Holistic indoor environmental quality assessment as a driver in early building design

Rohde, Lasse; Jensen, R. L.; Larsen, O. K.; Jønsson, K. T.; Larsen, T. S.

Published in:
Building Research and Information

DOI (link to publication from Publisher):
10.1080/09613218.2020.1770051

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

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

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 combined indoor environmental quality (IEQ), 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. Design experiments demonstrate that the applied approach can meet the challenges of early stage DDS pointed out in existing literature. Findings from the experiments indicate that the **IEQ**Compass can provide: (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 assessment results, 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 design teams who are tasked with balancing the many, often conflicting, interests such as Life Cycle Analysis (LCA), Building Energy Performance (BEP), 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). This puts an enormous responsibility on the design team and the availability of appropriate Design Decision Support (DDS) tools. Architects are trained to integrate qualitative elements such as aesthetics, functionality, atmosphere and context, but growing complexity and increasing technical performance requirements challenge the way architects evaluate and balance early stage decisions. This challenge calls for performance assessment tools that provide DDS in the early design stages by presenting design teams with easily accessible data on complex technical topics.

It is widely accepted that environmental performance considerations should influence design processes, but the question of how and when this is implemented remains (Lützkendorf, 2018). The Energy Buildings Performance Directive (EBPD) (The Council of the European Union, 2010) has successfully made BEP and LCA a priority in the built environment, and recent versions of the EBPD also mention the promotion of comfort and health 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 well-being of inhabitants (Rohde, Larsen, Jensen, & Larsen, 2019), meaning that IEQ considerations should be an essential part of early building design. However, IEQ performance considerations in the early design stages face a series of challenges, including that IEQ is a complicated concept that involves multiple disciplines such as HVAC, acoustics and material sciences. The currently available performance assessment methods often only assess a single discipline, resulting in poorly informed trade-offs between IEQ aspects (Ko, Schiavon, Brager, & Levitt, 2018). A combination of missing topic expertise and lack of appropriate DDS tools for early design means that IEQ is often not adequately resolved, with consequences for the inhabitants.

A range of tools developed in the last two decades provide potential advances in early stage DDS. However, most share two significant limitations: operationality (input availability, calculation speed, user interface, result interpretation) and the ability to guide designs holistically (assessment of all relevant areas, simple overview, known trade-offs). Most Building Performance Simulation (BPS) approaches require intense simulation performed by simulation experts at a stage where neither experts or advanced models for simulation are available (Atzeri, Cappelletti, Tzempelikos, & Gasparella, 2016; Catalina & Iordache, 2012). Thus, assessment results are often not available until the detailed design stage (compliance checks), where many critical design decisions have already been made (Rezaei, Bulle, & Lesage, 2019).

The authors suggest using early stage performance assessment tools for IEQ in the same way that environmental performance is assessed using BES and LCA tools. This requires user-friendly IEQ assessment tools with several objectives, including the ability to assess potential IEQ performance rapidly, guide design teams by comparing design alternatives and disseminate results for non-specialists. This has the potential to further knowledge of IEQ impacts and to generate interest and demand in the industry.

Acknowledging that building design is a complex multidisciplinary process that requires collaboration towards a diverse set of design objectives (El-Diraby, Krijnen, & Papagelis, 2017) the aim is not to optimize the design for IEQ performance. Instead, the methodology should contribute to the improvement of the overall design proposal by integrating IEQ concerns as one of the many vital design aspects. This calls for a framework that can operationalize early stage IEQ assessment, guide designs as a whole, and provide holistic IEQ assessment overview and design comparisons that enable known trade-offs.

The current study suggests and tests a methodology for early stage integration of holistic IEQ performance assessment. The methodology combines the presence of IEQ topic expertise with a newly developed DDS tool called **IEQ**Compass that provides simultaneous performance simulation. The proposed methodology is tested for potential integration into design practice, through actual design scenarios acting as proof of concept studies. This paper presents the results from two supplementary design case studies 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 evaluate trade-offs, and (4) evaluate the promotion of early-stage IEQ knowledge integration into design proposals. Results are based on qualitative data, through observations during design development and interviews with the participants, combined with quantitative assessments of potential IEQ performance using **IEQ**Compass. This research provides valuable insights into how design teams can be supported by BPS on technical design topics, without compromising the flexibility required during conceptual design development. Results indicate that DDS tools such as **IEQ**Compass can support holistic design processes and improve IEQ performance without compromising other crucial design topics.

Background

Traditional design practice

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). The technical aspects of conceptual design are thus often developed based on intuition and heuristics (Kanters, Dubois, & Wall, 2013). Performance assessments typically rely on advanced simulations that are not performed until the detailed or technical design stage, where the concept is almost final, and design options are few (Rezaei et al., 2019). IEQ performance assessment 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, BPS software is often not suitable for architectural design work due to complexity and incompatibility with the architect's working methods. Previous 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 are best achieved with both architectural and engineering expertise present in the design team. 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 et al. (2008) suggest assistance be provided as design performance analysis, without interfering with the creational design processes. The engineer should assist the generation and evaluation 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). Alternately, the integration of both disciplines in the early design phase is through practitioners with an equal understanding of aesthetic, functional and technical aspects or through a design team with the combined expertise to support Integrated Design Processes (IDP).

BIM, collaborative design and IDP

The digitalization of building information has changed workflows and responsibilities in the built environment for many stakeholders, mainly through the introduction of building information modelling (BIM) (A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), 2018; Sacks, Eastman, Lee, & Teicholz, 2018; Whyte & Hartmann, 2017). Although there is broad agreement about the potential benefits of digitalization the industry experiences only modest improvements in time, cost and performance (Smits, van Buiten, & Hartmann, 2017). BIM has a vast potential to support innovative and collaborative design approaches, which is encouraged as a means to deliver high performance buildings. Methods such as Integrated Design (ID) and IDP, promote early-stage engagement of stakeholders, interdisciplinary and simultaneous collaboration, and collective decision-making. However, although ID is theoretically well-founded, its implementation in practice currently lacks due to tool complexity, missing information and poor design decisions (Leoto & Lizarralde, 2019).

Integrated design is performed by a multidisciplinary design team where all relevant disciplines are activated from the beginning of the design process. This process can be supported by collaborative design charrettes and workshops that facilitate the development of common goals, knowledge sharing and problem solving (Forgues, D. & Lejeune, 2011). Collaboration and coordination are key to successfully overcoming challenges during the design process (Gagnon, Gosselin, & Decker, 2018) but availability of suitable BPS tools is also required to provide consistent feedback on the design direction (Jrade & Jalaei, 2013; Oti & Tizani, 2015). In IDP design teams are responsible for design optimization through iterative design processes. Design iterations are often aided by decision-making support tools such as quantitative assessment methods for sustainable building performance (Lützkendorf, 2018). BIM and IDP have transformed the traditional design process from a linear succession of fragmented task with minimal interaction between design teams, towards iterative and collaborative design processes. However, early-stage involvement of engineer specialists may be inhibited by structural challenges in the workflow between architects and engineers, such as fee structures, concerns about responsibility and liability, and architectural competition structures (Kanters & Horvat, 2012; Kovacic & Müller, 2014).

