ANNEX 69

Energy in Building and Communities Programme

International Energy Agency

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (EBC Annex 69) Deliverable 3: Guidelines for Low Energy Building Design Based on the Adaptive Thermal Comfort Concept

Energy in Buildings and Communities Technology Collaboration Programme

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ANNEX 69

EBC

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 31 member countries and 11 association countries, and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of 'low tech', robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
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Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements (*)
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities (*)
Annex 74: Competition and Living Lab Platform (*)
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO2 Emissions (*)
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Annex 84: Demand Management of Buildings in Thermal Networks
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Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Implementing Net Zero Emissions Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes

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Preamble

Reductions in energy use and provision of comfortable indoor environment to occupants are both key objectives of the building sector all around the world. However, establishing the appropriate balance between these often competing issues is challenging. Is it possible to achieve thermal comfort in buildings without increasing energy use?

The key point is to understand the occupants' real thermal demand. To maintain the indoor environment variables within narrow range is known to consume copious energy, but is the steady iso-thermal environment with minimal variations really necessary for thermal comfort? Previous studies have shown that staying in a steady thermal environment for long time periods may actually be harmful to human body, since it weakens the physiological thermoregulatory resilience and acclimation when people are finally exposed to heat stress. We now have enough evidence to show that tight control of indoor temperatures drives high energy costs and greenhouse gas emissions, and may not always provide benefit for occupant comfort and health. The current indoor environment standards for mechanically heated and cooled buildings are based on the PMV-method for specifying an acceptable comfort temperature range. The same standards also include an adaptive approach for office buildings relying on operable windows instead of mechanical cooling systems (e.g. ISO 7730, 2005, CEN 15251, 2012, ANSI/ASHRAE, 2013).

The Annex 69 project was approved unanimously at the Executive Committee Meeting of the IEA Energy in Buildings and Communities Programme, held on 14th November 2013 in Dublin, Ireland. The Annex will focus on the fundamental question of how to describe the mechanisms of occupant adaptive thermal comfort in buildings, as well as the application of the thermal adaptation concept in design, evaluation and control of built environments in order to reduce energy use. The participants will collaborate to establish a worldwide database of building performance, to develop and improve the adaptive method in indoor thermal environment standards, and to propose guidelines for using the adaptive approach in low energy building design, operation, refurbishment, and new personal thermal comfort systems. The project has three subtasks:

Subtask A: Collecting field data on comfort and occupant responses, and research into models of adaptation

Subtask B: Criteria and guidelines for adaptive comfort and Personal Thermal Comfort Systems in standards

Subtask C: Case studies - Practical learnings from exemplary adaptive buildings, supporting Subtasks A & B

In total 14 countries and organizations including universities and research institutes have participated in the project. Preparation phase started in January 2015 and lasted until December 2015. The Working phase started in January 2016 and lasted for three years. The Reporting phase started in January 2019 and plans to end in December 2019.

Through Annex 69, we hope to provide scientific description and clear understanding of how to develop quantitative description of occupants’ adaptive thermal comfort in buildings, which is a fundamental science question related to the appropriate design, evaluation and control methods of indoor environment in order to reduce building energy use.

1. Introduction

Designing and operating buildings for a good indoor climate and at the same time keeping the energy use for conditioning indoor spaces as low as possible is one of the world's challenges. In order to *minimise legal liability* and *maximise comfort*, indoor spaces are often designed and operated for constant, nearly steady-state thermal conditions uniform throughout the building (Deuble and de Dear 2012a). Comparison of predicted and real energy use in buildings shows that actual building energy use is often higher than designed for. This is called the energy performance gap (Sunnika-Blank and Galvin, 2012, Hansen et al. 2018, Teli et al. 2018, Hellwig 2019). Occupant behaviour is an often given reason for this (Gram-Hanssen, 2013, IEA EBC Annex 66, 2019). Occupant behaviour is often perceived as being random or not logical, and in many cases contradictory to a low energy use of a building, e.g. window opening at "wrong" conditions or using thermostats in a "wrong" way (Usable Buildings 2020, O'Brien and Gunay 2014). Therefore, building planners and operators are in favour of placing control on automatic systems, which manage the indoor environmental conditions and tend to refuse means for occupants to intervene in the building's automatic conditioning (Bordass and Leaman 1997). Subsequently, occupants are assigned a passive role (de Dear at el. 1997, Hellwig, 2018). Contrary to expectations, such buildings tend to provoke more complaints, occupant dissatisfaction or even contribute to sick building syndrome (Usable Buildings 2020, Marmot et al. 2006, Bischof et al. 2003) and at the same time do not fulfil the low energy expectation connected to their high degree of automation (Gilani and O'Brien, 2018, Hellwig et al. 2020a). In contrast, buildings designed and operated according to the adaptive thermal comfort concept inherently favour a certain indoor environmental variation, with indoor thermal conditions changing gradually in response to the prevailing outdoor conditions, while remaining within the limits that people readily adapt to. Furthermore, these buildings offer *appropriate* control to occupants in order to serve their diversity of indoor environment perception and needs (Hellwig, 2015, Roetzel et al. 2020). The idea behind such a design could be described as designing for "global thermal zones" (Auliciems, 1981a) and serve diversity among occupants with a variety of control options.

