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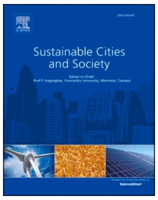

Enabling holistic design for high energy efficient office buildings through the use of subjective occupant feedback

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ABSTRACT

Today's high-performance buildings answer to a large and growing number of quantitative performance criteria. Performance gaps between design and actual performance have however been identified as a significant challenge for both energy performance, occupant satisfaction and operational costs. There is no doubt about the importance of a holistic approach to turn the inter-related series of building design and operational challenges into new opportunities. Discipline specific performance criteria are found to limit the possibilities for choosing holistic solutions. In this article we aim to use studies of available theory as well as our own insights of recent examples of holistic design in high-performance buildings to show how todays practice of discipline specific performance criteria and active technology leads to sub-optimal solutions. Through inductive reasoning and insights from literature, personal design experiences and related research activities, we present a view and show that subjective occupant feedback in the post-occupancy phase can gather crucial knowledge and documentation which can empower holistic design solutions and close the performance gaps in future buildings. We further suggest how new solutions for continuous subjective feedback can modernize and improve this process, enabling new ways of designing and operating buildings and contributing to realizing sustainable cities.

1. Introduction

Worldwide CO_2 emission mitigation efforts, a growing energy resource shortage and the fact that buildings are responsible for a large share of the world's primary energy use drives society towards new concepts for sustainable cities and buildings. New ambitious and holistic solutions for decreasing building energy use are a necessary direction for development. Following the trend seen internationally there has been a notable increase in focus on environmental issues in the Norwegian building industry. Real estate developers, corporate real estate and public institutions are already addressing sustainability and green solutions in their building development projects and in Facilities Management (FM) (Collins, Haugen, & Aamodt, 2017). Whilst some are adopting BREEAM or similar classification schemes, a focus on the development of innovative and high-performance ZEBs exists outside of classification. Positive results have been achieved by setting up consortia with many partners and close cooperation between research, education, industry and private and public partners in the real estate industry (Hestnes & Gustavsen, 2017). One successful consortium collaboration with a special focus on integrated / holistic energy design is the Powerhouse Alliance (Stene, 2018).

Implicit architectural values, established practices, and technical regulations have been found to undermine holistic approaches to sustainability (Grover, Emmitt, & Copping, 2020). A paradigm shift toward

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Abbreviations: FM, facility management; BREEAM Nor, building research establishment environment assessment method – Norway version; IED, integrated energy design; GHG, green house gas; ICT, information and communications technology; POE, post-occupancy evaluation; ZEB, zero emission buildings; HVAC, heating, ventilation and air conditioning; SBS, sick building syndrome.

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new ways of conceiving, designing, constructing, and operating buildings are needed for radical improvements in building performances. A holistic design approach is defined here as a design approach where design is seen as an interconnected whole, and problems are sought solved by integration of several technologies or disciplines. Another terminology for a similar concept is Integrated Design. Integrated Energy Design (IED) describes a defined design process for utilizing Integrated design for low energy buildings (Jørgensen, Andresen, & Bramslev, 2009). An integrated approach to building design seeks to incorporate all the important aspects in a holistic synthesis. It views the individual systems not as isolated entities, but closely connected and interacting with the rest of the building (Andresen, 2000). While the IED approach has an ultimate goal of reduced energy use, clearly in combination with comfort-oriented performance metrics, the focus in our definition of holistic design is directed at the summary experience of the occupants and users of the building. This focus brings other challenges and possibilities, especially since occupant experiences are a subjective matter and may be difficult to document quantitatively.

Green office buildings not only need to meet targets in relation to energy efficiency, they must also provide a healthy, comfortable, and productive indoor environmental quality. On a sustainable city scale, heating and cooling energy, power demand and so called “peak-shaving” are also important concerns (Becchio, Corgnati, Delmastro, Fabi, & Lombardi, 2016). As demands to decrease the use of energy become more prominent, these coincide with increasing demands for comfort in buildings (Zeiler, Savanovic, & Boxem., 2008). Although handled by separate design disciplines, these performance areas are highly intertangled. Energy-efficient buildings often need considerably more energy in use than originally predicted. Previous research has revealed what is generally called the energy performance gap (Menezes, Cripps, Bouchlaghem, & Buswell, 2012; van Dronkelaar, Dowson, Spataru, & Mumovic, 2016), which addresses a gap between expected and actual energy performance. Similar gaps are also found for both occupant comfort and satisfaction (Ornetzeder, Wicher, & Suschek-Berger, 2016) and for facility management and maintenance costs (Jensen, 2012; Knudsen, Andersen, & Hansen, 2016). For this reason, highly ambitious efficiency aims in such buildings could easily contradict the demand for satisfactory working conditions (Ornetzeder et al., 2016).

We have experienced, through several years of practice, examples where discipline-specific performance criteria have limited the possibility for holistic design solutions and forced the designers to choose sub-optimal solutions. These examples are in most cases related to how comfort issues are addressed in relation to energy use and regulations. Occupant comfort or satisfaction is a subjective and highly psychological matter, and physical criteria alone have been shown not to be sufficient to describe or predict the quality felt by the user. The current focus on quantitative and discipline-specific criteria alone also promotes solutions which fail to involve the user, keeping the user out of the loop in both design and operation stages. We believe user involvement and the gathering of subjective feedback from users can allow a paradigm shift toward more holistic design solutions. Satisfaction, for instance, is a summary state and may incorporate the user’s personal impressions, perceptions, and expectations regarding several domains. This makes satisfaction assessments very fit for assessing the performance of holistic design solutions. However, such assessment is not trivial, as it is impossible to evaluate the occupant’s subjective opinions without collecting subjective information from the occupants themselves. This information is traditionally collected through POE’s as spot measurements, and this knowledge and insights have already heavily impacted building design by closing the gap between ideal reference conditions and real-world situations. This may be the key to combining holistic, efficient, robust, and sustainable solutions with a satisfied, productive, and involved user. It may also contribute to minimizing the performance gaps and a higher degree of synthesis between user and building promoting optimal performance.

The aims of this article are to: 1) Show how an unbalanced focus on quantitative and discipline-specific performance criteria has limited the holistic design opportunities in modern office building design, causing sub-optimal solutions in terms of energy use, occupant satisfaction, construction cost, maintenance cost, robustness and lifetime Green House Gas (GHG) emissions. This argument is supported by practical examples experienced by the authors during the design of three Plus Energy office buildings which had a specific focus on holistic design using the IED approach. 2) Argue for how Information and Communication Technology (ICT) enabled by continuous subjective feedback from occupants can, similar to traditional Post-Occupancy Evaluations (POE), contribute to bringing occupants into the loop and improving the possibilities for holistic and integrated design choices, ultimately contributing toward higher performance in future buildings and sustainable cities.

We investigate this through inductive reasoning based on our own experience with real-life attempts to implement holistic building design, knowledge and evidences from the scientific literature, as well as our own findings from research with continuous subjective occupant feedback systems (Lassen, Goia, Schiavon, & Pantelic, 2020; Lassen, Josefsen, & Goia, 2020). Although the investigation presented in this paper is not based on quantitive data, we aim through this research at contributing to the state of the knowledge by unveiling weaknesses and inadequacies in the current design practice for achieving the goal of sustainable, comfortable and healthy buildings, and further suggesting a future direction for using occupant involvement in design to empower holistic design practices.

The authors have collaborated on the design of several Plus Energy Buildings (Andresen, Dokka, & Johansen, 2018; “ZEB Definitions” n.d.) and Powerhouse (Stene, 2018) buildings such as Powerhouse Kjørbo (Dokka, Berggren, & Lassen, 2015), Powerhouse Brattørkaia (Jenssen, 2019), Powerhouse Montessori Upper Elementary School, Powerhouse Telemark, and Gullhaug Torg 2A. All of which are commercial buildings constructed in a commercial setting, designed with an especially high focus towards holistic, passive, robust and sustainable solutions using established design processes such as IED. They have also performed research through the Powerhouse alliance and related research projects such as the *Zero Emission Buildings* (ZEB) project (Hestnes & Gustavsen, 2017), the *Naturligvis* project (Stoknes et al., 2017), and the *SmartTune* project (“Cloud-Based Tool for Management and Tuning of Smart Energy Efficient Buildings” 2019).

The article is organized in two sections. In the first section we present the challenges we find to be relevant when attempting to create optimal buildings in today’s conventional setting. We start by describing difficulties with performing holistic design with conventional design methods and discipline-specific performance criteria. Further we describe the limitations of active climatization concepts in high performance buildings. We then explain why holistic design is a necessary way forward. Finally, we illustrate by presenting examples from real projects where discipline specific performance criteria have limited the ability to choose holistic solutions.

In the second section we argue how continuous subjective occupant feedback has the potential to empower holistic design choices. We start by describing how subjective feedback from POE’s has been found to be important for improving both design and operation. We continue by presenting the emerging technological possibilities for automated and continuous collection of subjective occupant feedback and their benefits. Finally, we argue how this possibility can empower holistic design and improve the quality and performance of future high-performance buildings.

2. The challenge: difficulties in designing for the future with discipline-specific performance criteria

2.1. *The design process as we know it*

Khemlani and Kalay (Khemlani & Kalay, 1997) describe the problems of integrated design stating how buildings must fulfill a large number of diverse criteria, codes and rules. The list of criteria seems to be ever-increasing, and likewise, the list of professionals involved in a building design process. It is difficult for the specialists to have a clear vision of the holistic goals of the project. Each specialist tries to optimize the design for his/her own discipline, which may come at the expense of other disciplines (Khemlani & Kalay, 1997).