Decision support systems

BPS tools can be used as Decision Support Systems (DSS) to aid complex decision making and problem solving (Shim et al., 2002). However, performance assessments provide little value for IDP if they are not integrated into the actual design process. Examples of lacking integration include late stage compliance checks, isolated assessments, and BPS procedures exclusively handled by third parties (Lützkendorf, 2018). BPS tools play a vital role when evaluating and comparing design variants as they predict the impact of design choices. Such predictions should be performed at all relevant design stages, particularly in the early stages, where the decisions have the biggest impact (Lützkendorf, 2018). This calls for initiatives that bridge the gap between the need for early stage assessments and the currently available advanced simulation tools. Previous research recommends applying quick and inexpensive methods for the early design stages, and more accurate methods as the design develop (Omrani, Garcia-Hansen, Capra, & Drogemuller, 2017). Early stage assessment should be performed with caution, however, as oversimplification, incorrect assumptions and input uncertainties compromise assessment results and can lead to misinformation and inappropriate decisions (Gilani, O'Brien, Gunay, & Carrizo, 2016).

Many assessment methods have been developed to evaluate building performance, as well as to raise awareness, enable goal formulation and provide DDS (Lützkendorf, 2018). Existing methods for building performance assessment in the early design stages face a series of challenges including that simulation data is often not available (Leoto & Lizarralde, 2019; Østergård et al., 2016), that the tools are perceived as overly complicated, and that result interpretation requires specialized knowledge (S. Attia et al., 2009; Pieter de Wilde, 2019; Leoto & Lizarralde, 2019; Weytjens, Attia, Verbeeck, & De Herde, 2011).

BPS tools in early design

Several performance assessments tools have been developed to provide early stage DDS, particularly for Building Energy Simulation (BES) (Malmqvist et al., 2018) and Life Cycle Assessments (LCA) (Rezaei et al., 2019). Some of these assessment methods seek to reduce assessment time and costs through automation by utilizing BIM in the early design stages, e.g. to inform LCA analysis (Rezaei et al., 2019) or site analysis (Li et al., 2019). Other methods are dedicated to providing on time simulations by reducing the assessment complexity, or by providing detailed goal-setting and bottom-up reference values (Hollberg, Lützkendorf, & Habert, 2019). In line with performance-based design ideas (Bakens, Foliente, & Jasuja, 2005) DDS tool can also take an optimization approach using 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).

Indoor environment assessment methods

Assessment methods for IEQ are much less developed, mainly because there is no framework for holistic IEQ performance evaluation and no generally accepted list of aspects to consider. Available IEQ decision-support tools are predominately limited to single-aspect evaluations and optimizations such as for daylight (Mavromatidis, Marsault, & Lequay, 2014), solar (Nault, Peronato, Rey, & Andersen, 2015), envelope design (Catalina & Iordache, 2012; Negendahl & Nielsen, 2015), passive cooling strategy (Omrani et al., 2017) and window layout (Oh, Sung, & Kim, 2017).

A few studies provide multi-objective IEQ optimization, such as thermal and visual (Atzeri et al., 2016; X. Chen, Yang, & Sun, 2016), or thermal, visual and IAQ (Jakubiec, Doelling, Heckmann, Thambiraj, & Jathar, 2017; Ko et al., 2018), but still only include a limited amount of criteria within each aspect. This is a cause of concern, as the design team has to consider all interdependent objectives simultaneously to provide holistic DDS. A window strategy optimized for daylight (in isolation) 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 have limited detail 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 rely on traditional advanced simulations as performance input.

An increasingly applied approach is to provide early IEQ simulation through integrated CAD environments, for instance, using Rhino and Grasshopper in combination with different plugins (Energy+, Honeybee, Ladybug, Radiance). This approach is challenged by the need to apply several tools (or multiple plugins) to achieve sufficient IEQ content coverage and by a lack of a framework to compare results between tools (Andrade & Bragança, 2016).

In summary, most IEQ assessment methods focus on one or two aspects, leading to the development of a series of parallel simulation models, which increase the workload and requires simulation expertise. The few multiple-aspect tools available have considerable limitations for a holistic IEQ assessment such as broad concept level work (metrics that have not reached maturity to be integrated into design processes), limited criteria inclusion (relying on key performance indicators or overly simplified IEQ indexes), and comfort-only metrics (ignoring health impacts). The consequences of having to compare disconnected simulation results, or aggregated results with insufficient IEQ content, is that design teams will have a hard time understanding how a specific design variation affects the overall IEQ performance (Ko et al., 2018).

Decisions in the early design stages

The current research is presented from the perspective that contemporary building design is a complex activity that should contain elements of both creativity, intuition and rational decision-making. The role of the design team is to solve the many complicated requirements through human creative competence, with the aid of various expert input and building performance analysis (Pieter de Wilde, 2019).

A considerable body of literature has been dedicated to understanding how designers think and act (Lawson, 2005), including empirical studies of design processes such as through linkography (Goldschmidt,

2014) and protocol analysis (Cross, 2001; Hay et al., 2017; Kan & Gero, 2017). Previous studies have analysed how architects make decisions when integrating technical performance requirements such as through observation (Blanco, 2016), follow-up interviews with architects (Kanters et al., 2013) or analysis of documents after the design process (Leoto & Lizarralde, 2019). Findings include that design teams base decisions on previous experience, intuition and heuristics, as they perceive BPS tools as complex and time-consuming (Kanters et al., 2013; Leoto & Lizarralde, 2019; Reinhart & Fitz, 2006). When applied, BPS is often used to validate design strategies in isolation, which compromise the overall performance of the project (Leoto & Lizarralde, 2019).

Recognizing that decision making is guided by both the availability and the presentation of results (Doelling, 2014), a few tools address result interpretation challenges by providing visual feedback of assessment results for architectural DDS (Jakubiec et al., 2017; Ko et al., 2018). These studies argue that the use of integrated visualization models can provide holistic DDS for design teams by providing a better foundation for understanding interactions, trade-offs and synergies between and among IEQ aspects. Combining multi-aspect IEQ BPS with integrated visualization methods, allows design teams to consider the impact of their design decisions on holistic IEQ performance (Ko et al., 2018).

IEQCompass

In the present study, design teams were tasked to test a newly developed holistic IEQ assessment tool called **IEQ**Compass (beta version) (Larsen et al., 2020) for its ability to aid IEQ considerations in early design processes. In previous publications, the tool has been referred to as IV20, which was the national prototype name. The current version of the tool has been developed for multifamily residential projects in Denmark, which has a temperate climate (relatively cool summers, moderately cold winters, large seasonal variations in daylight). The **IEQ**Compass tool was developed as part of the REBUS project (Renovating Buildings Sustainably) (REBUS, 2016), which is a dedicated R&D partnership that consists of various stakeholders from the building industry. The **IEQ**Compass development team includes a wide range of building professionals such as researchers, consultant engineers, architects, manufacturers and professional building owners. 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 assesses the potential IEQ performance based on building geometry, climate data sets, and available information on building context, constructions and components. The assessment consists of 40 IEQ criteria split across four main areas: acoustics (ACOU), indoor air quality (IAQ), thermal (THER) and visual (VIS). By calculating a range of IEQ parameters identified in international standards and literature reviews, the tool automatically assesses the performance of all 40 criteria and scores them on a 0-10 scale. For instance, the risk of cold down-draft is assessed through the number of hours that air speeds exceeds a dissatisfaction threshold according to standards for local thermal discomfort. Down-draft airspeeds are calculated using window height and the difference between outdoor and indoor temperatures based on climate data and information about the building envelope. Each score is assigned a relative weight and is visualized graphically on a holistic performance overview (Design Compass, see Figure 2). The tool also generates aggregated scores in per cent with a matching IEQ label (letters' A' to 'G') for each main area score (ACOU, IAQ, THER, and VIS) and the overall potential IEQ performance. The tool visualizes both non-aggregated, partially aggregated, and fully aggregated results to provide nuanced assessments while accommodating for the needs of different stakeholders.