The adaptive thermal comfort concept has been developed over many years and proven in numerous field studies (e.g. Webb 1964, Nicol and Humphreys 1973, Auliciems 1981b, de Dear et al. 1997, McCartney and Nicol 2002, Manu et al. 2016), showing that people are satisfied with a wide range of thermal conditions. Prerequisite is that people are provided with means to make themselves comfortable, that they know which opportunities they have, that it is socially acceptable to use these opportunities and that they are willing to use them (Hellwig, 2015). However, the overall understanding of how to design for such opportunities enabling the occupant to make themselves comfortable in relation to climate and building type, thus how to convert the adaptive thermal comfort concept into building design and concepts for operating buildings, is still limited. There are still common misunderstandings in the interpretation of the adaptive comfort approach among building planners and operators e.g. regarding the amount of control, the seriousness of this topic or the level of information needed by occupants for which reason guidance (e.g. CIBSE 2010, Cook et al. 2020) and knowledge transfer (e.g. Hellwig and Boerstra 2017, 2018) is absolutely essential. Consequently, there is still a gap between scientific research and real-world-application, which this report aims to diminish.

Hellwig et al. (2019) identified challenges and barriers to the adoption of the adaptive thermal comfort concept, which can be summarised as follows:

- Limited understanding of human thermo-physiology, adaptation and acclimatisation
- common interpretation of thermal comfort as the need for a static temperature
- limited understanding of the adaptive thermal comfort concept among practitioners, comprising the conceptual model behind the equation and the impact of contextual non-quantifiable factors
- assumed high accuracy of classic calculation models for thermal comfort
- underestimation of the role of personal control in comfort perception
- missing guidance on how to design adaptive opportunities
- missing interlinkage between the conceptual model of adaptive thermal comfort and building design beyond using it for determining acceptable temperature ranges
- missing interlinkage between the conceptual model of adaptive thermal comfort and operational practice in buildings
- different use and interpretation of terminology used (building conditioning types, building classes)
- a preconception of roles of the stakeholders in the process, which e.g. assigns a passive role to occupants
- limitations in planners' ability to further develop their design and adapt their building design for future climate conditions
- narrow interpretation of the adaptive thermal comfort concept as suitable only for non-conditioned and free-running buildings, hence not relevant e.g. in actively heated or cooled buildings

In line with the activities within IEA EBC Annex 69 Subtasks A, B, and C, the present report includes four main sections, addressing the above listed identified challenges and barriers to the adoption of the adaptive thermal comfort in practice by explaining the adaptive thermal comfort principles, by illustrating the benefits from applying the adaptive principles in buildings, through guidance on how to implement the adaptive principles in the design and operation of buildings, especially providing guidance on how to design for adaptive opportunities. The Appendices contain additional information on standards, checklists for stakeholders in the design and operation of buildings as well as documentation and lessons learnt from the buildings investigated within this Annex 69 Subtask C.

This report is formulated with the help of frameworks (Hellwig et al. 2019, Hellwig et al. 2020) developed to facilitate the adoption of adaptive principles in the design and operation of buildings. We aim to provide the knowledge on a general level of understanding, so that it is possible to apply the knowledge in different types of building usage, different climate zones and occupant groups. However, the majority of examples used in this report stems from office buildings, which is mainly rooted in the fact that the majority of research studies focussed on this type of building. Nevertheless, we have supplemented this report with examples from other building types.

