, and social equality. Thus, it may be the time to complement political agendas such as the Energy Performance of Buildings Directive (Council of the European Union, 2002; European Parliament, 2010), with an ambition to also improve IEQ in dwellings. There is a growing political understanding that energy efficiency and IEQ should not be seen as mutually exclusive (CIBSE, 2013; Watson, 2017).

The rapidly increasing world population adds extra pressure to climate adaption requirements and acts as a driver for increased urbanisation as the current answer to high population accommodation and sustainable living. Increased urban density leads to increased exposure to noise and air pollution reducing the potential of a healthy and comfortable indoor environment. When buildings are too tall and too close, it also compromises privacy from risk of unwanted view in and reduces access to daylight, sunlight, and view out. United Nations expects two-thirds of the world's population to be located in urban centres by 2050 (United Nations, 2014). This makes the development of urban dwellings, with low-energy consumption and high-quality indoor environment, one of the keys to sustainable living in the decades to come.

The Energy Performance of Buildings Directive (Council of the European Union, 2002; European Parliament, 2010) has resulted in energy labelling for European buildings as part of the building code. Many national variations of energy efficiency assessment tools (Be18 in Denmark) calculate a theoretical energy demand for both existing and new buildings. As a result, energy-efficiency databases for buildings are well developed in a European context. However, most IEQ assessment tools are designed for evaluating new buildings only or are expensive certification options for best practice buildings (such as LEED, BREEAM, DGNB, WELL), meaning that developments in overall IEQ are mostly unknown – particular for older dwellings.

The REBUS project (REBUS, 2016) has developed an IEQ assessment tool called IV20 based on simple-input calculations. The tool assesses the IEQ potential of the building, based on a range of collected building data. IV20 is designed for use in the early design stages, as opposed to assessments based on expensive and time-consuming measurements or occupancy surveys. The independence of measurements and surveys removes bias from user responses and user behaviour and enables assessments of IEQ potential in both existing builds and unrealised design proposals. This makes the tool ideal for benchmarking samples of the existing building stock. This approach also allows for identification of the specific reason(s) for a certain performance in any part of the assessment, by tracing an assessment sub-score back to the building data that influence it.

This paper will compare decades of well-documented positive developments in calculated energy demand, with new data on the developments in potential IEQ in dwellings. IEQ assessment results of 61 multistory dwellings will be presented, followed by a brief discussion of the main trends. IEQ developments are then compared to overview plots from building energy certification (Danish Energy Agency - Danish building energy certification) to compare developments within IEQ and energy efficiency over time. Based on this analysis, the authors will highlight tendencies in how the building code emphasis on energy efficiency has affected the overall IEQ for multistory buildings in the last 150 years.

2 Methods

2.1 Categorizing cases into building periods

The analysis of Danish multistory dwellings is based on IEQ assessments of a series of case studies compared to an analysis of energy certification for multistory dwellings. This paper will use the building typology scheme TABULA (IEE Project TABULA, 2012) to organise the buildings into time periods. These periods are separated by building tradition shifts, affecting building typologies in a Danish context from 1851 and onwards. Many of these shifts are energy-consumption driven, and thus defined by the introduction of building codes with increasingly strict energy requirements. This paper investigates how energy consumption driven requirements have affected the potential IE in multistory buildings by comparing the advances in energy efficiency (using the national energy label database) with changes in IEQ in the cases assessed.

It is outside the scope of this paper to explain the differences in the individual building code requirements, but since the introduction of the first Danish energy requirements in 1961, the focus has been on limiting energy consumption for heating. This has primarily been done through improved insulation levels and later through heat recovery of exhaust air and improved air tightness. Since the '98 building code, there has been a focus on increasing passive solar gains, primarily through increased glazed areas, window orientation optimised for solar gains and higher window g-values. Also, the 2020 building code requires that windows have a neutral or positive energy balance in the heating season (E-ref in the Danish Building Regulations). These changes are expected to have influenced the indoor environment on several levels, in particular, thermal IE which is directly tied to heating demands, but also for visual IE and indoor air quality (IAQ) as a result of changed window areas, new window properties and the introduction of mechanical ventilation. The analysis of the IEQ assessed cases would focus mainly on thermal IE, visual IE and IAQ, as many energy-efficiency initiatives influence air change rates, daylight conditions, or thermal comfort variations.