A key advantage of the **IEQ**Compass is that it provides fully operational criteria selection, performance targets and performance evaluation methods for holistic IEQ, which would typically require manual intervention and IEQ topic expertise (Pieter de Wilde, 2019). As this is combined with automatic performance simulation and result visualization, the design team can receive early-stage DDS without compromising the flexibility and pace of the early design process.

Besides the inclusion of acoustic performance, which is rarely part of multi-aspect assessments, the **IEQ**Compass includes a range of individual criteria that are often not considered. Examples of such criteria include the potential to provide direct sunlight access, view out access and quality, and view in privacy (limited exposure to being viewed upon from neighbouring outdoor areas, such as public spaces or balconies). While most multi-aspect assessments focus

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

exclusively on selected comfort metrics (Atzeri et al., 2016; Catalina & Iordache, 2012), the **IEQ**Compass also evaluate health and well-being dimensions such as source control (humidity, emissions and particles) and opportunities for adaption to user preferences.

In addition to providing performance simulation results for each criterion, the **IEQ**Compass highlights cause-and-effect chains. For example, a low daylight performance score can be translated into a potential impact on occupant health and comfort. Due to the integration of calculation and scoring, performance results can be traced back to its indicators (glazed area, shading coefficients) and the related building characteristics (facade design, window component, overhang), which aids design teams in addressing lacking performance. As the tool combines the assessment of all relevant IEQ aspects, this cause-and-effect chain also provides vital information on inter-aspect trade-offs that allows for holistic design improvements.

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

According to Lützkendorf (2018), the preconditions for the successful integration of environmental issues in buildings is '… a basic understanding of the subject of environmental issues, the development and use of suitable assessment methods, the provision and use of appropriate data and tools, as well as the systematic integration of environmental aspects into the design and decision-making processes.'. The current study seeks to integrate IEQ topics into early design processes by providing the listed preconditions through the application of the newly developed IEQ assessment tool. The **IEQ**Compass tool has been selected for this study as it provides holistic IEQ assessments (all four main IE areas), DDS functionality, and promotes a more front-loaded multidisciplinary design process for IEQ concerns. The present study is the first application example of **IEQ**Compass in a design process. The design scenarios presented in this study test to which extent the tool accommodates essential functionality highlighted in previous DDS tool recommendations. According to literature, early stage decision support tools should provide:

- improved practicability and user-friendliness (Lützkendorf, 2018)
- 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)
- promotion of early-stage IEQ expertise integration and knowledge building within the design team (Cole, 1998)
- dialogue and communication support between central parties of the project (Cole, 2005)
- early-stage DDS through timely performance feedback and design variation comparison (Østergård et al., 2016)
- mechanics, intelligence and usability that make it effective and informative (rather than just evaluative) (S. G. Attia & De Herde, 2011)
- clear presentation of advantages to convince clients about early integration (Kanters et al., 2013)

Previous investigations of sustainable design processes collect data from various sources such as follow-up interviews (Kanters et al., 2013), post-design analysis of documents (Leoto & Lizarralde, 2019) and design work observations (Blanco, 2016). The current study consists of two complementary setups (Table 1) that combine these three data types. Both setups were designed to evaluate whether the tool can provide operational DDS and potentially overcome the obstacles summarized above.

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, site plan development
Dwelling	Refurbishment	New apartment design
Time span	3x 45 minutes ('condensed design process')	Two months ('regular design process')
Project phase	Early design stage (renovation)	Preparation and Brief, Concept Design, Developed Design, Technical Design
Users	Multidisciplinary 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

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

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 design team made several iterations on a renovation proposal for an apartment building. The design team was supported by a specialist team, who operated the tool to provide IEQ simulation input.

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 BPS 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 was 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 between stages (e.g. between the competition stage and project development).

Performance data were collected for different design iterations in both setups using **IEQ**Compass. Results from both setups will be presented as simplified design processes 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 both tool operationality and the potential influence on early stage DDS as interpreted by the participants. Interviews were semi-structured to 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 investigated method helps break down the identified barriers for integrating BPS tools and engineering expertise into early design or not.

Interview data were analysed using the grounded theory research method (Glaser, Strauss, & Strutzel, 1968), which has been applied to analyse architectural design processes previously (Kanters et al., 2013). Interviews were broken down 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 statements.

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 dwellingsousing 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 competitions department and project development) - constructing architect x2 (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)*

The integration of qualitative and quantitative methods build on mixed methods techniques that combine knowledge to provide a holistic perspective on the investigated topics. 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 (predicted) IEQ performance improvements, but observations are required to explain when and how the tool was used. Interviews allow for further 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 simultaneously 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 estimated costs low. 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, led by two supervisors and an external censor (architect).

Workshop setup (condensed design process)

The design team was asked to generate design proposals while a specialist team (Table 2) presented them with simultaneous IEQ performance assessments to guide their design choices. The design team was briefly introduced to the **IEQ**Compass tool and the aim of the workshop. The first part of the 3x 45 minutes design workshop was developing a preliminary renovation proposal without interference from the specialist team. The preliminary design proposal provided input for simulations to calculate the potential IEQ score and to evaluate energy performance.

The specialist team presented the BPS results to the design team to inform the following design iterations. Using the IEQ performance assessment as the point of departure, the design team revised their proposal while consulting the specialist team and receiving live **IEQ**Compass score feedback on design variations.

Based on the IEQ assessment of the revised proposal, the design team made decisions on 'surface material', 'user influence' and 'building component' level. The workshop closed with IEQ assessment comparisons between the baseline, 'as built' (realised renovation) and the workshop proposal. Finally, a semi-structured group interview was conducted with the design team concerning immediate reflections on the design process.

Workshop case and participants

The case building is an apartment block at Fyrkildevej in Aalborg, Denmark, which was designated for deep renovation. Before the workshop, the participating architectural firm made a renovation proposal for an identical building, as part of the REBUS project. The architectural firm was invited to participate in the workshop as this presented an opportunity to compare design proposals (through quantitative assessment) and design processes (through observations and interviews) on identical projects - with and without the use of the **IEQ**Compass tool. The workshop proposals faced the same requirements for functionality, aesthetics, buildability and cost as to the original proposal.

The design team was assembled to include a broad representation of skills and backgrounds. Two participants had been part of the design process of the identical building: one in the early competition stage and the other during the design development. However, the workshop task was to generate a new design proposal with a focus on IEQ using the feedback provided by the **IEQ**Compass. As such, project familiarity was not considered an issue for the study. Instead, it provided an opportunity for participant reflections on the differences in workflow between the workshop and the original design process. The renovation was in-process when the workshop was carried out, meaning that the design team was not influenced by information on the realized IEQ or other insights gained from studying the completed project.

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 present performance 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 (2) can be compared to the realized renovation score (3) which represents a deep renovation 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 impact of the tool on 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 observation during the workshop, (2) a semi-structured group interview with the design team immediately following the workshop, and (3) semi-structured individual interviews ten days after the workshop. Individual interviews were conducted with 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 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. Students work in small design teams through all design stages, and they are highly trained in integrating technical parameters such as energy efficiency, statics and IEQ. This provides a unique opportunity to study the influence of the tool from the earliest design stages to validation and communication of results.

The participants were introduced to the tool at the beginning of a two-month project period. Supervision was performed by an architectural supervisor (architect), and a technical supervisor on indoor environmental and energy efficiency topics (engineer). Design process observations were performed during select supervisor meetings and the project exam.