During the design process, many choices must be made based on more or less "hard data", and many judgements and value tradeoffs must be carried out. According to Andresen (2000), the design process is an iterative process with the following central activities; Problem definition (preliminary), Generation of alternatives (ideas, potential solutions), Performance prediction (modeling and simulation), Evaluation (of potential solutions compared to performance criteria). The stages that follow the initial explorations should include an increasing amount of quantitative assessment. In the last two activities (performance prediction and evaluation), analytical methods are more commonly used. Building design involves value conflicts and judgments. It is widely recognized that human judgement is an important part of the decision process, and this often results in a decision process that is far from rational (Andresen, 2000). The necessary quality in each discipline is normally assured by quantitative performance criteria. It is impossible to list all criteria exhaustively, as different criteria might be relevant according to the governing regulations, ambitions, and certifications (such as BREEAM certification etc.) which is chosen for the building. In Table 1 we show a list of the criteria thatwere found to limit holistic design in the case buildings which are presented in Sections 2.4.2–2.4.4 of this paper, and that we use in this research to exemplify challenges in design of high-efficiency buildings caused by domain-specific indicators that limit holistic approaches.

These types of criteria are used for supporting design choices and for providing documentation and are normally devised from existing theory through standards and regulatory codes. Increasingly complex buildings have spurred the need for more technical expertise, as well as more specific standards and performance criteria. This makes the act of maintaining a holistic design strategy increasingly demanding as we move towards high performance buildings (Andresen & Hegli, 2017). Multi-criteria design is an increasingly popular field in the literature and in the professional practice, where analysis combining two or more domains are carried out to find balanced solutions for competing parameters (such as, for example, structural requirements with environmental requirements, comfort requirements with energy requirements, life-cycle requirements with energy requirements, etc). Holistic design is also adopted in the practice of architecture when it comes to combining different performance requirements with architectural and spatial expression.

Table 1
Examples of quantitative performance criteriafound in the case buildings.

Performance indicator	*Discipline*	*Project*	*Confliciting element in design*
Acoustical reverberation time	Acoustics	Powerhouse Kjørbo	Exposure of thermal mass (concrete slabs) to indoor environment.
Draft rate, air temperature, temperature symmetry	Thermal comfort	Powerhouse Kjørbo	Thermal mass, stratification, displacement ventilation
Draft rate, air temperature, temperature symmetry	Thermal comfort	Gullhaug Torg 2A	Natural ventilation (automatically operable windows)
Sound insulation index – noise from outside	Acoustics	Gullhaug Torg 2A	Natural ventilation (automatically operable windows)
Sound insulation index - Acoustical flanking transmission	Acoustics	Powerhouse Telemark	Low-exergy hydroinic heating system

However, when it comes to bringing the occupant into the loop across the different domains of indoor environmental quality, and how this is then combined with other design requirements, it is hard to find evidences of progress in the scientific literature involving the global, summary satisfaction assessment of the occupants.

Building design solutions are often implemented and optimized without taking the whole building performance into account. The optimization procedures employed usually only include a limited number of quantifiable performance metrics. There are numerous examples of how comfort, environmental issues and aesthetics have been downplayed in the design of, energy efficient buildings, for instance. In general, designers tend to overemphasize issues that can be modeled numerically. It has long been known by designers that the calculated daylight factors in a room actually tell us very little about the sensation of the lighting quality experienced by the occupant in the room (Andresen, 2000). However, it is still the case that many regulations for building permissions make use of performance metrics that tell us very little about the actual performance for matters that are subjective to the occupant as well as performance under more realistic conditions. In this particular case, daylight assessment through new metrics calculated with climate-based daylight simulations has been successfully implemented in research and practice in recent years, leading to a better representation of the indoor daylight conditions. However, although better assessment methods continously emerge and new performance metrics and criteria are defined, the process of uptaking such methods and metrics in building regulation is slow and may result in sub-optimal solutions.

2.2. Limitations of active concepts in building climatization

On average, 30 % of total construction cost in a new Norwegian standard office building are invested in technical disciplines (HVAC, plumbing, electrical, automation, telecommunications) (Revfem, 2018). In the experience of a property developer working with large scale commercial buildings, 40 % of the investment cost of a new low energy (but otherwise standard) office building was associated with the climatization system. For buildings with more ambitious energy efficiency goals, this number is expected to be higher. Although most of the technical systems have an expected technical lifetime of 20–30 years, the property developer finds that, in practice, the lifetime is closer to 10 years, as many technical systems are replaced when a new tenant enters a lease and a "cosmetic refit" is performed to achieve a new layout with modern technology in the building. They view this practice as un-sustainable and sub-optimal (Stoknes et al., 2017).

Studies have found that there exists a large performance gap between design (simulated) and actual (measured) energy performance (Zou, Xu, Sanjayan, & Wang, 2018). The performance gap is not only evident for energy performance, but is also found to exist for occupant comfort and satisfaction (Ornetzeder et al., 2016) and for facility management and maintenance costs (Jensen, 2012; Knudsen et al., 2016). In a comparison of 12 field studies from the United States and six countries in Europe, covering 467 buildings with approximately 24 000 total occupants, the air-conditioned buildings showed between 30 % and 200 % more instances of symptoms of sick building syndrome (SBS) than in the naturally ventilated buildings (Seppanen & Fisk, 2002). The causes for these performance gaps can be many. One study emphasizes the lack of operational understanding in the design phase as an important factor for the energy and facility management-related gaps (Jensen, 2012). Another study identifies the dominant factors to be related to specification uncertainty in modeling, occupant behavior, and poor operational practices (van Dronkelaar et al., 2016). It has been emphasized how causal factors for the energy performance gap often relate to the use of unrealistic input parameters regarding occupancy behavior and facilities management in building energy models, further associated with the lack of feedback to designers once a building has been constructed and occupied (Menezes et al., 2012). The information flow in the building operation phase has been pointed out to be detached from the other parts of a building's lifetime, making it difficult to measure and evaluate the performance gap for occupant satisfaction-related issues (Lucas, 2012).

Several studies have emphasized factors and phenomena related to human psychology as causes for performance gaps related to occupant comfort and satisfaction. Madsen and Gram-Hansen (2017) emphasize the role that technology plays in shaping our habits, and how occupant expectations and habits change when they are introduced to new and advanced technology. In the same way, technology and the possibilities and expectations that follow with it may shape and affect the occupant's evaluations of comfort or satisfaction (Madsen & Gram-Hanssen, 2017). Expectations are found to heavily influence occupants perceptions, comfort and expectations to the indoor climate, which has been particularly investigated for the thermal domain (Fountain, Brager, & De Dear, 1996; Kim & de Dear, 2012a, 2012b; Luo et al., 2016; Schweiker, Rissetto, & Wagner, 2020). Building design and technologies are found to influence thermal expectations and heat-related habits, which coincides with the theories of practice describing how materiality affects practices through reconfiguring practical understandings, for example comfort expectations (Hansen, Gram-Hanssen, & Knudsen, 2018). How building design affects occupant habits and actions is in fact a normal consideration in early phase architectural design. Building organization and programming of functions are related to occupant behavior and habits. This perspective and exercise is however seldom shared with other disciplines in the design team. Technical experts in a project tend to regard the user as having a one-way relationship to building assets, essentially leaving the user out of the loop. Most buildings are designed to satisfy the needs of their users, but studies show that occupants perspectives on subjects like indoor climate and architecture often diverge from the designer's expectations. It is assumed that a portion of the performance gap can be attributed wrongful presumptions about user behavior (Jensen, 2012). High-performance buildings are designed to decrease building energy use and provide the benefits of greater comfort, health, and usability to occupants. Building automation and control are tools to mitigate energy-inefficient occupant behaviors. Automated buildings rely on automated and actively controlled systems to maintain the desired indoor environmental conditions. Occupant interactions with building systems are often discouraged, as the building operators want to avoid occupants disturbing the set-points in the finely tuned systems (Day & O'Brien, 2017). A growing body of literature has however found that full automation of indoor climate measures come at a great risk - occupant tolerance for discomfort is significantly reduced as occupant control possibilities are removed (Cole & Brown, 2009; Day & Heschong, 2016; Karjalainen, 2013). Several studies have found that the opportunity for occupants to interact with their indoor environment and with the building operation in general positively affects their satisfaction (Boerstra, 2016; Hellwig, 2015; Leaman & Bordass, 1999). The adaptive principle describes how people, when experiencing discomfort, "react in ways which tend to restore their comfort" (Humphreys & Fergus Nicol, 1998). It recognizes that a person is not a passive receiver of sensations and perceptions but is an active and dynamic participant in a system for maintaining a thermal equilibrium with the environment. The ability to control your personal environment is found to be of great significance for occupant satisfaction with thermal comfort (Boerstra et al., 2015; Baker & Standeven, 1996; Day & O'Brien, 2017; Hellwig, 2015; Kwon, Remøy, van den Dobbelsteen, & Knaack, 2019). Comfort expectations and the availability and constraints of effective control are clearly important measures in this context (Hellwig, 2015), although they are not normally considered in building design. Studies have also found that occupants perceptions of the different indoor environmental quality domains are affected by other domains. One example of this is how thermal comfort perception is influenced by the light color and intensity (Huang, Zhu, Ouyang, & Bin, 2012; Levin & Emmerich, 2013; te Kulve, Schlangen, & van Marken Lichtenbelt, 2018).

One example of this can be found in the thermal comfort domain. Based on established theories and models, a very small temperature range of about 1−2 °C is usually adopted as best-practice in existing office buildings to ensure occupant thermal comfort (Fountain et al., 1996; Lassen, 2018; Mendell, 2009). Studies have however found that only 8 % of buildings in the ASHRAE Global Thermal Comfort Database II meet the threshold of 80 % satisfied occupants (as intended in ISO 7730), if one includes votes from 0 to +3 ('neutral' to 'very satisfied'). In total 43 % of the occupants were thermally dissatisfied, 19 % neutral and 38 % satisfied (Karmann, Schiavon, & Arens, 2018). This indicates that the discipline-specific performance criteria for thermal comfort do not ensure satisfied occupants, and there is a considerable performance gap between theory and practice. In this case, there is a great deal to be learned by studying information from the operation phase.