2.2 Sampling and data collection procedure

Sixty-one Danish multifamily apartments were rated using the IV20 tool for assessment of IEQ in multistory dwellings. The cases were selected on three criteria to ensure good representation of the Danish multistory dwelling building mass with the available resources;

1) Location within one of the largest Danish cities (see Introduction for increased urbanisation arguments),
2) Year of construction spread across as many building code periods as possible (minimum 5 cases for each period to be included in the analysis),
3) Availability of drawings and access to the dwellings.

Registrations were made in November/December 2017 by a team of three assessors to minimise the risks of variations in the use of the tool. Data for the case studies were collected through a combination of on-site registration, visual inspection, analysis of drawings and various online databases. The on-site registration was performed using a registration template organised for a systematic registration of IV20 input on site level, building level, dwelling level and room level. The online databases include building project archives, aerial photographs, and digital maps for site-specific traffic noise and pollution levels.

2.3 Dataset – key figures

The cases registered covers 8 of the 10 Danish energy-related building typologies identified in the Danish contribution to the TABULA project (Wittchen & Kragh, 2012). The period before 1851 is not included as it has no energy labels for multistory dwellings before 1851. The 2007-2011 period was excluded as it was not possible to obtain access to at least 5 cases for the IEQ assessment.

The IEQ cases cover buildings constructed from 1883 to 2016 (134 years), and are split between 3 of the 4 largest Danish cities as follows; Aalborg area - 27 cases, greater Copenhagen area - 23 cases, and greater Aarhus area - 11 cases. Year of construction ranges for the periods are as follows: 1851-1930 (period 1); 1931-1950 (period 2); 1951-1960 (period 3); 1961-1972 (period 4); 1973-1978 (period 5); 1979-1998 (period 6); 1999-2007 (period 7); 2007-2011 (period 8); 2011-onwards (period 9).

Building energy labels were extracted from the national energy label database (Energistyrelsen) for the 179280 multistory dwellings in the period from 1851 to 2015 (165 years). The analysed energy labels span across the nine different Danish building periods listed above. Period 4 marks the introduction of the first energy requirements in BR61, with period 5 through 9 being defined by increasingly tightened requirements for BR72, BR77, BR98, BR08 and BR10.

3 Results

3.1 IV20 cases – IEQ overview tendencies

Figure 1 shows the IV20 score for air quality, thermal IE, and visual IE respectively, for each of the 61 registered cases listed by year of construction. Note that while