Project case

Students were tasked to design a housing complex for the project site 'Limfjordsværftet' in Aalborg, Denmark (4350 m^2). The design task involved both site planning and the design and layout of 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 with three bedrooms (115 m^2), 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 instead be discussed qualitatively. Qualitative data were collected in three ways; (1) observations during selected supervisor meetings, (2) observations during 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 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

A simplified version of the workshop design process that specifically impacts IEQ performance is presented in Table 3. Numbers in brackets below 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 [#1]. There was no interference from the specialist team during this stage, and the design team was instructed not to be constrained by the workshop focus on IEQ. The design teams worked primarily with plan layout topics such as zoning, flow, spatial qualities, access to private outdoor areas, efficient use of m^2 and flexible furnishing. They also considered IEQ aspects such as cross-ventilation, daylight access, and risk of overheating. The design team considered moving the façade out to avoid shade from a balcony on the floor above but decided to keep the overhang as a measure against overheating. 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 single 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 workshop 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 (integrated graphical scoring, Figure 2) as the point of departure for a series of iterations aiming to improve IEQ performance [#3-#6]. The first step included balanced mechanical ventilation to improve IAQ performance [#3]. Then the design team discussed whether to replace panel walls with well-insulated wall sections or French windows. The topics considered included drafts, heating systems, view out, view in, daylight access and risk of excessive passive solar. The design team increased 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 resulted in minor setbacks in noise exposure and 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 workshop phase, the design team made minor adjustments towards the final workshop renovation proposal. At this stage, the design team discussed surface materials, IEQ performance robustness, and were presented with a range of 'user influence' options on solar shading, window opening and mechanical 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 [#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 only slightly better than the 'baseline' performance at 69%. As indicated by the arrows in Figure 2, the significant improvement 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 drastically improves both VIS and THER, by maximizing scores for both direct sunlight, daylight and summer comfort through several iterative design steps (Table 3). The IAQ improvements help bring the workshop proposal score to 85%. This is 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).

The 16% point improvement from the baseline (vs 3% in the original proposal) indicates a significant potential gain from applying the methodology in design workshops. As the workshop proposal met the same budget restrictions as the original proposal, the workshop is an exemplification of how early stage integration can lead to improved investment of resources. The workshop proposal improved IEQ performance through a more efficient application of traditional renovation measures, including (1) ensuring that all relevant topics were considered and (2) finding a good balance between performance of ‘conflicting criteria’ such as daylight access and excessive solar gain.

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 workshop 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. As a member of the competitions departments explained:

> 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.

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 performance or a room programme – it is never merely about what they think looks good. In that sense, the team did not worry that early-stage technical evaluations would limit their creativity as according to one of the architects of the team:

> 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 of the constructing architects 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:

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%	ACOU = 74% IAQ = 66% THER = 72% VIS = 66%	N/A		
#2 'New plan layout'	70% (+1%)	ACOU = 73% (-1%) IAQ = 70% (+4 %) THER = 71% (-1%) VIS = 66%	**ACOU:** **IAQ:** **THER:**	↑ ↓ ↑ ↓	Fewer rooms with low absorption surfaces More exposure to noise in the main room Option to dry clothes outside the envelope Fewer rooms with radiators under the window (draft)
#3 'Mechanical ventilation'	76% (+6%)	ACOU = 76% (+3%) IAQ = 89% (+19%) THER = 75% (+4%) VIS = 66%	**ACOU:** **IAQ:** **THER:**	↑ ↑ ↑ ↑ ↑	Mechanical ventilation with sufficient sound dampening Balanced mechanical ventilation Mechanical ventilation in the bathroom Filtration of the outdoor air No drafts from intake air due to preheated air supply
#4 'Increased glazing: west'	78% (+2%)	ACOU = 74% (-2%) IAQ = 89% THER = 74% (-1%) VIS = 74% (+8%)	**ACOU:** **THER:** **VIS:**	↓ ↓ ↑	Larger windows w. low sound insulation (compared to walls) Increased risk of downdraft due to increased window heights Larger windows result in better daylight conditions
#5 'Tripple pane windows'	80% (+2%)	ACOU = 78% (+4%) IAQ = 89% THER = 78% (+4%) VIS = 74%	**ACOU:** **THER:**	↑ ↑	Window components w. better noise reduction properties Window components w. lower U-value: less risk of radiant temperature asymmetry and less risk of downdraft
#6 'Increased glazing: east'	80% (+0%)	ACOU = 78% IAQ = 89% THER = 72% (-6%) VIS = 80% (+6%)	**THER:** **VIS:**	↓ ↑	Larger windows result in more hours w. too high temperatures Larger windows result in better daylight conditions
#7 'External solar shading' – Workshop final	85% (+5%)	ACOU = 78% IAQ = 89% THER = 89% (+17%) VIS = 82% (+2%)	**THER:** **VIS:**	↑ ↑	External solar shading results in fewer hours w. too high temperatures Moveable external shading: separate for each window and with no view out interference when 'not active'

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

> 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 and test a concept in less than an hour for it to be operational. 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.

According to literature, competition teams with both architects and engineers, have the potential to make robust designs by integrating technical requirements in the early concept proposals (Kanters et al., 2013). However, the competition department team member expressed that consultant engineers often do not wish to participate in the early stages as it is costly 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. He elaborated that the engineers assess the performance of the finished concept and typically conclude that it fails to perform (in some aspects). If the team wins a competition with an 'all-glass building', then the client will get just that – with only expensive and inefficient half measures available to remedy lacking performance. The authors believe that early multidisciplinary workshops that apply low effort BPS tools could be one way to address this issue, 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. Although IEQ had not been a focal point in the renovation, everyone expected IEQ performance to have improved, as expressed by a project development architect:

> 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 is A/B/C/D (labels), then it becomes very simple for a client to set requirements.

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

Project results

Table 4 provides an overview of the eight weeks of student project work. **IEQ**Compass assessments were performed in the earliest design stages from week three to five. As the project developed rapidly on both urban scale and apartment scale at this stage, the assessments were used to both compare varying apartment layouts, and to evaluate the general performance of large-scale design options such as different massing and orientation options. After deciding on a concept to detail from week six to week eight, assessments were used to test the influence of small-scale design variations such as floor plan and façade designs.

IEQCompass helped indicate how design improvements unrelated to IEQ, such as functionality, aesthetics and energy efficiency would influence IEQ performance. Also, the tool was explicitly used to show lacking IEQ performance allowing the project groups to work towards improved 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 presents a simplified summary of how the tool was used to guide, test and document a series of IEQ improvements (for the concept selected for detailing).

Both student groups showed 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 projects, indicating that the pursuit of overall IEQ improvement does not dictate priorities between areas. Despite the very similar overall performance, the variation between areas is as high as 16% points (IAQ). Group 1 got balanced results (+/-8% points from the average) although choosing to prioritize THER at 90% slightly over VIS at 75%.

Group 2 almost perfected the potential IAQ with 98% and choose 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 gain. This compromise was made to prevent the need for mechanical cooling of the apartments, which impose a penalty in the Danish energy labelling system (which would compromise the zero-energy ambition).