2.3. *Designing for natural climatization*

The main goals of building climatization is to optimize human health, comfort, and productivity. Active technology is often used to *counteract* natural physical forces to keep indoor climate at desired levels. There do however exist alternatives that can avoid the downsides of active control and climatization, while maintaining a healthy, satisfying, and productive environment. The concepts of *"passive"* or *"natural"* climatization refer to climatization concepts that seek to make use of the laws and forces of nature to combine energy performance with optimized human health, comfort, and productivity. These systems seek to *interact* with physical processes and minimize the need for active technology and energy expenditure. Research has shown that occupants are often more content in naturally ventilated buildings, even though they have "on paper" less optimal indoor climate conditions (Brager, 2004; Cheung, Schiavon, Parkinson, Li, & Brager, 2019; Hellwig, Brasche, Bischof, & Friedrich-schiller-university Jena, 2006). Natural or passive climatization concepts may come in many forms and should not necessarily be confused with natural ventilation. A passively climatized building may have a mechanical or hybrid ventilation system if necessary, but should to the largest extent possible make use of the natural driving forces available (Stoknes et al., 2017). There are several practical examples of how naturally climatized buildings can combine high energy performance and healthy, satisfied, and productive occupants. They also support the use of robust and simple solutions and materiality, potentially reducing operation and maintenance costs and supporting a longer lifespan and lower lifetime GHG emissions. Norwegian examples of naturally climatized buildings all include heating and/or mechanical ventilation systems, but still heavily lean on passive principles for climatization (Stoknes et al., 2017).

Passive climatization concepts have been found to offer a higher quality in several areas, although the gained benefits are often difficult to quantify by simulation or physical measurement. In studies evaluating lessons learned from existing buildings, it is found that avoiding unnecessary complexity and designing for manageability is crucial for successful performance. Passive solutions are found to be generally better than active, and should be preferred when possible (Bordass & Leaman, 1997). This is confirmed by our own experience; buildings designed with passive concepts perform better in the domains of environmental performance, robustness, occupant satisfaction, indoor climate, operation, and maintenance costs as well as investment costs than active concepts. In a sustainable cities context, buildings designed with passive concepts which have a high thermal inertia can offset thermal loads and thereby enable power peak-shaving and demand-side energy management, weighted concepts in future smart and sustainable cities (Becchio et al., 2016; Hoyt, Arens, & Zhang, 2014). The main challenge of passive or natural climatization concepts is that the solutions are multidisciplinary and most often demand holistic and integrated design efforts. Given their multidisciplinary nature they also tend to struggle with meeting and documenting all relevant discipline-specific performance criteria. A few examples of this are given in the following section.

2.4. Cases illustrating design challenges with holistic design and discipline specific performance criteria

2.4.1. General overview

In the following we present cases from three construction projects in chronological order where several of the authors were involved in the design, construction, and operation phases. The projects have high environmental ambitions and are designed with a special focus on holistic design by the use of the IED process. They share a common focus on passive or natural climatization concepts, as previously described. In the presentation of each project we present some background information, a description of the design process and finally one or more examples of cases where discipline specific performance criteria were perceived to limit holistic design. The examples mentioned for each case project are snapshots of situations where discipline-specific performance criteria limited the possibility to find holistic solutions for the overall goals of the project. In some cases the performance criteria led to sub-optimal solutions, while in other cases they forced the project to seek dispensation from regulations, and in other cases they forced the project to invest in extensive design and simulation work beyond what one could expect from a commercial project to provide documentation for the holistic solution. Many of the examples happen to be related to thermal comfort and acoustical criteria. The limitation in holistic design is however not only linked these domains but may just as well be linked to other criteria. A brief overview of the projects is given in Table 2.

2.4.2. Powerhouse Kjørbo

2.4.2.1. Background. Powerhouse Kjørbo is a complex of 5 cube-shaped office buildings which are connected by hallways. They are located at Kjørbotangen in Sandvika, west of Oslo, Norway. Unit 4 and 5 were retrofitted to plus energy standard in 2010−2014. The buildings have an envelope heat loss coefficient of 0.25 W/m^{2}K, are extremely airtight and have a high thermal mass. The ventilation system utilizes displacement ventilation and central air pre- heating and cooling with an efficient rotary heat exchanger. The heating system consists of centrally placed radiators and a ground source heat pump. The heated floor area per unit is approximately 1870 m^2. It was the first building to be completed according to the Powerhouse criteria (Stene, 2018) (Figs. 1 and 2).

2.4.2.2. Process. The building was designed to achieve ambitious environmental criteria with a Powerhouse standard in relation to energy balance over the life cycle, as well as certification to BREEAM-Nor “Outstanding”. An important focus was applied to the organization of programmable spaces in the building as a means of achieving several of the performance criteria in the most holistic manner possible. Together with the tenant, the architect, interior architect, energy consultant, ventilation expert and acoustician were all involved in the studies behind the planning principles. The geometry of the building and orientation on the site in relation to sun exposure, views, daylight were given special importance and resulted in a solution with open office landscape to the south and single offices to the north to prevent overheating of enclosed rooms. In addition, this gave most of the workplaces good view and daylight conditions. Guidance was also made for how noisy activities should be separated from open work zones. The fact that the tenant was actively involved throughout the process was crucial for the choice of the final ventilation concept, where it is necessary to keep doors open during building operation to ensure airflow between rooms. These types of solutions are robust and also give the areas a greater degree of flexibility in use. By involving many stakeholders and disciplines early in the planning process, the project achieved a high degree of innovation in relation to both technical and architectural concepts.

Fig. 1. Powerhouse Kjørbo exterior. Image courtesy of Snøhetta.

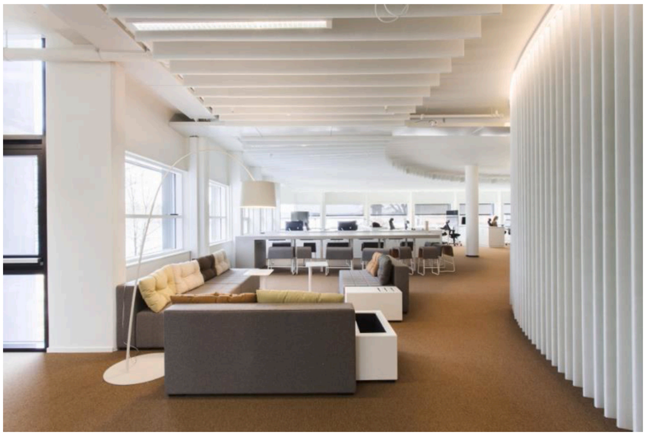

Fig. 2. Powerhouse Kjørbo interior. Image courtesy of Snøhetta.

2.4.2.3. Example 1: exposure of thermal mass vs. acoustical criteria. Energy consultants wished to utilize a passive concept for climatization of the building, which would heavily reduce energy use for space heating

Table 2
Overview of project case examples.

	Location	*Heated floor space*	*Functions*	*Completion*	*Environmental classifications*
Powerhouse Kjørbo	Sandvika, Norway	5,200 m^2	Office	2014	Plus energy building Passive house BREEAM Outstanding
Gullhaug Torg 2A	Oslo, Norway	500 m^2 4,500 m^2 5,000 m^2	Retail, Office, Residential	Expected 2022	Nearly zero energy buildling BREEAM Excellent
Powerhouse Telemark	Porsgrunn, Norway	8,313 m^2	Office	2020	Plus energy building Passive house BREEAM Outstanding

and cooling and lead to simpler and more robust solutions. The concept involved increasing the effective thermal mass of the building by exposing the structural concrete slabs in the building to the interior environment. This could be best acheived by excluding a suspended ceiling and/or removing carpet on the floor. Both measures were found to be practically feasible and cost effective. However, this would heavily reduce the amount of acoustical damping material which could be fitted in the rooms. The acoustical design consultants argued that it would be impossible to meet the criteria specified in standard NS 8175:2012 for acoustical reverberation time with less than 50–70 % of the ceiling covered in acoustic baffles. Even then, it would not be possible to meet the criteria for reverberation time in the bass segment. The minimum criteria for acoustical reverberation time critically threatened the chosen holistic design concept of passive climatization. It was argued that the criteria for reverberation time in the bass segment are unnecessarily strict, as there are few sound sources in this segment in office buildings. Users would not notice a difference. It was also contested how reverberation time is used as the only quantitative criteria for maintaining a high acoustical performance for the users. Many argue that other parameters, such as the Speech Index (SI) are more important to the subjective experience of the user. Further, the passive climatization concept would effectively eliminate all mechanical noise from the ventilation system, leading to a significantly quieter office environment than what is normal in office buildings. This would be positive for the experience of the users but was not at all accounted for by the reverberation time criteria. The issue was solved by the project choosing not to use the specified standard for acoustical criteria. This was only possible as the project was (on paper) a retrofit, and it was not necessary to meet all building code criteria relevant for new buildings. It was not found possible to omit the carpets on the floors, which represent a compromise between acoustical and energy criteria. Ideally, the designers would have benefit from the direct access to use experiences with occupant satisfaction in similar buildings, rather than a theoretical metric (reverberation time). Though we know that many existing buildings have less exposed acoustical damping material than what was necessary to comply with the criteria in this case, the lack of a full understanding on how satisfied are the users in similar buildings which do not meet the criteria for reverberation time was definitely a challenge in the design process.