The target group of the guidelines in this report are building planners (architects, engineers, sustainability certification consultants/councils) and building operators (facility managers, operators, owners, and tenants). Furthermore, the guidelines in this report are intended as critical sources and guidance to educate future building professionals and stakeholders.

The report includes four main sections, as outlined below.

Section 2 summarises the three adaptive comfort principles, i.e. physiological, behavioural and psychological adaptation. The section follows with a discussion on the effectiveness of the adaptive principles and on the order of activation of adaptive responses. It ends with a brief account on the development of adaptive models.

Section 3 describes the benefits from applying the adaptive principles in buildings, including energy savings, resilience to climate change, improved usability and thermal satisfaction, as well as improved health and well-being.

Section 4 presents the developed framework for adopting the adaptive comfort principles in design and operation of buildings. The main elements of the framework are described, i.e. the building context, adaptive responses and actions, the building planning and design, –the adaptive opportunities design, and the operational planning and operation. Each of these subsections includes guidelines to facilitate the integration of adaptive principles. Section 4 ends with considerations and recommendations for adopting adaptive comfort in conditioned buildings, including advice for facilitating free-running mode in building operation as often as possible and ways to integrate the use of the adaptive principles in permanently or long-season conditioned spaces.

Appendices

Appendix 1 summarises information on adaptive models used in international and national standards, as well as examples of models developed by research in various locations and climates.

Appendix 2 provides checklists of parameters that can help stakeholders implement measures to ensure the availability of adaptive opportunities in buildings.

Appendix 3 is a collation of case studies with practical learnings from adaptive buildings investigated in Annex 69 Subtask C.

Appendix 4 lists publications, presentations and workshops related to Activity B2 of IEA EBC Annex 69.

2. Adaptive thermal comfort principles

Research on human thermal perception dates back to the beginning of the 19th century (Houghten and Yagloglou, 1923a,b). For many decades, a rather static view on thermal comfort dominated research on thermal comfort. This view concentrated on the thermoregulatory responses of the human to variations of the indoor thermal environment (further details see section 2.1). In this view, the human was solely reacting to the prevailing conditions, thus a passive recipient. In contrast, the adaptive view on human thermal perception considers the human being perceptive, but as taking on an active role in the complex relationship between environmental conditions and individual perception. The adaptive approach is based on the pioneering works of Webbs (1964), Auliciems (1969a, 1969b, 1981a, 1981b), Nicol and Humphreys (1973) and Humphreys (1973, 1976, 1978). Important work was summarised in Nicol et al. (2012) and Humphreys et al. (2016). Building on their work de Dear et al. (1997) phrased the three adaptive principles: behavioural, physiological, and psychological adaptation. These three principles are summarised with examples in the following subsections, and in Figure 1.

2.1. Human thermoregulation and physiological adaptation

The human body needs to keep its core temperature within a limited range between 35.5 and 37.8°C in order to work efficiently. At the same time, conditions surrounding the human body can easily range from below -15°C to up to more than 40°C outdoors and usually between 10°C and 36°C indoors. In order to keep the core temperature stable, the human body unconsciously adjusts to these fluctuations. Mechanisms close to thermal neutrality zone are vasoconstriction and vasodilation, which is either the reduction or increase of blood flow from the body core to the extremities such as hands and feet in order to control the amount of heat dissipating. Mechanisms activated later are sweating or shivering in conditions further to the warm or cold side of thermal neutral zone.

Physiological adaptation (acclimatisation) serves to reduce thermal stress on the human body after recurring exposures beyond the comfort range on both, the cold or hot side. Subsequently, the body adjusts physiological parameters, e.g. an enhanced metabolic expenditure (van Marken Lichtenbelt et al. 2014) or a lower onset temperature of sweating in order to increase the heat loss from the body core in warm to hot environments (Hori, 1995; Taylor, 2014). This modifies the response of the thermoregulation system. An important point to be made here is, that physiological adaptation requires repeated exposures to non-neutral conditions, such as warm or cold conditions outside the comfort range. Therefore, tight control around thermal neutrality reduces the potential of physiological adaptation. In contrast, exposures outside thermal neutrality have in addition positive health effects. For instance, excursions to the cold and warm side of neutral conditions improve the health status of patients with type 2 diabetes and in general cardio-metabolic health in humans (Hanssen et al. 2015, Schrauwen and van Marken Lichtenbelt 2016, Pallubinsky et al. 2017, Pallubinsky et al. 2020). However, Schellen (2018) recommends that it is advisable to protect the elder from temperature disturbances, but suggests that younger adults may benefit from milder temperature drifts.