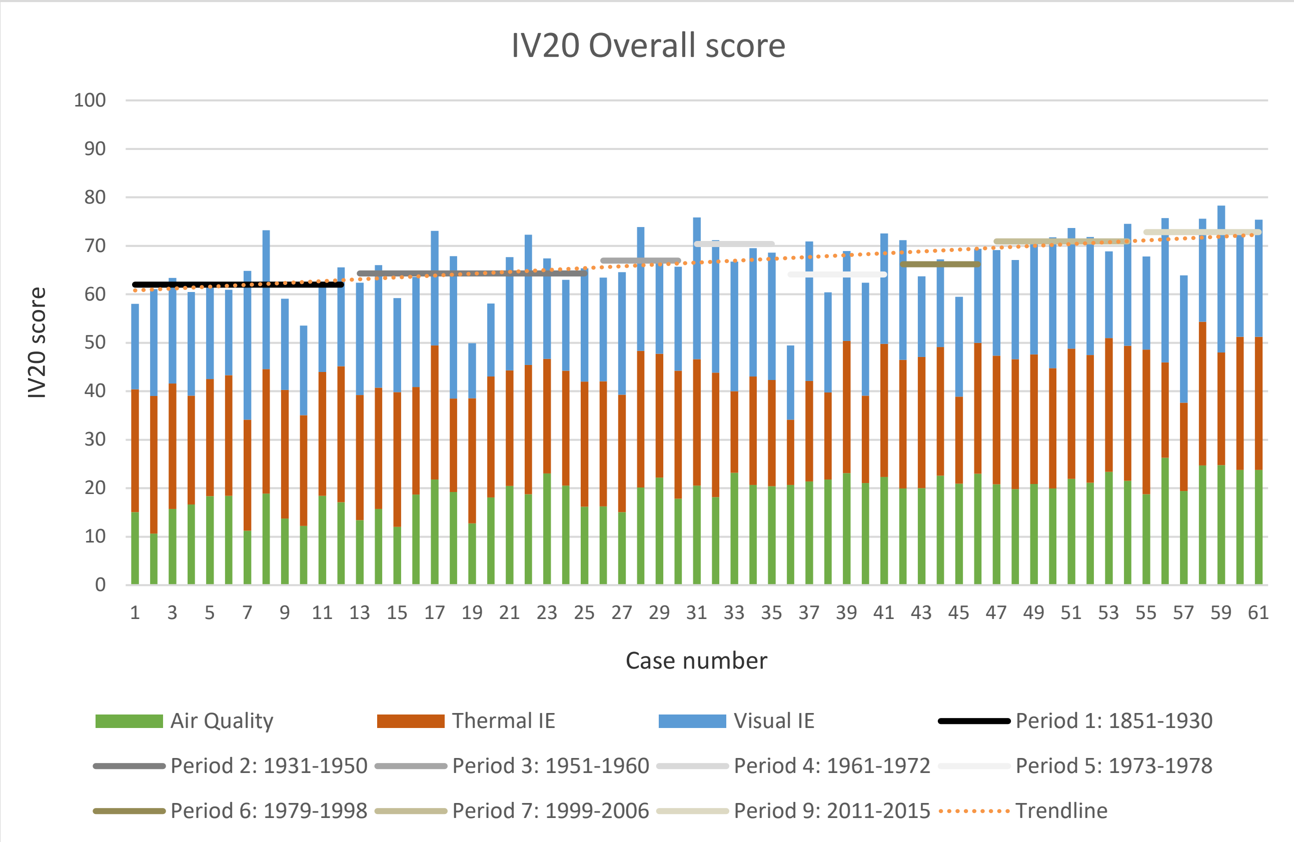

Figure 1: IV20 score for 61 registered multifamily dwellings (chronologically ordered by year of construction) showing contributions from air quality, thermal IE, and visual IE, as well as averaged values for eight different building periods.

acoustic IE is part of IV20 assessment and weighted equally with the other three domains, it is not part of the current analysis that compares developments in IEQ with improvements in energy efficiency. Energy efficiency improvements driven by building code requirements influence the performance of IAQ, thermal IE and visual IE directly, but have a more indirect influence on acoustic IE. Better insulated and more airtight envelopes are expected to reduce noise from outside the building, but due to space conservation reasons, acoustic IE will not be discussed further. The three areas analysed contribute equally to the overall IV20 scores shown for this paper.

The data in Figure 1 shows modest improvements in IEQ over time as highlighted by the trend line (significant tendency, t-test: $p=0.0007$). The earliest period (1851-1930) has the lowest average IV20 score of 62 pts (out 100 pts), while the most recent period (2011-2015) has the highest average of approx. 73 pts. The improvements over time are relatively small compared to the differences between individual cases, such as the 1973-1978 period containing both the lowest of all scores at approx. 49 pts as well as a score of approx. 73 pts positioned in the top third. The significant inter-period variations suggest that IE variations are more dependent on case-specific conditions than the requirements of the applied building code at construction. The large variations within building periods call for greater sample size, allowing for further statistical analysis. However, a tendency for development can still be found in the analysed cases.