2.4.2.4. Example 2: thermal mass, stratification, displacement ventilation vs. thermal comfort criteria. In the preferred climatization concept, utilization of thermal mass in the building would be combined with displacement ventilation and centrally placed wall mounted radiators to maintain thermal comfort for occupants. Several experts held forth that there would be problems with draft near diffusors as well as cold rooms/corners which were far from the radiators and closer to cold surfaces, such as windows. This issue was offered a large amount of study during the design phase. Simulation results showed that temperature, draft, and air quality would be more variable than what is normal with a more active climatization concept, and the risk of climate conditions approaching the prescribed comfort boundaries would be higher. Many experts were skeptical to the solution and feared that occupants would be uncomfortable, but the solution was in the end chosen by the design team. Two Post Occupancy Evaluations have been conducted after the building was taken into use, investigating the occupant's satisfaction with air quality and thermal conditions (Lassen, 2019; Søgnen, 2015). Both studies show higher than average satisfaction levels for both thermal comfort and air quality, although spatial temperature variations throughout the spaces were found to be 2 °C or more. These Post-occupnacy Evaluations (which naturally were performed after the building had been designed and taken into use) are good examples of how subjective information from real buildings can be valuable as documentation in a holistic design process. In similar discussions on this topic during the design of other buildings after Powerhouse Kjørbo, the results of these studies have been used effectively to argue that the solution is robust. Unfortunately, this is a rare case since POE studies seldom are performed in practice, due to costs, and to the limited time-dimension that they offer in assessing long-term performance in buildings (POE are usually one-point-in-time assessments).

2.4.3. Gullhaug Torg

2.4.3.1. Background. "Gulhaug Torg" is an ongoing construction project in the design stage aiming to realize the first modern naturally ventilated office building in Norway which requires no delivered energy for heating, cooling, or ventilation. The site is located in an urban district of Oslo, and the building will contain retails, office, and housing functions where the office areas will have full natural ventilation. This challenging exercise has called for a deep investigation into the question of occupant comfort and well-being, and at how a natural ventilation concept can be realized within the relevant performance criteria for office buildings in Norway. Natural ventilation with outside temperatures down to −20 C, combined with limited availability of heating and cooling power in the building, implies that the thermal conditions in the offices will vary more than in conventional office buildings. Ventilation will be solved with automatically controlled vents in the facades, while heating and cooling is solved with Thermally Activated Building Structures (TABS) with heating and cooling pipes in the floor. Office spaces are planned as free seating/activity based, open space offices. The building is currently in the detailed design phase and the construction is expected to start in Fall 2021 (Figs. 3 and 4).

2.4.3.2. Process. In the simplest of terms, the concept of natural climatization for "Gullhaug Torg" consists of having optimal control at the interface between outdoor climate and indoor climate, correlating with conditions for occupant comfort. Unilateral acceptance for other disciplines has been a necessary characteristic of the design process and has been a considerable factor in the advancement of invention. Early phase investment by all design team members has proven essential in the holistic design methodology. The design process was arranged as an integrated design process and was supported by several research initiatives. It has continued for over 5 years, and large resources have been

Fig. 3. Gullhaug Torg 2A exterior. Image courtesy of Snøhetta.

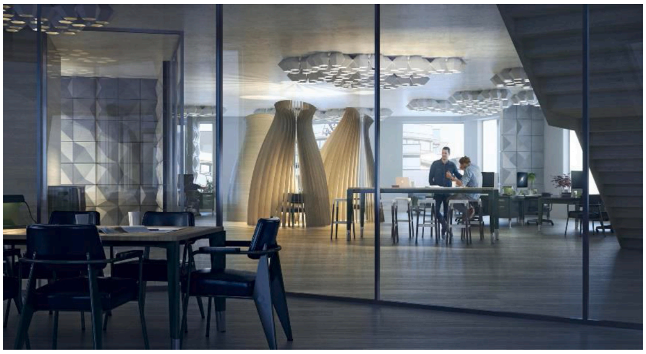

Fig. 4. Gullhaug Torg interior. Image courtesy of Snøhetta.

necessary to overcome the challenges given by the tight design constraints. The inclusion of a concrete superstructure as an integral part of the project is resultant of multiple considered factors in the early phase holistic design process, and mainly due to thermal mass properties crucial to the climatization concept. The shape of the building footprint, with many angles and facets, was devised as a consequence of the natural ventilation concept. As many rooms as possible would have exterior corners which create a wind-induced pressured difference between two air-vents in the same room, driving cross ventilation through the room.

2.4.3.3. Example 1: thermal comfort. Despite of all possible measures taken to prevent draft from opened vents and windows, it became clear early in the design process that persons sitting on the vicinity of openings would experience draft and thermal conditions that fall outside of the thermal comfort criteria specified in the relevant standard NS-EN 15251 during weather extremes. A document was prepared stating the challenges and suggesting measures for mitigation. The document was presented to the labor inspection authority as the project applied for dispensation from the relevant criteria. Among the suggested measures for comfort mitigation was a system for continuous post occupancy satisfaction feedback regarding indoor climate. If the system registered occupants becoming discontent with the indoor climate in the building, measures would be taken to improve the issues. If the feedback indicated that the full natural ventilation solution could not be combined with satisfied users, a mechanical ventilation unit would be installed. This solution was approved by the labor inspection authority which granted a dispensation from the thermal comfort criteria. Ideally, there would already exist similar post occupancy studies, or systematically collected feedback, which could have been used as documentation with the labour inspection authority. This would have significantly lowered the risk for both the builder and the authorities.

2.4.3.4. Example 2: general acoustical criteria and site-noise from adjacent river. In the period between the realization of Powerhouse Kjørbo and the design phase of Gullhaug Torg there has been a tightening of the legislation governing acoustic performance in office environments. The challenges of an enhanced demand on acoustic performance in internal environments, has proven to be a key conundrum with regard to not only the effect on performance of thermal mass, but fundamentally when designing with consideration of material mass in a life cycle and embodied emission perspective. Throughout the course of the design phase, questions have arisen as to the validity of current acoustic legislation for naturally climatized environments. While legislation gives room for interpretation, the veto ultimately rests with the consultant of record, which gives rise to potential fragility for holistic design practice. Acoustic demands from external noise sources have also proven to be a contentious area when designing for natural climatization – noise sources and their interpretation in legislation and practice have demonstrated some polarizing loopholes for practitioners. The Gullhaug Torg site is immediately adjacent to a high flowing river sluice forming the dimensioning characteristics of the sonic environment. Compliant acoustic practice requires urban noise from vehicular traffic to be the dimensioning site factor for design. The rationale for this is that naturally occurring sound sources are not considered as noise. Compliant requirements for noise impedance on apertures are by their nature, highly restrictive on naturally driven air flows and therefore represent an impact on ventilation. Lab testing of products, workarounds in terms of opening degrees, timing of openings to limit theoretical averaged noise levels in working hours and other solutions to work within legislation are yet to meet with discipline specific criteria. Compliance would never be able to be adequately measured in the field, nor would it be representative. While representing a considerable opportunity for developer-approved research-in-use through user feedback; at the time of writing, advancement on this subject remains pending.

2.4.4. Powerhouse Telemeark

2.4.4.1. Background. Powerhouse Telemark is a ten storey plus-energy office building situated in Porsgrunn, Norway designed according to the Powerhouse definition (Tapper & Dokka, 2019). The building was completed in 2020. The design of the energy- and climatization concept of Powerhouse Telemark is based on the experience from Powerhouse Brattørkaia (Jenssen, 2019) and Powerhouse Kjørbo (Dokka et al., 2015). In addition, the concept is modified to have a floor-based low exergy heating and cooling system ("The Research Project Low-Ex" n. d.), which has been used in the projects Lia Kindergarten (Dokka, Myrup, & Solsem, 2019) and House Zero ("The House Zero Project" n. d.). The Lowex-concept is based on low temperature heating and high temperature cooling, using energy wells as a source for heating and cooling. The idea of the Lowex-system is to thermally stabilize the building by coupling it to the stable thermal condition in the ground, instead of viewing it as an active heating and cooling system working to keep a constant setpoint temperature in all the spaces in the building. The concept is a holistic approach to maximizing the efficiency of the entire thermal system, from boreholes and ground source heat pump to the thermal energy distribution system and radiant heating and cooling surfaces. Since the active floor slabs with embedded pex pipes act in a very slow manner, control of the system is best acheived by using slow changing parameters like the temperature in the middle of the floor slab with a forecasted mean temperature (e.g. the next 48 h). This contrasts with conventional fast-acting HVAC-control systems based on keeping the air temperature in the individual rooms constant. This demands that the thermal resistance from the water pipes to the room air must be very low. This sets rather strict demands for architectural indoor design as many common flooring options like carpets and wood may not be used. It also strongly influences the acoustic design of the spaces (Figs. 5–7).

2.4.4.2. Process. The high number of design constraints set rather strict demands for designers and subcontractors in the project. To get the

Fig. 5. Powerhouse Telemark exterior during construction. Image courtesy of Skanska.

Fig. 6. LowEx hydronic pipes before poured concrete slab. Image courtesy of Skanska.

Fig. 7. Finished polished concrete in PHT, with embedded pex-pipes for low temperature heating and high temperature cooling. Image courtesy of Skanska.

intended performance of the system all the designers (architects, HVAC-engineers, building physicist, acoustic engineer, structural engineer, control engineers) the project management (general and technical project leaders) and all the subcontractors (electric systems, ventilation, plumbing, automation and concrete) are required to have a minimum understanding of the system. In addition, many different suppliers with special expertise in their products, play an important role in design and of the different components in the system.

2.4.4.3. Example 1: floor design and acoustical flanking transmission. In the case of Powerhouse Telemark, the pex pipes are embedded in a polished concrete slab of approximately 100 mm thickness. This solution is optimal for the Lowex-system with low thermal resistance from the pipes to the room air. However, it raises several other design challenges related to other disciplines. Especially on how the floors should be zoned for maximum flexibility (e.g. between cell offices and open landscape), and how acoustical flanking transmission is solved between rooms which share the same slab section with slab and pipes continuing under the section walls. According to the LowEx concept, a low number of zones is optimal for simplicity, efficiency, and robustness. The discipline specific criteria for sound proofing between rooms according to NS 8175:2012 however demands that the concrete slab is physically divided under the partitioning walls. In this case, hydronic pipes could not pass under the walls and one zone must be created for each room. To satisfy the owners demand for flexibility, this would have to be done in a grid of 4 × 4 m also where wall was not present today. This gave many heating/cooling zones, increased thermal losses in the system, increased complexity in operation and a less robust solution. This example shows how it may be difficult to prioritize and make informed decisions when several quantitative discipline-specific criteria are contradictory to each other; especially as new and holistic solutions are being considered. It is unknown what would have been the consequence for the subjective satisfaction of the occupants if the project had chosen to let the slabs and hydronic system continue under the walls. Especially if this fact was communicated to the user securing realistic expectations. This would only have been possible to determine by collecting subjective user feedback from users in existing buildings with a similar solution. The knowledge from this feedback could have been used to assess the impact of each of the discipline-spcific criteria and reach a sound compromise.