Project interviews and observations

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

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 development*	**Site plan** Typology, volume, orientation	**Apartment layout** Function, Circulation, light and spatiality	**Materials** Tectonics and at-mosphere	**Midway critique** Final concept direction	**Concept iterations** Optimization 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	Setting goals for IEQ	Assess: orientation studies	Assess: Apartment com-	Assess: Finding the critical	Assess: Basic model	Assess: Iteration 1 and 2	Assess: Iteration 3 (final)	Communication of the process and
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%	ACOU = 76% IAQ = 50% THER = 69% VIS = 65%	N/A
GROUP 1	**2** **'External solar shading'**	68% (+3%)	ACOU = 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
GROUP 1	**3** **'Window properties and surfaces'**	71% (+3%)	ACOU = 80% (+4%) IAQ = 50% THER = 77% (-1%) VIS = 79% (+12%)	**ACOU:** ↑ 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)
GROUP 1	**4** **'Mechanical ventilation'**	82% (+11%)	ACOU = 83% (+3%) IAQ = 82% (+32%) THER = 90% (+13%) VIS = 75% (-4%)	**ACOU:** ↑ 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%	ACOU = 38% IAQ = 91% THER = 69% VIS = 71%	N/A
GROUP 2	**2** **'Added external shading, reduced glazed area, and improved acoustic performance'**	74% (+7%)	ACOU = 63% (+25%) IAQ = 97% (+6%) THER = 76% (+7%) VIS = 60% (-11%)	**ACOU:** ↑ 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) **THER:** ↑ 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
GROUP 2	**3** **'Further acoustic improvements'**	78% (+4%)	ACOU = 79% (+16%) IAQ = 97% THER = 76% VIS = 61% (+1%)	**ACOU:** ↑ Improved sound insulation of floor separation ↑ Sound dampening of staircase elevator **VIS:** ↑ Better daylight access from larger bathroom windows
GROUP 2	**4** **'Improved efficiency and functionality of external shading'**	84% (+6%)	ACOU = 79% IAQ = 98% (+1%) THER = 92% (+16%) VIS = 66% (+5%)	**IAQ:** ↑ Service agreement for kitchen exhaust hood **THER:** ↑ 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)

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

Early-stage decision support

On the Concievement of design ideas. All participants had previous experience with IDP and managed to apply the tool in early design. One group used the tool mainly as verification of their design choices. 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 tool. 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 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 the project aesthetics that allowed them to evaluate designs architecturally while using BPS to 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 the 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 IE 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 efficiently. 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 significant 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 IEQ criteria to consider. They reflected that traditionally IEQ criteria would be handled in an arbitrary order by a range of separate tools. As **IEQ**Compass united all criteria in a single tool, different aspects 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 four? The **IEQ**Compass manual compares tool scoring to PD and PPD to provide relatable performance indication (when applicable). Also, the tool has a built-in comparison with Danish building code minimum requirements. However, such requirements only exist for 8 of the 40 criteria assessed by the tool. Another challenge is that project conditions differ widely.

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

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 tool highlights which criteria (output) are influenced by individual input (e.g. window areas influence THER1.1, THER1.2, ACOU1.1 and VIS 1.1). The students also 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

According to Leoto and Lizarralde (2019), the development of better simulation tools and a deepening of the knowledge of professionals is a vital step in the overcoming the current challenges for ID-practice. This study indicates that the investigated tool 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). Visual representation of IEQ performance enabled design teams to react to lacking performance in the early design stages and allowed for increased understanding of the synergies and trade-offs of their proposed design alternatives. This is in line with previous research indicating that the ability to make decisive and good design changes is enhanced through the immediate understanding of design performance (Doelling, 2014; Jakubiec et al., 2017).

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 each design alternative is possible through simultaneous calculation and assessment of all parameters combined with integrated 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.

Early design explorations

In the early conceptual design stages, design teams used the tool to investigate early stage decisions on orientation, building shape and room dimensions, using a combination of predetermined project site information, default component values and simple geometric information This is an important finding as conceptual decisions are often taken based on rules of thumb and experience, while performance analysis is only employed after decisions are made (Kanters et al., 2013; Leoto & Lizarralde, 2019; Reinhart & Fitz, 2006). Early application of performance assessment may solve the issue that simulation tools merely influence 'sizing and optimization' because fundamental design-strategic decisions have already been made (Pilgrim, Bouchlaghem, Loveday, & Holmes, 2003; P De Wilde, Voorden, Brouwer, Augenbroe, & Kaan, 2001).

Workshop participants suggest supporting early design explorations further by grouping IEQ criteria by project phase relevance. Such criteria grading could help indicate which of the 40 criteria to give a higher focus during early conceptual developments, e.g. due to high impact or little/no option to change later. The participating practitioners argued that without proper guidance, it could be challenging to determine input on components and controls systems in the early stages. Instead, they suggested applying default values for some input during early design exploration, leaving them for later stage detailing.

Student participants initially expressed insecurity of what constitutes as 'poor' and 'good' performance for specific criteria. The students suggested integrating benchmark values that would enable a better understanding of what represents good performance for individual criteria.

Precision, responsiveness and functionality

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

The most efficient route to sufficient level IEQ assessments lies in the right balance between precise simulation methods and appropriate model resolution levels. 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). The **IEQ**Compass tool presents a workflow that combines accurate IEQ assessments (following international IEQ standards) without compromising assessment speed, such as from advanced input requirements and highly labour consuming simulation and result interpretation.

The **IEQ**Compass tool uses much of the same input as required for mandatory BEP, which reduce the workload for registration and manual input. By identifying recurring performance analysis tasks (well-defined in IEQ standards) and integrating them into a single framework, automation can free up design team resources. As brought forth by de Wilde (2019) and Van Treeck et al. (2018), there is a potential to reduce the need for manual intervention further by using BIM to extract information on building geometry, components and systems. Future versions of the tool should utilize this potential to increase simulation speed and consistency further.

Omrani et al. (2017) suggest combining the use of quick and inexpensive methods for the early design stages, with detailed methods in the later stages. Although the tested tool bridge these goals by providing both the agility needed for conceptual design and the precision required for detailed design, the tool has a lower detail level than some single-aspect assessment methods. As pointed out by 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. As a result, design teams may decide to expand holistic results using selected dedicated assessment tools such as for daylight simulations, as was the case in one of the student projects. As evident from the student project, the benefits of using a single holistic IEQ assessment tool are compromised if design teams lose the overview of inter-aspect trade-offs.

The use of overlapping tools also reintroduce concerns raised by Leoto & Lizarralde (2019) about inconsistencies in input as the design changes. The best way to avoid such inconsistencies is to develop the tool to accommodate the requested functionality. One example could be to providing visualisations of more detailed breakdowns of the results such as representations of results that relate time and space as suggested by Jakubiec et al. (2017).

Previous literature has raised concerns that design teams who rely on predicted performance to make informed decisions, are vulnerable to both high uncertainty in BPS model input, poor modelling assumptions and oversimplified occupant behaviour (Abuimara, O’Brien, Gunay, & Carrizo, 2019; Y. Chen, Liang, Hong, & Luo, 2017; Gilani et al., 2016). Future research efforts should focus on validating the results from early stage multi-aspect tools, e.g. by comparing results with dedicated high detail simulation methods. Also, investigations of finished projects could indicate to which degree the scoring and weighting generated by the tool matches the realized IEQ performance (such as through monitoring and surveys).

Integrated design processes

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 without compromising other key aspects. The findings are likely to apply outside the topic of IEQ, and the proposed methodology for holistic performance assessment should be relevant for the integration of other technical aspects such as energy performance, LCC and LCA.

The workshop demonstrated the responsiveness of **IEQ**Compass by providing real-time assessments and comparisons between design proposal variations. Since the workshop case was an existing building modelled 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, such as changing room dimensions and plan layout. This design freedom provides a significant advantage to most tools that rely on pre-simulated meta models with parameter variations on 'expected' parameters, as such unpredicted changes could render the pre-simulated models useless.