3.2 Energy labels – Energy-efficiency tendencies

Figure 2 shows developments of energy efficiency for multifamily dwellings over the last 165 years, by plotting the averaged primary energy demand by construction year (using primary energy factors from BR10). The data plotted comes from the Danish building energy certification, and includes 179,280 Danish multifamily dwellings constructed between 1851 and 2015.

The data in Figure 2 shows a very significant tendency towards drastically decreasing energy demands over time (t-test: $p=2.2\cdot10^{-16}$), particularly from 1961 to 2015, with a factor 2.63 improvement (averaged yearly energy demand in kWh/m2/year; period 3: 117.8 and period 9: 44.8). While the average energy demand is unchanged for the first 100 years analysed (averaged yearly energy demand in kWh/m^2/year; period 1: 120.2, period 2: 120.3, and period 3: 117.8) it has dropped dramatically in the most recent 50 years. The most significant drop in the almost 25% drop from period 3 (1951-60: 117.8 kWh/m^2/year) to period 4 (1961-1972: 90.3 kWh/m^2/year), where the first energy requirement was introduced with the BR61 building code.

Energy demand reduction has been a significant focus in the most recent Danish building codes, which is reflected in an increasingly lowered energy demands for period 7, 8 and 9 (1999-2015). The average energy demand by construction year is effectively halved in just two decades from 91.2 to 44.8 kWh/m^2/year with the introduction of the BR98, BR08 and BR10 building codes.