3. The opportunity: subjective feedback as a holistic performance marker

3.1. Documentation supporting holistic design choices

Post Occupancy Evaluations (POE) are currently the only established method for collecting subjective evaluations from building users. POEs have been described as the most people-oriented method for analyzing architectural spaces and can play a role in attempts to determine an acceptable balance between creativity and utility in construction projects (Li, Froese, & Brager, 2018). This can be done by bringing in the element of user satisfaction as well as the actual functioning of the building in the use phase (Meir, Garb, Jiao, & Cicelsky, 2009). The subjective data gathered in POEs can integrate the pre- and post-handover phases in the building life cycle; the various stakeholders in the building process, the various building disciplines, practice with research, subjective and objective dimensions of building use and experience, and lastly, bridge the static performance of the building with the dynamic functioning when real users interact with and modify static features (Meir et al., 2009). One well-established example of knowledge and tools generated by subjective information in POE's is the Adaptive Comfort Model (de Dear & Brager, 1998), which is currently incorporated in standards and used around the globe. Other examples are the learnings presented by Leaman and Bordass (Bordass & Leaman, 1997; Leaman & Bordass, 1999). However, despite the widely declared interest in them, POEs are rarely used in the building industry (Roberts, 2001). The most common explanations for this are that POEs are expensive and that conducting POEs may uncover legal liabilities (Hadjri & Crozier, 2009). Besides, POE's are point-in-time surveys and convey a snapshot rather than a long-term measurement. Studies, such as (Parkinson, Parkinson, & De Dear, 2019a; Parkinson, Parkinson, & de Dear, 2019b), have pointed out that continuous monitoring systems may be better for characterizing long-term (or general) performance, even if the quality of the equipment for long-term monitoring is not of laboratory grade, opening up to an entire new world of possibilities enabled by recent advamement in information and communication technology such as networs of (inexpensieve) distributed sensors and user interfaces.

The term subjective is defined as "based on or influenced by personal feelings, tastes, or opinions" ("Subjective" 2019). Subjectiveness, or subjective feedback, is referred to in a large number of studies in the indoor climate field (de Dear & Brager, 1998; Fanger, 1970; Kim, Schiavon, & Brager, 2018; Von Grabe, 2016; Wang et al., 2018) but the term is rarely elaborated on or defined. If a building occupant or laboratory test subject is to provide information about his or her perception of the indoor climate, the information will in all cases be subjective. This is because the individual has made an active decision and chosen what to answer through a cognitive thought process. If the goal of providing thermal comfort in buildings is to have satisfied occupants, then the comfort performance can only be verified via subjective evaluation. In addition to POE questionnaires, subjective feedback may also be collected non-intrusively through occupant control actions which can provide important information about the subjective preferences of the occupant if held up against information about the current physical ambient conditions. Another potential data source for subjective opinions are the fields of Participatory Sensing or Participatory Comfort Control which aim to let occupants in a democratic manner vote for their desired indoor climate settings using their smart phone. By using modern sensor and communication technology, it is possible to collect data from several of the strategies and actions occupants use to interact with their environment, and thus their preferences. This type of data is often called Human-in-the-loop data, defined as: *"Occupancy and/or behavior data that are collected with humans involved in measurement and recording –knowingly or unknowingly– that are comprised of studies where a researcher manually records occupants as well as studies that use active engagement of occupants in their own recording (e.g., using thermostat interactions to collect data)"* (Wagner & Brien, 2018).

The recent research field of Occupant behavior focuses on the fact that occupants can influence energy consumption. With tightening requirements regarding building energy performance and sustainability, researchers, architects, planners, engineers, and building managers have begun to recognize the importance of understanding building occupants' behavior. In research regarding occupant behavior in buildings, focus is laid on collecting data which sheds light on occupant behavior in actual buildings (Laaroussi, Bahrar, El Mankibi, Draoui, & Si-Larbi, 2020). Some of this data can be said to be subjective occupant feedback and can answer the same questions as those asked in POE's, without the cost of the POE studies. The data may also be continuous, adding additional value compared to POE studies which are taken at one point in time. Subjective data must originate from occupant actions, which again relate to how occupants interact with their building. One can distinguish between *adaptive* and *non-adaptive* occupant action triggers, as well as *contextual factors*. *Adaptive triggers* or actions are defined as those rooted in occupant discomfort (or expectation of discomfort), such as opening a window, closing the blinds, or making a complaint. *Non-adaptive triggers* or actions are those that are part of occupants' tasks, such as shutting off the light when leaving the room, closing the window before going home, or answering a questionnaire. *Contextual factors* can be grouped into physical environmental factors; psychological factors, which are related to individual and social factors; and physiological factors. Several examples of contextual factors that are highly relevant for building design choices are mentioned in the literature, such as *physical factors*; building quality, availability of controls, interior design, ease of use of system interfaces, view to outside, feedback effects of control, *psychological factors*; knowledge, expectations, awareness, *Social factors*; ownership of building (Wagner & Brien, 2018). This illustrates how occupant satisfaction is a holistic design effort, as users are heavily affected by the context in which they interact with the building and experience the indoor environmental quality.

Satisfaction is derived from Latin "satis" (enough) and "facere" (to do or make). To provide satisfaction, we have to do or make "enough"(-Oliver, 2002). While attitudes can be politically or ethically based, satisfaction refers more directly to whether our expectations to a certain object, service or experience are fulfilled (Oliver, 2002). However, satisfaction also contains components of judgement (cognition) and affect (emotion) (Oliver, 2002). Research regarding satisfaction, or specifically, customer satisfaction, mainly originates from the field of market psychology where the goal is to understand how consumers evaluate consumables and which aspects are important to increase the possibility for them to repeat-purchase a product. Another, less known application is to investigate the determinants of employee satisfaction. The occupant's satisfaction with the indoor climate may be seen as a part of this, and in this case occupants are being regarded like consumers of the product (building). They are entitled to be satisfied with the indoor environmental product. When the building occupant is identified as a consumer of indoor climate, this opens for the use of market psychology and theory of customer satisfaction for understanding the psychological processes for satisfaction evaluation in an indoor climate perspective. To date there has not been conducted much research investigating the theoretical implications of this view, although they may be many and important.

Satisfaction is the summary state of a psychological process. It results at the end of the consumers processing activities and not necessarily when the product or service outcomes are observed. It is a voluntary process and not a necessary part of sensory processing, but rather an evaluative step that often is performed during or after the consumption of the product, which in the case of the building can for instance be the indoor environmental quality (Kim & de Dear, 2012a, 2012b; Oliver, 2014). Nevertheless, we also define satisfaction with indoor climate conditions as an ultimate goal when creating indoor climate conditions, after health and productivity. Indoor environmental satisfaction may be compared to customer satisfaction. Occupants who are satisfied with the overall environmental quality of their workspace are widely assumed to be more productive (Leaman and Bordass, 2007; Seppänen & Fisk, 2006).

As satisfaction is a summary state, it may incorporate impressions, perceptions, and expectations from several domains. It is therefore difficult to isolate satisfaction with one perception from the other (Oliver, 2002). This may be in many cases be a limitation but could on the other hand make satisfaction assessments very fit for assessing the performance of holistic design solutions.

3.2. New possibilities for subjective occupant feedback

In the conclusion of a study by Arens, De Dear and Zhang, the authors make the following reflection: *"Building temperature ranges should be based […] on real-time empirical feedback about their occupants' requirements. In the future, one can envision measures that enhance occupant feedback capability being incorporated in normal building control and operation, and being specified in building designs."*(Arens, Humphreys, de Dear, & Zhang, 2010). Today, nearly 10 years later, the development in information and communication technologies can make it possible to realize this vision. The concept of the Internet of Things (IoT) represents the overarching framework of a digital revolution that has unfolded during the last 10–15 years. The term generally refers to the concept of network- addressable devices embedded in everyday objects, allowing them to invisibly interact. This technological evolution has made advanced Information and Communication Technology (ICT) functionality reachable, affordable, and possible to implement into context suitable for continuous occupant feedback. A plethora of new technologies and methods for occupancy and occupant behavior sensing and data acquisition are being developed during the latest years.

Several recent research approaches related to smart building (Balaji et al., 2018; Jia et al., 2018) have investigated continuous subjective data collection, such as participatory sensing apps where occupants voluntarily provide feedback through a smartphone app (Hang-yat & Wang, 2013; Jazizadeh, Ghahramani, Becerik-Gerber, Kichkaylo, & Orosz, 2014; Konis & Annavaram, 2017), internet enabled thermostats, or wearable and static devices where control behavior is tracked and logged (Gupta et al., 2016; Kim et al., 2019; Liu, Schiavon, Das, Jin, & Spanos, 2019). Both participatory sensing apps and more generalized apps for occupant feedback and control are already available in the market today as Smart building solutions. Early efforts have already been made in developing complete methodologies to monitor the performance of buildings in sustainable cities from the occupant perspective (Kansara & Ridley, 2012). We mention here three main types of available occupant feedback solutions.

3.2.1. Measurements of occupant control actions

New sensor and wireless communication technology has made possible a development in data collection from occupant control actions. As the price, size, and convenience of wireless sensing equipment has improved, it has become possible to gather information for occupant interactions with windows, thermostats and personal environmental control devices such as heaters and fans (Carreira, Costa, Mansur, & Arsénio, 2018; Parkinson et al., 2019a; Parkinson et al., 2019b). Furniture such as office desks and chairs may have incorporated personal heaters and fans as well as internet connection providing usage statistics (Kim et al., 2019). Occupant control actions provide important information about the subjective preferences of the occupant, when held up against information about the physical ambient conditions. Using modern sensor and communication technology, such as non-intrusive load monitoring techniques, it is possible to collect data from several of the strategies and actions occupants use to interact with their environment, and thus their preferences (Gopinath, Kumar, Prakash Chandra Joshua, & Srinivas, 2020).