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.

Limitations and bias

The two setups demonstrate that early integration of IEQ BPS can support decision making in environments that are friendly towards the presented methodology. The authors realize that not all design teams will have the required insight, interest or resources to follow the presented methodology. The three design teams of the current study incorporate integrated design in their usual practice, and some participants have experience with using simple BPS to aid decision making (such as integrated CAD environments for parametric exploration of design spaces). Also, the design teams had some level of IEQ expertise present when applying the tool, something that is not necessarily available for in the early design stages of smaller projects. However, tests indicate that the tool can support collaborative and integrated design processes, and further the integration of IEQ performance assessment in early design with reduced requirements for topic expertise and a limited investment of resources.

The workshop had a strong IEQ focus, and it is no surprise that efforts to improve on the low performance areas indicated by the investigated tool resulted in improvements according to assessments made by the same tool. However, it is interesting that with just a few hours of effort the design team managed to produce a new design proposal with a significantly higher (predicted) performance than the original proposal without compromising other aspects, including estimated costs.

The workshop was designed to put the design team at the centre of the creative design processes and decision making, with the indirect influence of the specialist team. The workshop was deliberately designed as a half-day collaborative IEQ workshop (or design charrette), in which the presence and guidance of domain experts is a prerequisite for multidisciplinary IDP work. However, in this case, the specialist team who operated the **IEQ**Compass model and interpreted results consisted partly of tool developers. This additional tool insight means that conclusions on the specialist team side (such as interface user friendliness) should instead be drawn from the student projects.

Generalizing findings from student projects should be done with caution, but the participating students were trained in a practice oriented environment on projects set up to mimic actual design work practice. Their architect/engineer profile and IDP schooling mean that they closely represent a professional integrated design team with access to IEQ expert knowledge. The student projects provided substantial evidence for the applicability of the assessment method in projects with fewer constraints (new built) and the support of design developments from design brief to validation.

The **IEQ**compass developer team played active roles in both the testing of the tool and the writing of the paper, which introduce an objectivity bias when evaluating results. Different initiatives were taken to limit this influence, in the two tested setups. The workshop facilitator role was performed by a consultant engineer with no previous experience with the tool (and no role in the writing of this paper). This limited the roles of the authors and tool developers to introducing and operating the tool, making observations. In the student workshop, the influence of the developers/authors was considerably lower, as the design teams both operated the tool and controlled the design process. Also, ongoing design guidance and final project evaluation were provided by the architectural supervisor and industry representatives with no connection the development or tests of the tool.

Conclusion

This research demonstrates promotion of early stage integration of IEQ aspects through the use of assessment tools developed specifically to provide DDS. Observations and interviews reveal that fast-paced, visualized assessments allow for more in-depth IEQ considerations than traditional practice, without taking focus away from other vital design parameters. The visual result dissemination provides a holistic overview of IEQ performance, resulting in known trade-offs between IEQ aspects, leading to gradually increasing overall IEQ performance between iterations in the three tested scenarios.

The workshop results indicate 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 significantly within the same project boundaries through the use of holistic assessment methods in a multidisciplinary design team setting, by shifting a modest amount of resources to the early design stages. This integration of holistic IEQ performance assessment requires early integration of IEQ experts and the availability of quick and inexpensive methods for IEQ performance prediction.

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 considerations. Project work findings demonstrate that high-level IEQ performance can be combined with zero-energy requirements without compromising other crucial design parameters, such as functionality and aesthetics.

Both practitioners and students expressed that the tool was more user-friendly than existing alternatives. Participant 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. Participant feedback revealed opportunities for the future development of the tool, particularly regarding improved overview in the early design explorations.

The presented research is the first step to demonstrate that the proposed methodology can integrate holistic IEQ performance assessment in early stage design processes. Future research should aim to: (1) automate extraction of input data from BIM to integrate into the current workflow in architectural practice, (2) expand the visual representation of results to provide additional information of performance related to time and building geometry, and (3) accommodate participant suggestions for early design exploration, including grouping IEQ criteria by project stage relevance. Practitioners are recommended to encourage early integration of IE experts and to apply early stage multi-aspect IEQ performance predictions to support decision making towards high performance indoor environments.

Disclosure statement

No potential conflict of interest reported by the authors.

References

A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.). (2018). *Building Information Modeling - Technology Foundations and Industry Practice*. Springer, Cham.

Abuimara, T., O'Brien, W., Gunay, B., & Carrizo, J. S. (2019). Towards occupant-centric simulation-aided building design: a case study. *Building Research & Information*, *47*(8), 866–882. https://doi.org/10.1080/09613218.2019.1652550

Andrade, J., & Bragança, L. (2016). Sustainability assessment of dwellings – a comparison of methodologies. *Civil Engineering and Environmental Systems*, *33*(2), 125–146. https://doi.org/10.1080/10286608.2016.1145676

Asadi, S., Amiri, S. S., & Mottahedi, M. (2014). On the development of multi-linear regression analysis to assess energy consumption in the early stages of building design. *Energy and Buildings*, *85*, 246–255. https://doi.org/10.1016/j.enbuild.2014.07.096

Attia, S., Beltrán, L., De Herde, A., & Hensen, J. (2009). "Architect friendly": A comparison of ten different building performance simulation tools. *IBPSA 2009 - International Building Performance Simulation Association 2009*, 204–211.

Attia, S. G., & De Herde, A. (2011). Early design simulation tools for net zero energy buildings: A comparison of ten tools. *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, 94–101. Retrieved from http://ibpsa.org/proceedings/BS2011/P_1148.pdf

Attia, S., Hensen, J. L. M., Beltrán, L., & De Herde, A. (2012). Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs. *Journal of Building Performance Simulation*, *5*(3), 155–169. https://doi.org/10.1080/19401493.2010.549573

Atzeri, A. M., Cappelletti, F., Tzempelikos, A., & Gasparella, A. (2016). Comfort metrics for an integrated evaluation of buildings performance. *Energy and Buildings*, *127*, 411–424. https://doi.org/10.1016/j.enbuild.2016.06.007

Bakens, W., Foliente, G., & Jasuja, M. (2005). Engaging stakeholders in performance-based building: lessons from the Performance-Based Building (PeBBu) Network. *Building Research & Information*, *33*(2), 149–158. https://doi.org/10.1080/0961321042000322609

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81–92.

https://doi.org/10.1016/j.buildenv.2012.11.009

Blanco, J. (2016). Beyond the checklist: an approach to understand practitioner experience during sustainable design process. *Architectural Engineering and Design Management*, *12*(4), 266–278. https://doi.org/10.1080/17452007.2016.1178628

Brager, G. S. (2013). Benefits of Improving Occupant Comfort and Well-being in Buildings. *Proceedings of the 4th International Holcim Forum for Sustainable Construction: The Economy of Sustainable Construction*, 181–194. Retrieved from https://src.lafargeholcim-foundation.org/dnl/93603859-d59e-498a-b056-405d16e39171/F13_OrangeWS_Brager.pdf

Bryman, A. (2006). Integrating quantitative and qualitative research: How is it done? *Qualitative Research*, *6*(1), 97–113. https://doi.org/10.1177/1468794106058877

Catalina, T., & Iordache, V. (2012). IEQ assessment on schools in the design stage. *Building and Environment*, *49*, 129–140. https://doi.org/10.1016/J.BUILDENV.2011.09.014

Chen, X., Yang, H., & Sun, K. (2016). A holistic passive design approach to optimize indoor environmental quality of a typical residential building in Hong Kong. *Energy*, *113*, 267–281. https://doi.org/10.1016/j.energy.2016.07.058