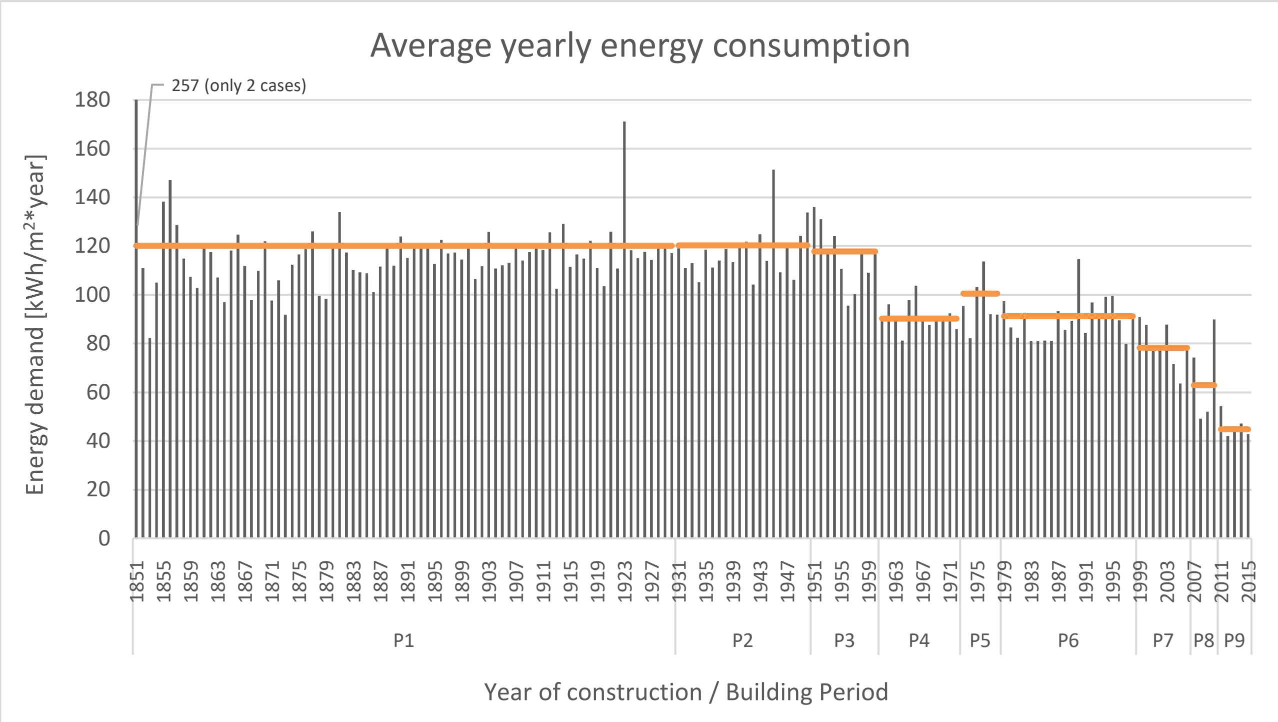

Figure 2: Calculated primary energy demand for 179,280 Danish multifamily dwellings plotted as averaged values by year of construction from 1851 to 2015. The orange lines show time period averages for each of the nine different building codes.

Going further back, we get a factor 2.69 improvement of the average energy demand by period between the 1931-1950 period (120.31 kWh/m^2/year) and the 2011-2015 period (44.78 kWh/m^2/year). When comparing this to the modest factor 1.13 improvement (64.3% in 1931-1950 period, to 72.8% in the 2011-2015 period) in indoor environment in the same period (as exemplified by the IV20 score in Figure 1), it becomes very clear that the building code requirements has prioritized energy efficiency above indoor environmental improvement.

3.3 IV20 cases – IEQ area by area

More than two-thirds of the 10.8 pts overall IV20 score increase over time can be accredited to IAQ improvements, with an overall score contribution ranging from 15.5 pts from the earliest period (1851-1930) to 23.1 pts in the latest period (2011-2015) (see Figure 1). The rest of the overall score increase is from a slight improvement in visual IE ranging from 21.2 pts from the earliest period (1851-1930) to 24.7 pts in the latest period (2011-2015). Thermal IE shows no improvements over time, with an average overall contribution of 25.2 pts from the earliest period (1851-1930) to 25.1 pts in the latest period (2011-2015) and an average of 24.7 pts across all time periods.

3.3.1 Tendencies – IAQ

Although modest, air quality improvements are relatively stable across all periods, with the most significant improvements in the range of period 1 through 4, and again from period 7 to 8. The main reason for the positive development in the early periods are due to air change improvements (IAQ2 in Figure 3 below), through improved conditions for natural ventilation. The boost from period 7 to 9 comes from the introduction of mechanical ventilation with fixed ventilation rates in the later time periods (7 out of 10 cases with mechanical ventilation is from period 9; 2011-2015) improving scores for both air change and particular matter in intake air (IAQ2 and IAQ1 in Figure 3 below).

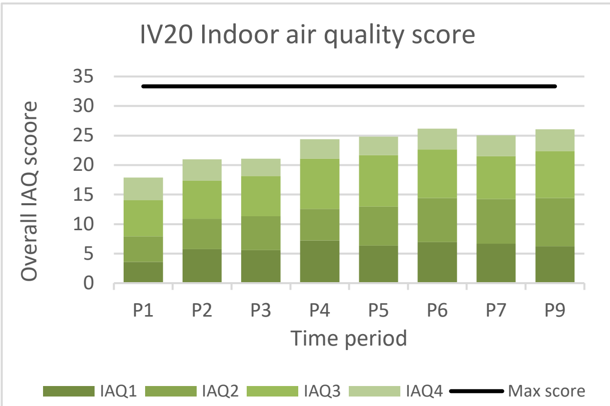

Figure 3: Averaged overall IAQ score for eight different periods, showing contributions from four different IAQ areas.

Decreased adverse effects of air polluting indoor activities, make a small contribution to the overall IAQ improvements, although the two most recent time periods indicate a small step back. The positive part of this development comes from preinstalled components with a beneficial influence on the IAQ such as stove type (combustion-based vs electric), and exhaust hood availability and efficiency. The recent negative development is due to fewer modern apartments (1999+) having covered spaces for drying clothes leading to increased particle and humidity loads.