Physiologists call a slowly increasing/decreasing temperature as in a seasonal change a mild ‘heat [or cold] strain/stress’ (Taylor 2014). As argued by Hellwig et al. (2020), such a wording could lead non-physiologist to misinterpret the meaning and conclude that such ‘stressful’ changes should not be reflected indoors because they would lead to discomfort and cause complaints. As numerous field studies, summarised in data-bases (de Dear 1998, McCartney and Nicol 2002, Földvary et al. 2018), have shown, such gradual changes would be perceived as a natural change. Contrary, extreme and rapid temperature changes as in heat waves have indeed the potential to exert a heat strain on the human body.

2.2. Behavioural adaptation

Behavioural adaptation is first mentioned in the work by Auliciems (1969a, 1969b, 1981a, 1981b), Nicol and Humphreys (1973) and Humphreys (1973, 1976, 1978). It comprises behaviours such as e.g. changing posture or activity, clothing level adjustments or adjustments to the indoor thermal environment by adaptive opportunities (e.g. window opening or using a fan). These behaviours regulate the rate of internal heat generation and the body heat loss via convection, long-wave radiation, evaporation or conduction. The probability of these behaviours varies with changing outdoor conditions (e.g. Nicol, 2001; Baker and Standeven 1997, de Carli et al. 2007; Haldi and Robinson 2009; Cândido et al. 2011; Schiavon and Lee 2013, Wang et al. 2018). For example, our level of clothing decreases with higher outdoor temperatures and the likelihood to use a ceiling fan increases with higher indoor temperatures (see also section 4.3).

2.3. Psychological adaptation

Psychological adaptive mechanisms have been researched much less than the other two mechanisms. At the same time, there is a large variety in psychological adaptive mechanisms mentioned. The most researched one relates to the notion of perceived control: People, who perceive a higher degree of control over their indoor environment, e.g. by the the amount of privacy or the availability of openable windows, feel more satisfied with the conditions and accept a wider range of indoor temperatures (e.g. Paciuk, 1990; Fountain et al., 1996; Hellwig, 2015, Boerstra, 2016). Additional effects are changed expectations (Bischof et al. 2002, Brager and de Dear, 2003; Strengers, 2008; Luo et al. 2016, Wang et al. 2017), for example due to pro-environmental attitudes (Leaman and Bordass, 2007; Deuble and de Dear 2012b), but also social factors (Nicol and Humphreys, 1973).