3.2.2. Continuous occupant feedback

Pervasive ICT devices such as smartphones have become ubiquitous among office occupants in the industrial world and have made possible a new way of gathering continuous feedback regarding indoor climate. The fields of Participatory Sensing or Participatory Control aim to let occupants in a democratic manner control the ambient temperature via the HVAC system using their smart phone. The key idea behind participatory sensing is to empower ordinary people to collect and share sensed data from their surrounding environments using their mobile phones (Kanhere, 2011). This can be done either in real-time or by using personal votes to generate a personal comfort model for each user. The individual differences in use of the subjective voting solution result in potential challenges related to fairness between occupants (Shin & Yus, 2017). Even though participatory sensing and control solutions in theory are continuous data streams, they may in reality not be continuous for individual users if they do not make use of the solution on a regular basis. Several research studies have been conducted on the concepts of Participatory Sensing and Participatory Control (Erickson & Cerpa, 2012; Gupta et al., 2016). In addition, there are some commercial products available that utilize Participatory Control in office buildings (Smart Buildings Center, 2015).

3.2.3. Continuous occupant satisfaction voting

Continuous occupant satisfaction surveys are voting polls aimed at collecting voluntary responses from a representative number of users. Most often this is done by on-touch voting machines (fixed button or touch screen) placed in an environment where the user passes by. Most often the survey responses are entered by single presses at smiley face buttons ranged from “Angry” via “Neutral” to “Happy”. The concept relies on the low cost in time and effort for users to enter their response, resulting in high response numbers. This technique has in later years had large success used in airports, retail, public facilities, and healthcare. The concept has only been tested in a small number of research studies for application in indoor climate in buildings (Berquist, Ouf, & O’Brien, 2019).

Most of these solutions focus on non-intrusive data collection from occupant *preferences* or *perceptions*, which normally are discipline-specific (e.g. temperature sensation or perception, air quality perceptions). However, preferences and perceptions are, as described above, substantially different from occupant *satisfaction* evaluations. In general, we can assume preferences and perceptions to represent our senses more directly, than comfort of satisfaction verdicts (which are summary states). Two recent research papers by two of the authors studied three different types of continuous subjective feedback collection, *satisfaction evaluations, complaints* and *control actions* (Lassen, Goia et al., 2020; Lassen, Josefsen et al., 2020). One of the studies argued that feedback collection types are different and complementary, as they collect different types of subjective information from the occupants. While the summary state of satisfaction is believed to be of most interest for a holistic design application, the other feedback types bring valuable data, for example for determining which aspects of indoor climate the occupants complain about. The studies found that the systems were taken into use by un-informed occupants in field tests, and that the data was useful and (fairly) representative of the occupant opinions found in simultaneously performed surveys. The useage frequency of a publicly located polling station showed a decline over time, and maintaining sufficient data volumes over time is an issue which should be addressed in future applications. The data validity and reliability was different for the different collection types, showing higher biases for the satisfaction feedback. Further work is needed to fully determine and understand the mechanisms and extent of the biases, but in general the studies concluded that these methods of continuous subjective occupant feedback are an efficient and useful way of collecting the subjective opinions of building occupants.

3.3. How can subjective feedback contribute to holistic design?

Discipline-specific performance criteria are not suited for supporting holistic design choices, as they only relate to physically quantifiable phenomenon studied in a specific context and do not support the fundamental nature of subjective occupant satisfaction. In a design process, holistic design alternatives are often rejected due to the lack of quantitative documentation for subjective phenomena. As satisfaction is a summary state, it may incorporate impressions, perceptions, and expectations from several domains, making satisfaction assessments very fit for assessing the performance of holistic design solutions. Subjective occupant feedback is the only information source that quantifies the experiences of the users of buildings. This information is unique as it can contain information based on environmental, psychological, and social information already collected, evaluated, and processed by the individuals using a building. It is impossible to evaluate the occupant’s subjective opinions without collected subjective information from the occupants themselves. This information is traditionally collected through POE’s as spot measurements. Unfortunately, these types of investigations are seldom performed as they are costly and time consuming. Using digitalized continuous subjective feedback systems, it is possible to collect preferences, control actions, complaints, and satisfaction verdicts from occupants in a systematical way at low cost as we have showed in a recent research actvity (Lassen, Josefsen et al., 2020). The feedback is then collected in a different way, and it is not always possible to collect exactly the same information as that which can be collected through survey questions in a POE. On the other hand, the continuous feedback has the advantage of being an uninterrupted stream of information, and in some cases having a spatial element on the exact locations of feedback enriches the depth of the collected data. These spatial and temporal subjective elements can add dimensions that are not accessible though spot surveys and measurements. Other studies, such as (Parkinson et al., 2019a, 2019b), have pointed out that for physical measurements, continuous monitoring systems are better at characterizing long-term performance than ad hoc measurement strategies using precision equipment. Although different, these sources represent various degrees and types of subjective “summary” evaluations from occupants from the use phase of a building. This type of information can be treated in the same way as usability studies performed by product developers and market analysts, or usage data collected from visitors to a webpage or social media platform for informing design decisions on interaction design.

Continuous subjective feedback is expected to potentially improve holistic design in the following three ways; Firstly, it can act as the support and documentation needed for leveraging holistic design choices when new buildings are designed. By developing specific methods for collecting representative and quality-checked data from occupants, we can evaluate, document, and learn from previous design choices. User feedback from completed projects can go into new projects as qualitative documentation of the performance of previous choices. In this way supporting an iterative design process from project to project, where the user is subjectively part of the evaluation process. As an example, satisfaction verdicts (or portion of dissatisfied verdicts) in a database from buildings with one type of acoustical damping solution can be compared to similar verdicts from occupants in buildings with another solution. The learnings can be used when designing a new building. Secondly, continuous subjective occupant feedback can be used as an argument for testing of new innovative solutions in a building, where also a fallback solution is available. When tracking of occupant satisfaction is present, it will be possible to continuously evaluate the performance of an innovative solution and determine if and how to implement changes or alternatives. This can reduce the risk involved of choosing new solutions or deviating from business-as-usual. As an example, there may be risk related to using natural ventilation for buildings in a cold climate. As a precautionary measure, the satisfaction of occupants may be continuously monitored post-construction. If occupants report to be dissatisfied during cold periods, compensating measures can be made at an early stage. Thirdly, continuous subjective occupant feedback can be used to inform optimized tuning and control of the indoor environment. This can again reduce the risk involved when choosing alternative indoor climate solutions, as the chance of faulty control is reduced when user feedback is collected. As an example, continuous occupant feedback can be used as a tool for calibrating and fault-checking the control sequences in any system, thereby lowering the risk of solutions which are especially sensitive or disposed to faulty of badly calibrated control systems (for instance an HVAC system using displacement ventilation, or a slow-reacting hydronic heating system).

Further, continuous subjective feedback has potential to reduce the performance gap for both energy performance, occupant satisfaction and maintenance. The subjective data gathered can help integrate the pre- and post-handover phases in the building life cycle; the various stakeholders in the building process, the various building disciplines, practice with research, subjective and objective dimensions of building use and experience, and lastly to bridge the static performance of the building with the dynamic functioning when real users interact with and modify static features. Occupant satisfaction and energy use can be improved by involving occupants in the loop and tracking of occupant satisfaction. Indirectly, it can enable better-informed and more holistic design choices and solutions that are simpler, more robust, have a longer lifetime and lower environmental impact. Designers will gain a better understanding of the users' needs and preferences.

4. Conclusions

In this article we have argued that modern high-performance buildings have become more technological, complex, and automated. The number of discipline-specific performance criteria and experts involved in a design are increasing, limiting the possibility to make holistic design choices. Users are not invited to interact in fear of them disturbing automation setpoints. However, these buildings do not meet their own design performance goals in practice, and systematic performance gaps between design and real performance have been identified for both energy performance, occupant satisfaction, operation, and maintenance. We have presented our own insights of recent examples of holistic design in high-performance buildings where discipline-specific performance criteria limit holistic design choices. We have highlighted the importance of a holistic approach to turn the inter-related series of building design and operational challenges into new opportunities, both on the building, city, and societal scale.

Further, we have argued how involving the users in the loop and collecting continuous subjective occupant feedback in the post occupancy phase can help close the performance gaps and empower future holistic design choices. Information and Communication Technology (ICT) enabling continuous subjective feedback from occupants can, similar to traditional Post-Occupancy Evaluations (POE), contribute to bringing occupants into the loop. Occupant-centric data streams open up the possibilities for holistic and integrated design choices, reducing the performance gaps and ultimately contributing toward higher performance in future buildings and cities. Thereby possibly enabling a paradigm shift toward new ways of conceiving, designing, constructing, and operating with radical improvements in building performances.

Declaration of Competing Interest

The authors declare no potential conflict of interest. It should however be noted that some of the authors are employed by the companies that were responsible for realizing the buildings used as case-studies in the article. There are, however, no direct financial interests related to the topic or the buildings discussed, and neither authors nor companies involved have invested in the topic in question.

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References

Andresen, I. (2000). *A multi-criteria decision-making method for solar building design.* the Norwegian University of Science and Technology.

Andresen, I., & Hegli, T. (2017). The integrated design process. In A. G. Hestnes, & N. L. Eik-Nes (Eds.), *Zero emission buildings* (1st ed).

Andresen, I., Dokka, T. H., & Johansen, V. S. (2018). *Kriterier for FutureBuilt Plusshus - Revisjon Des-2018*. https://www.futurebuilt.no/content/download/13880/94166.