3.3.2 Tendencies – Thermal IE

The data shows no overall thermal IE improvements throughout more than 150 years, despite advances in envelope air-tightness and insulation levels. Interestingly, 7 out of 8 cases with an overall thermal score below 20 pts are constructed within the last 50 years (period 4-9; 1961-2015). The reason for this lack of improvement is primarily due to issues of too high summer temperatures (evaluated through a summer comfort calculation) (TER1 in Figure 4 below), that is almost non-existing until energy requirements were introduced in the 1961 building code. Issues with high temperatures are the direct result of building code demands to lower energy consumption for heating; heating demand reduction initiatives (such as reductions in infiltration, line losses and lowered U-values for walls and windows) and passive heat gain strategies (such as heat recovery and increased solar gains). Analysis of the IV20 cases shows that area-weighted average U-values in the first three periods (1851-1960) is 0.91. After 1961, however, the average U-value decreases steadily by period down to 0.24 for cases in the latest three periods (1979-2015).

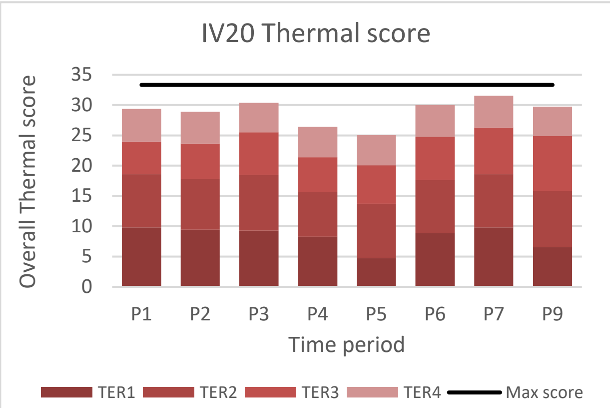

Figure 4: Averaged overall thermal IE score for eight different periods, showing contributions from four different thermal areas.

These issues offset the positive developments in winter comfort (TER3 in Figure 4), mainly from lowered draft risk because of improved air tightness and a lowered risk of downdraft from significantly lowered window U-values, ranging from 2.5 in the first two periods (1851-1950) to approx. 0.8 in period 9 (2011-2015). Improvements from pre-heated intake air (here mainly from mechanical ventilation with heat recovery) make a substantial difference in period 9 (2011-2015) resulting in the best winter comfort sub-scores.

3.3.3 Tendencies – Visual IE

Visual IE shows modestly increasing scores over the analysed time periods, with period 4 (1961-1972) breaking the overall tendency by being the highest scoring period by a margin. This development is reflected clearly in the daylight assessment (VIS1 in Figure 5), showing daylight quantity and distribution improving gradually over time, but with period 4 (1961-1972) being far above the trend line and period 5 (1973-1978) being far below.

The VIS1 sub-score for daylight quality (colour falsification) dampens the positive developments in daylight score, by penalising projects with a sub-par colour rendering (Ra-value). More than half of the projects in period 5, 7 and 9 are penalized for colour falsification (12 out of 21 projects), compared to just 1 in 20 for the other time periods (2 out of 40 cases). The main contribution of this colour falsification comes from window coating or window film (low g-value) designed to limit passive solar gains to fight the risk of too high temperatures.

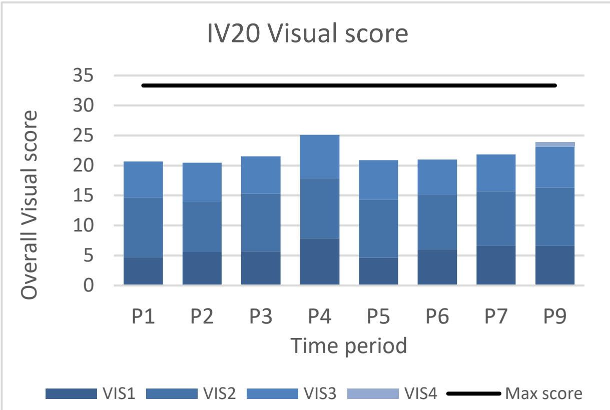

Figure 5: Averaged overall visual IE score for eight different periods, showing contributions from four different visual areas.