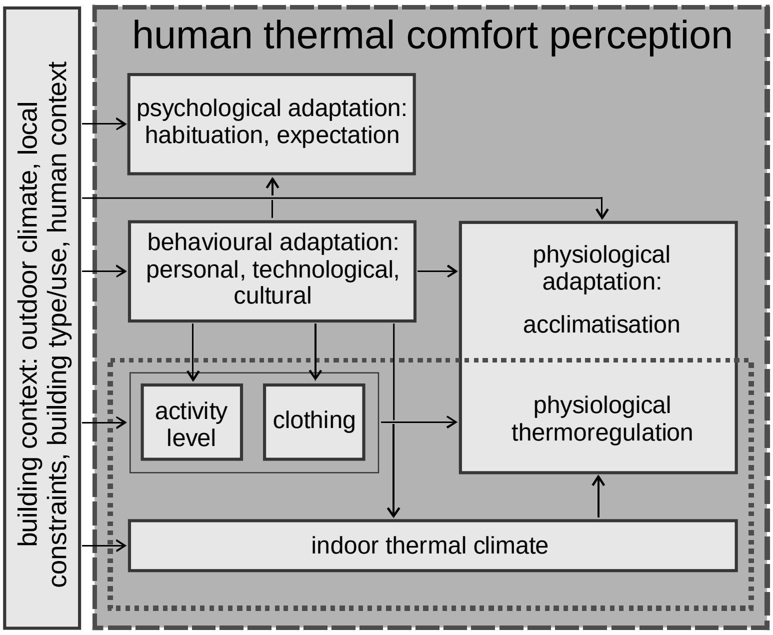

Figure 1: Integrated view on factors, mechanisms and main interrelations constituting human thermal comfort perception. Factors influencing the physiological adjustments by thermoregulation determine a human body's heat balance, and form the basis for thermal sensation models (dotted line rectangle). They are accomplished by behavioural adaptation, psychological adaptation and acclimatisation processes (as part of physiological adaptation) and describe together thermal comfort perception (dashed line rectangle) in dynamic environments.
This figure is a reprint from: Hellwig, R. T.et al. (2020c) and was published first In S. Roaf, F. Nicol, & W. Finlayson (Eds.), 11th Windsor Conference - Resilient Comfort, Proceedings, ISBN 978-1-9161876-3-4, pp. 529-545, Copyright (2020) with permission of the authors.

2.4. Effectiveness and application order of adaptive principles

While the overall effect of thermal adaptation has been shown and quantified in numerous research projects, a few studies tried to look at and compare the effectiveness of adaptive principles. According to a series of experimental studies, the largest effect has been assigned to clothing level adjustments (behavioural adaptation), followed by physiological adaptation especially on the warm side and psychological adaptation (Schweiker and Wagner, 2015).

Only recently, studies provided proof for a certain order in which adaptive responses are applied by humans (Figure 2). The first response is the vasomotor response (section 2.1) which is initiated autonomously by the human thermoregulation system. Behavioural actions (section 2.2) are initiated as second response, consciously and as a result of a discomfort signal coming from the skin (Romanovsky, 2014). Only if these responses are not sufficient to re-establish comfort, shivering or sweating are activated by the body autonomously. Nicol and Humphreys (1973) had supposed this order based on findings from Cabanac (1971). However, only recently Schlader et al. (2017) provided experimental proof for this. The success of the behavioural actions is confirmed by psycho-physiological signals based on the skin's sensing that the temperature has started to change in the desired direction, positive alliesthesia (Cabanac, 1996), which is an important feedback to confirm the perception of high personal control and relaxes comfort expectations (Hellwig, 2015). Acclimatisation occurs only after repeated exposure to temperatures different from previously prevailing temperatures and serves to optimise the body's effort for thermoregulation (section 2.1).

As such, this is again showing the importance to design buildings which afford sufficient individual control opportunities, which at the same time need to be easily understood and leading to a noticeable change of the thermal conditions – preferably towards comfortable conditions.

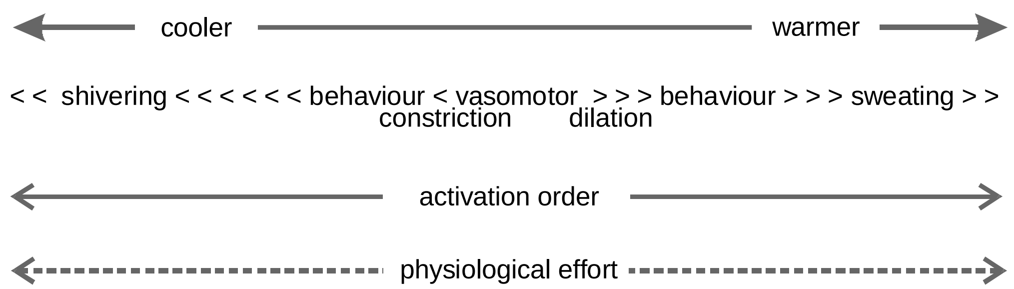

Figure 2: Hierarchy of activation of physiological autonomous (vasomotor, shivering, sweating) and behavioural body responses (simplified from Vargas and Schlader 2018, based on Schlader et al. 2017).
This figure is a reprint from: Hellwig, R. T.et al. (2020c) and was published first In S. Roaf, F. Nicol, & W. Finlayson (Eds.), 11th Windsor Conference - Resilient Comfort, Proceedings, ISBN 978-1-9161876-3-4, pp. 529-545, Copyright (2020) with permission of the authors.