Chen, Y., Liang, X., Hong, T., & Luo, X. (2017). Simulation and visualization of energy-related occupant behavior in office buildings. *Building Simulation*, *10*(6), 785–798. https://doi.org/10.1007/s12273-017-0355-2

Cole, R. J. (1998). Emerging trends in building environmental assessment methods. *Building Research & Information*, *26*(1), 3–16. https://doi.org/10.1080/096132198370065

Cole, R. J. (2005). Building environmental assessment methods: Redefining intentions and roles. *Building Research and Information*, *33*(5), 455–467. https://doi.org/10.1080/09613210500219063

Cross, N. (2001). Design cognition: results from protocol and other empirical studies of design activity. In *Design Knowing and Learning: Cognition in Design Education* (pp. 79–103). https://doi.org/10.1016/B978-008043868-9/50005-X

de Wilde, Pieter. (2019). Ten questions concerning building performance analysis. *Building and Environment*, *153*, 110–117. https://doi.org/10.1016/j.buildenv.2019.02.019

Doelling, M. C. (2014). Space-based Thermal Metrics Mapping for Conceptual Low-Energy Architectural Design. *Proceedings of Building Simulation and Optimization, London 2014*. UCL, London, United Kingdom.

El-Diraby, T., Krijnen, T., & Papagelis, M. (2017). BIM-based collaborative design and socio-technical analytics of green buildings. *Automation in Construction*, *82*, 59–74. https://doi.org/10.1016/j.autcon.2017.06.004

European Union. (2019). *EPBD Commission Recommendation (EU) 2019-786*.

Forgues, D., & Lejeune, A. (2011). Value generation through integrated teams: a socio-cognitive approach. *J. Civil Eng. Arch.*, *5*(1), 13–21.

Gagnon, R., Gosselin, L., & Decker, S. (2018). Sensitivity analysis of energy performance and thermal comfort throughout building design process. *Energy and Buildings*, *164*, 278–294. https://doi.org/10.1016/j.enbuild.2017.12.066

Gerber, D. J., & Lin, S.-H. E. (2014). Designing in complexity: Simulation, integration, and multidisciplinary design optimization for architecture. *SIMULATION*, *90*(8), 936–959. https://doi.org/10.1177/0037549713482027

Gilani, S., O'Brien, W., Gunay, H. B., & Carrizo, J. S. (2016). Use of dynamic occupant behavior models in the building design and code compliance processes. *Energy and Buildings*, *117*, 260–271. https://doi.org/10.1016/j.enbuild.2015.10.044

Glaser, B. G., Strauss, A. L., & Strutzel, E. (1968). The Discovery of Grounded Theory: Strategies for Qualitative Research. *Nursing Research*, *17*(4), 364. https://doi.org/10.2307/2094063

Goldschmidt, G. (2014). *Linkography: Unfolding the Design Process*. https://doi.org/10.1016/j.destud.2015.10.003

Hansen, H. T. R., & Knudstrup, M.-A. (2005). The Integrated Design Process (IDP) - a more holistic approach to sustainable architecture. *The 2005 World Sustainable Building Conference, Tokyo*, 894–901. Tokyo, Japan: SB05Tokyo.

Hay, L., Duffy, A. H. B., McTeague, C., Pidgeon, L. M., Vuletic, T., & Grealy, M. (2017). A systematic review of protocol studies on conceptual design cognition: Design as search and exploration. *Design Science*, *3*(10). https://doi.org/10.1017/dsj.2017.11

Hensen, J. L. M. (2004). Towards more effective use of building performance simulation in design. *Proceedings of the 7th International Conference on Design & Decision Support Systems in Architecture and Urban Planning*.

Hester, J., Gregory, J., & Kirchain, R. (2017). Sequential early-design guidance for residential single-family buildings using a probabilistic metamodel of energy consumption. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2016.10.047

Hollberg, A., Lützkendorf, T., & Habert, G. (2019). Top-down or bottom-up? – How environmental benchmarks can support the design process. *Building and Environment*, *153*, 148–157. https://doi.org/10.1016/j.buildenv.2019.02.026

Hygh, J. S., DeCarolis, J. F., Hill, D. B., & Ranji Ranjithan, S. (2012). Multivariate regression as an energy assessment tool in early building design. *Building and Environment*, *57*, 165–175. https://doi.org/10.1016/j.buildenv.2012.04.021

Jakubiec, J. A., Doelling, M. C., Heckmann, O., Thambiraj, R., & Jathar, V. (2017). Dynamic Building Environment Dashboard: Spatial Simulation Data Visualization in Sustainable Design. *Technology|Architecture + Design*, *1*(1), 27–40. https://doi.org/10.1080/24751448.2017.1292791

Jrade, A., & Jalaei, F. (2013). Integrating building information modelling with sustainability to design building projects at the conceptual stage. *Building Simulation*, *6*(4), 429–444. https://doi.org/10.1007/s12273-013-0120-0

Kamari, A., Corrao, R., & Kirkegaard, P. H. (2017). Sustainability focused decision-making in building renovation. *International Journal of Sustainable Built Environment*, *6*(2), 330–350. https://doi.org/10.1016/j.ijsbe.2017.05.001

Kan, J. W. T., & Gero, J. S. (2017). Quantitative Methods for Studying Design Protocols. In *Quantitative Methods for Studying Design Protocols*. https://doi.org/10.1007/978-94-024-0984-0

Kanters, J., Dubois, M.-C., & Wall, M. (2013). Architects' design process in solar-integrated architecture in Sweden. *Architectural Science Review*, *56*(2), 141–151. https://doi.org/10.1080/00038628.2012.681031

Kanters, J., & Horvat, M. (2012). The design process known as IDP: A discussion. *Energy Procedia*. https://doi.org/10.1016/j.egypro.2012.11.128

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., … Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

Klitgaard, J., Kirkegaard, P. H., & Mullins, M. (2006). On the integration of digital design and analysis tools. *Digital Architecture and Construction*, *1*, 187–196. https://doi.org/10.2495/DARC060191

Ko, W. H., Schiavon, S., Brager, G., & Levitt, B. (2018). Ventilation, thermal and luminous autonomy metrics for an integrated design process. *Building and Environment*, *145*, 153–165. https://doi.org/10.1016/j.buildenv.2018.08.038

Kovacic, I., & Müller, C. (2014). Challenges for the Implementation of Integrated Design in the Planning Practice. *Procedia - Social and Behavioral Sciences*, *119*, 529–538. https://doi.org/10.1016/j.sbspro.2014.03.059

Kovacic, I., & Zoller, V. (2015). Building life cycle optimization tools for early design phases. *Energy*, *92*, 409–419. https://doi.org/10.1016/j.energy.2015.03.027

Kvale, S., & Brinkmann, S. (2009). *InterViews: Learning the Craft of Qualitative Research Interviewing* (2nd ed.). Los Angeles: SAGE Publications, Inc.

Larsen, T. S., Rohde, L., Jønsson, K. T., Rasmussen, B., Jensen, R. L., Knudsen, H. N., … Bekö, G. (2020). IEQ-Compass – A tool for holistic evaluation of potential indoor environmental quality. *Building and Environment*, *172*. https://doi.org/10.1016/j.buildenv.2020.106707

Lawson, B. (2005). *How Designers Think: The Design Process Demystified* (4th ed.). Oxford, UK: Architectural Press, Elsevier.