Arens, E., Humphreys, M. A., de Dear, R., & Zhang, H. (2010). Are ‘class A’ temperature requirements realistic or desirable? *Building and Environment, 45*, 4–10. https://doi.org/10.1016/j.buildenv.2009.03.014

Baker, N., & Standeven, M. (1996). Thermal comfort for free-running buildings. *Energy and Buildings*. https://doi.org/10.1016/0378-7788(95)00942-6

Balaji, B., Bhattacharya, A., Fierro, G., Gao, J., Gluck, J., Hong, D., et al. (2018). Brick: Metadata schema for portable smart building applications. *Applied Energy, 226* (September), 1273–1292. https://doi.org/10.1016/j.apenergy.2018.02.091

Becchio, C., Corgnati, S. P., Delmastro, C., Fabi, V., & Lombardi, P. (2016). The role of nearly-zero energy buildings in the transition towards post-carbon cities. *Sustainable Cities and Society, 27*(November), 324–337. https://doi.org/10.1016/j.scs.2016.08.005

Berquist, J., Ouf, M., & O'Brien, W. (2019). A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort. *Building and Environment, 150*, 88–98. https://doi.org/10.1016/j.buildenv.2018.12.064

Boerstra, A. C. (2016). *Personal control over indoor climate in offices impact on comfort, health & productivity*. Eindhoven University of Technology.

Boerstra, A. C., Te Kulve, M., Toftum, Jørn, Loomans, M. G. L. C., Olesen, B. W., & Hensen, J. L. M. (2015). Comfort and performance impact of personal control over thermal environment in summer: Results from a laboratory study. *Building and Environment, 87*, 315–326. https://doi.org/10.1016/j.buildenv.2014.12.022

Bordass, W., & Leaman, A. (1997). Design for manageability: Unmanageable complexity is a major source of chronic problems in building performance. *Building Research and Information, 25*(3), 148–157. https://doi.org/10.1080/096132197370417

Brager, G. (2004). Operable windows, personal control and occupant comfort. *ASHRAE Transactions, 110*(2). http://escholarship.org/uc/item/4x57v1pf.

Carreira, P., Costa, A. A., Mansur, V., & Arsénio, A. (2018). Can HVAC really learn from users? A simulation-based study on the effectiveness of voting for comfort and energy use optimization. *Sustainable Cities and Society, 41*(May), 275–285. https://doi.org/10.1016/j.scs.2018.05.043

Cheung, T., Schiavon, S., Parkinson, T., Li, P., & Brager, G. (2019). Analysis of the accuracy on PMV – PPD model using the ASHRAE global thermal comfort database II. *Building and Environment, 153*(April), 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055

“Cloud-Based Tool for Management and Tuning of Smart Energy Efficient Buildings.” 2019. Research Council of Norway, Prosjektbanken. 2019.

Cole, R. J., & Brown, Z. (2009). Reconciling human and automated intelligence in the provision of occupant comfort. *Intelligent Buildings International, 1*(1), 39–55. https://doi.org/10.3763/inbi.2009.0007

Collins, D., Haugen, T., & Aamodt, C. (2017). Bridging the gap between sustainable FM and sustainable buildings an exploratory study of six public buildings in Norway. *International Research Conference 2017: Shaping Tomorrows Built Environment*, 241–254.

Day, J. K., & Heschong, L. L. (2016). Understanding behavior potential: The role of building interfaces. *2016 ACEEE Summer Study on Energy Efficiency in Buildings*. https://www.researchgate.net/publication/308141281.

Day, J. K., & O'Brien, W. (2017). Oh behave! Survey stories and lessons learned from building occupants in high-performance buildings. *Energy Research and Social Science, 31*(September), 11–20. https://doi.org/10.1016/j.erss.2017.05.037

de Dear, R. J., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions, 104*(1), 145–167. http://escholarship.org/uc/item/4qq2p9c6.

Dokka, T. H., Berggren, B., & Lassen, N. (2015). Comparison of five zero and plus energy projects in Sweden and Norway – A technical review. In *7th Passive House Nordics | Sustainable Cities and Buildings*. http://passivhus.dk/7phn/.

Dokka, T. H., Myrup, M., & Solsem, M. (2019). Lia Kindergarten – A plus energy building: First year experience with regard to energy use. *IOP Conference Series: Earth and Environmental Science, 352*(1), 0–9. https://doi.org/10.1088/1755-1315/352/1/012061

Erickson, V. L., & Cerpa, A. E. (2012). Thermovote: Participatory sensing for efficient building HVAC conditioning. *BuildSys '12 Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, 9–16.

Fanger, P. O. (1970). *Thermal comfort* (pp. 419–422). Danish Technical Press.

Fountain, M., Brager, G., & De Dear, R. (1996). Expectations of indoor climate control. *Energy and Buildings, 24*, 179–182. https://doi.org/10.1016/S0378-7788(96)00988-7

Gopinath, R., Kumar, M., Prakash Chandra Joshua, C., & Srinivas, K. (2020). Energy management using non-intrusive load monitoring techniques - state-of-the-art and future research directions. *Sustainable Cities and Society*, (July), Article 102411. https://doi.org/10.1016/j.scs.2020.102411

Grover, R., Emmitt, S., & Copping, A. (2020). Critical learning for sustainable architecture: Opportunities for design studio pedagogy. *Sustainable Cities and Society, 53*, Article 101876.

Gupta, S. K., Atkinson, S., O'Boyle, I., Drogo, J., Kar, K., Mishra, S., et al. (2016). BEES: Real-time occupant feedback and environmental learning framework for collaborative thermal management in multi-zone, multi-occupant buildings. *Energy and Buildings, 125*, 1–13. https://doi.org/10.1016/j.enbuild.2016.04.084

Hadjri, K., & Crozier, C. (2009). Post-occupancy evaluation: Purpose, benefits and barriers. *Facilities, 27*(1–2), 21–33. https://doi.org/10.1108/02632770910923063

Hang-yat, A., & Wang, D. (2013). Carrying my environment with me: A participatory-sensing approach to enhance thermal comfort. *BuildSys, 13*. https://doi.org/10.1145/2528282.2528286

Hansen, A. R., Gram-Hanssen, K., & Knudsen, H. N. (2018). How building design and technologies influence heat-related habits. *Building Research and Information, 46*(1), 83–98. https://doi.org/10.1080/09613218.2017.1335477

Hellwig, R. T. (2015). Perceived control in indoor environments: A conceptual approach. *Building Research and Information, 43*(3), 302–315. https://doi.org/10.1080/09613218.2015.1004150

Hellwig, R. T., Brasche, S., Bischof, W., & Friedrich-schiller-university Jena. (2006). Thermal comfort in offices – Natural ventilation vs. air conditioning. *Conference Comfort and Energy Use in Buildings. Getting Them Right*, 1–11.

Hestnes, A. G., & Gustavsen, A. (2017). Introduction. *Zero Emission Buildings*, 15–22.

Hoyt, T., Arens, E., & Zhang, H. (2014). Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment, 88*, 89–96. https://doi.org/10.1016/j.buildenv.2014.09.010

Huang, L., Zhu, Y., Ouyang, Q., & Bin, C. (2012). A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices. *Building and Environment, 49*(1), 304–309. https://doi.org/10.1016/j.buildenv.2011.07.022

Humphreys, M. A., & Fergus Nicol, J. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE Transactions*, 1–14.

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

Jensen, P. A. (2012). Knowledge transfer from facilities management to building projects: A typology of transfer mechanisms. *Architectural Engineering and Design Management, 8*(3), 170–179. https://doi.org/10.1080/17452007.2012.669131

Jenssen, B. (2019). Powerhouse Brattørkaia – The Northernmost plus energy office building in the world. In *1st Nordic Conference on Zero Emission and Plus Energy Buildings 6–7 November 2019, Trondheim*.

Jia, R., Jin, B., Jin, M., Zhou, Y., Konstantakopoulos, I. C., Han, Z., et al. (2018). Design automation for smart building systems. *Proceedings of the IEEE, 106*(9), 1680–1699.

Jørgensen, P. F., Andresen, I., & Bramslev, K. (2009). *INTEGRERT ENERGIDESIGN IED*. www.ied.no.

Kanhere, S. S. (2011). Participatory sensing: crowdsourcing data from mobile smartphones in urban spaces. In *Proceedings - IEEE International Conference on Mobile Data Management, 2* pp. 3–6). https://doi.org/10.1109/MDM.2011.16

Kansara, T., & Ridley, I. (2012). Post occupancy evaluation of buildings in a zero carbon city. *Sustainable Cities and Society, 5*, 23–25. https://doi.org/10.1016/j.scs.2012.05.010

Karjalainen, S. (2013). Should it be automatic or manual – The occupant's perspective on the design of domestic control systems. *Energy and Buildings, 65*, 119–126. https://doi.org/10.1016/j.enbuild.2013.05.043

Karmann, C., Schiavon, S., & Arens, E. (2018). Percentage of commercial buildings showing at least 80% occupant satisfied with their thermal comfort. *Proceedings of 10th Windsor Conference: Rethinking Comfort*, 0–7. https://escholarship.org/uc/item/89m0z34x.

Khemlani, L., & Kalay, Y. E. (1997). An integrated computing environment for collaborative, multi-disciplinary building design. *CAAD Futures 1997*, 389–416.

Kim, J., & de Dear, R. (2012a). Nonlinear relationships between individual IEQ factors and overall workspace satisfaction. *Building and Environment*, 33–40. https://doi.org/10.1016/j.buildenv.2011.09.022

Kim, J., & De Dear, R. (2012b). Impact of different building ventilation modes on occupant expectations of the main IEQ factors. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2012.05.003

Kim, J., Schiavon, S., & Brager, G. (2018). Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control. *Building and Environment, 132*, 114–124. https://doi.org/10.1016/j.buildenv.2018.01.023

Kim, J., Bauman, F., Raftery, P., Arens, E., Zhang, H., Fierro, G., Andersen, M., & Culler, D. (2019). Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers. *Building and Environment, 148*(September 2018), 348–360. https://doi.org/10.1016/j.buildenv.2018.11.012

Knudsen, H. N., Andersen, R. K., & Hansen, A. R. (2016). House owners' interest and actions in relation to indoor temperature, air quality and energy use. *Proceedings of Clima*. http://vbn.aau.dk/files/234609590/Paper_Clima2016_hnk.pdf.