The developments in daylight are explained mainly by an increased glazed area starting with a window to wall area of 28% in the first two periods (1851-1951) to 41% for period 3-9. Tendencies are less clear for the other visual IE assessment topics such as Positive solar exposure (VIS2), View out quality and View in risk (VIS3), and they will not be discussed in this paper.

4 Discussion

The IV20 tool was developed for the early-stage assessment of renovation potential of multistory dwellings, but could potentially contribute to future labelling of IEQ of all Danish dwellings. The presented data for IEQ assessment is, however, limited by the modest sample size. Although the assessment is based on simple input, large quantity registration is time-consuming, and it will require mandatory IEQ labelling to achieve a sample size comparable to the almost 180,000 energy labels used for the energy efficiency analysis.

The IEQ assessments of the 61 cases presented is made using a beta version of the IV20 tool. While the assessment methodology and criteria of interest are set, the inter-area weightings and scoring may change slightly in the final version (expected ultimo 2019).

The IV20 tool is designed to assess the current conditions of a building, but for the historical perspective analysis of this paper, it would be more appropriate to reset 'wear and tear' to the time of erection. For instance, deteriorated window sealants can negatively influence the score for drafts in older buildings, but the influence on the scores presented here is negligible.

Most of the older case buildings have been partially renovated over the years, and in the case of recent and deep renovations, this may blur the results of both the IEQ and energy efficiency analyses slightly. For the present comparison of IEQ vs energy efficiency, this has very little influence, as the number of deep energy renovations is relatively small (average calculated energy demand for renovated projects is approx. 107 kWh/m^2/year vs approx. 105 kWh/m^2/year for non-renovated projects).

5 Conclusion

The analyses of the energy labelling database show a strong positive development within energy efficiency in the last approx. 50 years, boasting a factor of 2.63 improvement in the average calculated energy demand from period 3 to period 9. The majority of this improvement is in the last approx. 37 years from a tightened energy requirement in 1978, with a factor of 2.24 improvement from period 5 to period 9. This tendency follows tightened legislatorial demands from the introduction of the first building code energy demands (period 4), to a series of ambitious national energy frame reductions still being implemented.

IEQ assessments of the 61 cases indicate a very modest improvement in overall IEQ over time. This research shows that the average level of the main IEQ areas has not declined and that IAQ has improved slightly over time. Criteria level analysis shows that IAQ has been positively affected by ventilation strategy changes, supporting improvements in ventilation rates for natural ventilation, bathroom ventilation and the introduction of mechanical ventilation with filtering for newer buildings. Thermal IE has been affected by heat demand reduction initiatives, resulting in reduced comfort issues with drafts, but increased issues with overheating. Visual IE has mainly been affected by larger glazed areas, and a change in window components is contributing to improved daylight levels but also resulting in colour falsification that negatively affects the quality of daylight and view out.

The presented results indicate that the most recent building tradition has managed to improve energy efficiency significantly without negative consequences for the indoor environment as a whole. Improvements include significantly reduced issues with drafts, improved daylight access, and increased dilution and air filtration. However, increased window areas have introduced significant issues with too high room temperatures and new challenges such as exposure to view in (reduced privacy) and colour falsification through coated glass.

The average percentile improvement of IEQ over 150 years (+13%) is more than a magnitude lower than that for energy efficiency (+169%), which is fueled by decades of political and legislatorial priorities. While the average overall IEQ has not declined over the last 150 years, this study suggests that the building industry may have inhibited positive developments in IEQ through a narrow priority of energy-efficiency. For instance, the risk of overheated apartments is negatively influenced by energy reduction initiatives to reduce heat losses and increase gains. If urbanisation is the solution to increasing world population and energy conservation for living and transportation, then multistory dwellings have a considerable influence on the comfort and health of future generations – and should be a topic of interest for architects, engineers and politicians.

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