Leoto, R., & Lizarralde, G. (2019). Challenges in evaluating strategies for reducing a building's environmental impact through Integrated Design. *Building and Environment*, *155*, 34–46. https://doi.org/10.1016/j.buildenv.2019.03.041

Li, J., Li, N., Afsari, K., Peng, J., Wu, Z., & Cui, H. (2019). Integration of Building Information Modeling and Web Service Application Programming Interface for assessing building surroundings in early design stages. *Building and Environment*, *153*, 91–100. https://doi.org/10.1016/j.buildenv.2019.02.024

Lützkendorf, T. (2018). Assessing the environmental performance of buildings: trends, lessons and tensions. *Building Research & Information*, *46*(5), 594–614. https://doi.org/10.1080/09613218.2017.1356126

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard Rasmussen, F., Houlihan Wiberg, A., & Potting, J. (2018). Design and construction strategies for reducing embodied impacts from buildings – Case study analysis. *Energy and Buildings*, *166*, 35–47. https://doi.org/10.1016/j.enbuild.2018.01.033

Markelj, J., Kitek Kuzman, M., Grošelj, P., Zbašnik-Senegačnik, M., Markelj, J., Kitek Kuzman, M., … Zbašnik-Senegačnik, M. (2014). A Simplified Method for Evaluating Building Sustainability in the Early Design Phase for Architects. *Sustainability*, *6*(12), 8775–8795. https://doi.org/10.3390/su6128775

Mavromatidis, L. E., Marsault, X., & Lequay, H. (2014). Daylight factor estimation at an early design stage to reduce buildings' energy consumption due to artificial lighting: A numerical approach based on Doehlert and Box–Behnken designs. *Energy*, *65*, 488–502. https://doi.org/10.1016/j.energy.2013.12.028

Mora, R., Bédard, C., & Rivard, H. (2008). A geometric modelling framework for conceptual structural design from early digital architectural models.

Advanced Engineering Informatics, *22*(2), 254–270. https://doi.org/10.1016/J.AEI.2007.03.003

Nault, E., Peronato, G., Rey, E., & Andersen, M. (2015). Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs. *Building and Environment*, *92*, 679–691. https://doi.org/10.1016/j.buildenv.2015.05.012

Negendahl, K. (2015). Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction*, *54*, 39–53. https://doi.org/10.1016/J.AUTCON.2015.03.002

Negendahl, K., & Nielsen, T. R. (2015). Building energy optimization in the early design stages: A simplified method. *Energy and Buildings*, *105*, 88–99. https://doi.org/10.1016/j.enbuild.2015.06.087

Nielsen, A. N., Jensen, R. L., Larsen, T. S., & Nissen, S. B. (2016). Early stage decision support for sustainable building renovation – A review. *Building and Environment*, *103*, 165–181. https://doi.org/10.1016/J.BUILDENV.2016.04.009

Oh, J. H., Sung, J. E., & Kim, S. S. (2017). Development of window design guideline and tools for early stage decision support. *Energy Procedia*, *122*, 991–996. https://doi.org/10.1016/J.EGYPRO.2017.07.460

Omrani, S., Garcia-Hansen, V., Capra, B., & Drogemuller, R. (2017, May 1). Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. *Building and Environment*, Vol. 116, pp. 182–194. https://doi.org/10.1016/j.buildenv.2017.02.012

Østergård, T., Jensen, R. L., & Maagaard, S. E. (2016). Building simulations supporting decision making in early design – A review. *Renewable and Sustainable Energy Reviews*, *61*(August), 187–201. https://doi.org/10.1016/j.rser.2016.03.045

Østergård, T., Jensen, R. L., & Maagaard, S. E. (2018). A comparison of six metamodeling techniques applied to building performance simulations. *Applied Energy*, *211*, 89–103. https://doi.org/10.1016/j.apenergy.2017.10.102

Oti, A. H., & Tizani, W. (2015). BIM extension for the sustainability appraisal of conceptual steel design. *Advanced Engineering Informatics*, *29*(1), 28–46. https://doi.org/10.1016/j.aei.2014.09.001

Petersen, S. (2011). *Simulation-based support for integrated design of new low-energy office buildings*. Kgs. Lyngby: Technical University of Denmark.

Pilgrim, M., Bouchlaghem, N., Loveday, D., & Holmes, M. (2003). Towards the efficient use of simulation in building performance analysis: A user survey. *Building Services Engineering Research and Technology*, *24*(3), 149–162. https://doi.org/10.1191/0143624403bt068oa

REBUS. (2016). REBUS - Renovating Buildings Sustainably 2016-2020. Retrieved November 4, 2019, from http://rebus.nu/

Reinhart, C., & Fitz, A. (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings*, *38*(7), 824–835. https://doi.org/10.1016/j.enbuild.2006.03.012

Rezaei, F., Bulle, C., & Lesage, P. (2019). Integrating building information modeling and life cycle assessment in the early and detailed building design stages. *Building and Environment*, *153*, 158–167. https://doi.org/10.1016/j.buildenv.2019.01.034

Rohde, L., Larsen, T. S., Jensen, R. L., & Larsen, O. K. (2019). Framing holistic indoor environment: Definitions of comfort, health and well-being. *Indoor and Built Environment*, *E-pub*(ahead of print), 1420326X1987579. https://doi.org/10.1177/1420326X19875795

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers* (3rd editio). John Wiley & Sons Inc.

Shim, J. P., Warkentin, M., Courtney, J. F., Power, D. J., Sharda, R., & Carlsson, C. (2002). Past, present, and future of decision support technology. *Decision Support Systems*, *33*(2), 111–126. https://doi.org/10.1016/S0167-9236(01)00139-7

Smits, W., van Buiten, M., & Hartmann, T. (2017). Yield-to-BIM: impacts of BIM maturity on project performance. *Building Research and Information*, *45*(3), 336–346. https://doi.org/10.1080/09613218.2016.1190579

Struck, C., de Wilde, P. J. C. J., Hopfe, C. J., & Hensen, J. L. M. (2009). An investigation of the option space in conceptual building design for advanced building simulation. *Advanced Engineering Informatics*, *23*(4), 386–395. https://doi.org/10.1016/J.AEI.2009.06.004

The Council of the European Union. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). In *Official Journal of the European Union*. https://doi.org/doi:10.3000/17252555.L_2010.153.eng

Van Treeck, C., Wimmer, R., & Maile, T. (2018). BIM for energy analysis. In *Building Information Modeling: Technology Foundations and Industry Practice* (pp. 337–347). https://doi.org/10.1007/978-3-319-92862-3_20

Weytjens, L., Attia, S., Verbeeck, G., & De Herde, A. (2011). The 'architect-friendliness' of six building performance simulation tools: A comparative study. *International Journal of Sustainable Building Technology and Urban Development*, *2*(3), 237–244. https://doi.org/10.5390/SUSB.2011.2.3.237

Whyte, J. K., & Hartmann, T. (2017). How digitizing building information transforms the built environment. *Building Research & Information*, *45*(6), 591–595. https://doi.org/10.1080/09613218.2017.1324726

Wilde, P De, Voorden, M. Van Der, Brouwer, J., Augenbroe, G., & Kaan, H. (2001). The Need for Computational Support in Energy-Efficient Design Projects in the Netherlands. *Seventh International IBPSA Conference Rio de Janeiro Brazil*, 513–520. Rio de Janiero, Brazil.

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.

This is an Accepted Manuscript of an article published by Taylor & Francis in Building Research & Information on 4 June 2020 , available online: https://www.tandfonline.com/doi/full/10.1080/09613218.2020.1770051

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?*