Konis, K., & Annavaram, M. (2017). The occupant mobile gateway: A participatory sensing and machine-learning approach for occupant-aware energy management. *Building and Environment, 118*(June), 1–13. https://doi.org/10.1016/j.buildenv.2017.03.025

te Kulve, M., Schlangen, L., & van Marken Lichtenbelt, W. (2018). Interactions between the perception of light and temperature. *Indoor Air, 28*(6), 881–891. https://doi.org/10.1111/ina.12500

Kwon, M., Remøy, H., van den Dobbelsteen, A., & Knaack, U. (2019). Personal control and environmental user satisfaction in office buildings: Results of case studies in the netherlands. *Building and Environment, 149*(February), 428–435. https://doi.org/10.1016/j.buildenv.2018.12.021

Laaroussi, Y., Bahrar, M., El Mankibi, M., Draoui, A., & Si-Larbi, A. (2020). Occupant presence and behavior: A major issue for building energy performance simulation and assessment. *Sustainable Cities and Society*, (July), Article 102420. https://doi.org/10.1016/j.scs.2020.102420

Lassen, N. (2018). A study of running set-points and user IEQ satisfaction perspectives in the Norwegian commercial building stock. *39th AIVC Conference, Smart Ventilation for Buildings*, 180–189. www.rehva.eu.

Lassen, N. (2019). Case study of personal heaters in a plus energy building – Simulations of potential energy savings and results from a field test. In *1st Nordic Conference on Zero Emission and Plus Energy Buildings, IOP Conf. Series: Earth and Environmental Science, 352* pp. 1–8). https://doi.org/10.1088/1755-1315/352/1/012051

Lassen, N., Goia, F., Schiavon, S., & Pantelic, J. (2020). Field investigations of a smiley-face polling station for recording occupant satisfaction with indoor climate. *Building and Environment, 185*(September), Article 107266. https://doi.org/10.1016/j.buildenv.2020.107266

Lassen, N., Josefsen, T., & Goia, F. (2020). Design and in-field testing of a multi-level system for continuous subjective occupant feedback on indoor climate. *Building and Environment, 189*(October 2020), 1–58. https://doi.org/10.1016/j.buildenv.2020.107535

Leaman, A., & Bordass, B. (1999). Productivity in buildings: The 'killer' variables. *Building Research and Information, 27*(1), 4–19. https://doi.org/10.1080/096132199369615

Leaman, A., & Bordass, B. (2007). Are users more tolerant of 'green' buildings? *Building Research and Information, 35*(6), 662–673. https://doi.org/10.1080/09613210701529518

Levin, H., & Emmerich, S. (2013). Dissecting interaction among indoor environmental quality factors. *ASHRAE Journal, 55*(9), 66–72.

Li, P., Froese, T. M., & Brager, G. (2018). Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review. *Building and Environment, 133*(December 2017), 187–202. https://doi.org/10.1016/j.buildenv.2018.02.024

Liu, S., Schiavon, S., Das, H. P., Jin, M., & Spanos, C. J. (2019). Personal thermal comfort models with wearable sensors. *Building and Environment, 162*(September). https://doi.org/10.1016/j.buildenv.2019.106281

Lucas, J. D. (2012). *An integrated BIM framework to support facility management in healthcare environments*. Virginia Polytechnic Institute and State University.

Luo, M., De Dear, R., Ji, W., Bin, C., Lin, B., Ouyang, Q., et al. (2016). The dynamics of thermal comfort expectations: The problem, challenge and impication. *Building and Environment, 95*, 322–329. https://doi.org/10.1016/j.buildenv.2015.07.015

Madsen, L. V., & Gram-Hanssen, K. (2017). Understanding comfort and senses in social practice theory: Insights from a Danish field study. *Energy Research and Social Science, 29*(July), 86–94. https://doi.org/10.1016/j.erss.2017.05.013

Meir, I. A., Garb, Y., Jiao, D., & Cicelsky, A. (2009). Post-occupancy evaluation: An inevitable step toward sustainability. *Advances in Building Energy Research, 3*(1), 189–219. https://doi.org/10.3763/aber.2009.0307

Mendell, M. (2009). Indoor thermal factors and symptoms in office workers: Findings from the U.S. EPA BASE study. *Indoor Air*, (December), 1–26. https://escholarship.org/uc/item/7dx9w6x9.

Menezes, A. C., Cripps, A., Bouchlaghem, D., & Buswell, R. (2012). Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy, 97*, 355–364. https://doi.org/10.1016/j.apenergy.2011.11.075

Oliver, R. L. (2002). Cognitive, affective, and attribute bases of the satisfaction response. *Journal of Consumer Research, 20*, 418–430. https://doi.org/10.1086/209358

Oliver, R. L. (2014). *Satisfaction: A behavioral perspective on the consumer*. Routledge.

Ornetzeder, M., Wicher, M., & Suschek-Berger, Jürgen (2016). User satisfaction and well-being in energy efficient office buildings: Evidence from cutting-edge projects in Austria. *Energy and Buildings, 118*, 18–26. https://doi.org/10.1016/j.enbuild.2016.02.036

Parkinson, T., Parkinson, A., & de Dear, R. (2019a). Continuous IEQ monitoring system: Performance specifications and thermal comfort classification. *Building and*

Environment, 149(February), 241–252. https://doi.org/10.1016/j.buildenv.2018.12.016

Parkinson, T., Parkinson, A., & De Dear, R. (2019b). Continuous IEQ monitoring system: Context and development. *Building and Environment, 149*(October 2018), 15–25. https://doi.org/10.1016/j.buildenv.2018.12.010

Revfem, J. (2018). *Teknisk Ukeblad: Hva Koster Det å Oppføre et Typisk Kontorbygg?*. Teknisk Ukeblad På Nett TU.No. 2018 https://www.tu.no/artikler/hva-koster-det-a-oppfore-et-typisk-kontorbygg-br/441201.

Roberts, P. (2001). Who is post-occupancy evaluation for? *Building Research & Information, 29*(6), 463–465. https://doi.org/10.1080/09613210110072674

Schweiker, M., Rissetto, R., & Wagner, A. (2020). Thermal expectation: Influencing factors and its effect on thermal perception. *Energy and Buildings, 210*(March). https://doi.org/10.1016/j.enbuild.2019.109729

Seppanen, O., & Fisk, W. J. (2002). *Relationship of SBS-symptoms and ventilation system type in office buildings publication date*.

Seppänen, O. A., & Fisk, W. (2006). Some quantitative relations between indoor environmental quality and work performance or health. *HVAC and R Research, 12*(4), 957–973. https://doi.org/10.1080/10789669.2006.10391446

Shin, E.-j., & Yus, R. (2017). Exploring fairness in participatory thermal comfort control in smart buildings. *BuildSys, 17*(November), 0–9.

Smart Buildings Center. (2015). *Keeping employees productive through thermal comfort the value of thermal comfort in the workplace*, 09 (pp. 1–4).

Søgnen, O. B. (2015). *Indoor climate in a zero energy building an analysis of the thermal environment and indoor air quality*. Norwegian University of Science and Technology.

Stene, R. (2018). *Powerhouse: About us*, 2018 https://www.powerhouse.no/en/about-us/.

Stoknes, S., Berg, H. B., Edwards, K., Myrup, M., Heier, E., Lassen, N., et al. (2017). *Passiv Klimatisering Av Fremtidens Energieffektive Bygg – Erfaringsrapport*. Oslo, Norway.

Subjective. (2019). *Lexico oxford dictionary*, 2019 https://www.lexico.com/definition/subjective.

Tapper, C. S. F., & Dokka, T. H. (2019). Powerhouse telemark: A plus energy building with a low exergy heating and cooling system. *IOP Conference Series: Earth and Environmental Science, 352*(1), 0–8. https://doi.org/10.1088/1755-1315/352/1/012056

“The House Zero Project.” n.d. (Accessed June 8, 2020). https://harvardcgbc.org/research/housezero/.

“The Research Project Low-Ex.” n.d. (Accessed June 8, 2020). https://avantor.no/miljo/forskningsprosjektet-lowex.

van Dronkelaar, C., Dowson, M., Spataru, C., & Mumovic, D. (2016). A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in Mechanical Engineering, 1*(January), 1–14. https://doi.org/10.3389/fmech.2015.00017

Von Grabe, J. (2016). How do occupants decide their interactions with the building? From qualitative data to a psychological framework of human-building-interaction. *Energy Research and Social Science*. https://doi.org/10.1016/j.erss.2016.01.002

Wagner, A., & Brien, W. O. (2018). *Exploring occupant behavior in buildings*. https://doi.org/10.1007/978-3-319-61464-9

Wang, J., Wang, Z., de Dear, R., Luo, M., Ghahramani, A., & Borong, L. (2018). The uncertainty of subjective thermal comfort measurement. *Energy and Buildings, 181*, 38–49. https://doi.org/10.1016/j.enbuild.2018.09.041

“ZEB Definitions” n.d. ZEB: The Research Centre on Zero Emission Buildings (Accessed May 23, 2020) https://zeb.no/index.php/no/om-zeb/zeb-definisjoner.

Zeiler, W., Savanovic, P., & Boxem, G. (2008). Design decision support for the conceptual phase of sustainable building design. In *11th International Conference on Indoor Air Quality and Climate (Indoor Air 2008)*. PaperID:9.

Zou, P. X. W., Xu, X., Sanjayan, J., & Wang, J. (2018). Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives. *Energy and Buildings, 178*, 165–181. https://doi.org/10.1016/j.enbuild.2018.08.040