2.5. From adaptive principles to adaptive models

Numerous field studies have been conducted in different locations and climates confirming the role of adaptive principles on human comfort (e.g. Nicol and Humphreys 1973, Auliciems 1981b, de Dear et al. 1997, McCartney and Nicol 2002, Manu et al. 2016). Based on the adaptive comfort approach, the comfort temperature of occupants who have opportunities to adapt to the thermal environment that they experience is primarily related to the outdoor climatic conditions (Humphreys, 1978). This relationship has formed the basis for the development of adaptive comfort models from field survey data. The developed regression models have the form: $T_c = aT_{rm} + c$, where T_c is the expected comfort temperature and T_{rm} is the running mean outdoor temperature. Two such models have been adopted in international standards, i.e. the adaptive model based on the European SCATs database (McCartney and Nicol, 2002) is included in EN 15251:2007 (CEN, 2007), its imminent successor EN 16798 (CEN, 2019) and ISO 17772-1 (ISO, 2017) and the model derived from ASHRAE RP 884 worldwide database (de Dear et al. 1997) is included in ASHRAE standard 55 (ASHRAE, 2017). Appendix 1 provides information on models used in international and national standards.

3. Benefits from applying the adaptive principles in buildings

Adaptive thermal comfort models predict human thermal adaptation to the outdoor climate as well as the indoor, which explains the tendency for indoor neutrality to change in harmony with the outdoor climate, and predict this relationship to be stronger in buildings where people are more connected to the natural swings of the outdoor climate. Designs that apply the adaptive comfort principles by leveraging on our ability to adapt to the outdoor climate result in more variable indoor temperatures, with the following benefits: reduce or avoid mechanical energy use, help mitigate climate change, increase thermal satisfaction of occupants, and improve occupants' health and well-being (Table 1).

Table 1. Benefits from applying the adaptive principles in buildings.

The first version of this table was published in: Hellwig, R. T.et al. (2020c) In: S. Roaf, F. Nicol, & W. Finlayson (Eds.), 11th Windsor Conference - Resilient Comfort, Proceedings, ISBN 978-1-9161876-3-4, pp. 529-545, Copyright (2020) with permission of the authors.

Adaptive performance aspect	Benefit
1. Wide and sloped comfort bands dependent on the prevailing local climate, enabling relaxed set points, and reflecting thermal preferences	***Energy savings*** - Avoid or reduce mechanical energy for thermal comfort
2. Systematic efforts to design and operate buildings consistent with the prevailing local climate, while empowering occupants to thermally adapt	***Resilience to climate change*** - of buildings and occupants: Adjust buildings to local climate and enhance their supportive thermal performance, enhance, rather than impair, physiological adaptation of occupants to the local climate
3. Designed, well implemented, and well-communicated adaptive opportunities and (objective and perceived) controls	***Usability and thermal satisfaction*** - Improved operation of the building according to the design intent, improved occupants' thermal satisfaction through increased perceived control
4. Designed and well implemented passively or low-energy actively regulated dynamic thermal environments that fluctuate within the adaptive comfort bands	***Health and well-being*** - Improved thermal satisfaction, improved well-being, thermal delight

1. *Energy savings* – Based on an extensive longitudinal field study on office buildings in Seoul, South Korea, Yun et al. (2016) found a statistically significant relationship between outdoor temperatures and optimum indoor comfort temperatures in mechanically cooled buildings, demonstrating the application of the adaptive comfort theory to mechanically conditioned buildings. A review by Yang et al. (2014) synthesizes evidence, from numerous mechanically cooled and heated case study buildings in varying climate zones, on cooling energy savings from setting a higher thermostat set point temperature in summer. In some of these case studies, the thermostat is set to vary according to a local adaptive comfort temperature. Furthermore, some case studies report peak-energy demand reductions. Based on a case

study building in Seville, Spain, Barbadilla-Martin et al. (2018) demonstrate an adaptive comfort algorithm that is effective for the optimization of HVAC systems in mixed-mode office buildings, making it possible to achieve energy savings without impairing the comfort of its occupants. Mixed-mode operation in India can lead to more energy-efficient operation (Gokarakonda et al., 2019).

2. *Resilience to climate change* – Thermally adaptive buildings are inherently more connected to outdoors. First, systematic design efforts to connect buildings to outdoors, lead to smooth building responses to climate variations, driven in part by humans, and decrease dependence on mechanical systems to attain acceptable indoor conditions for thermal comfort. Second, repeated occupants' exposures to thermal environments close to outdoors, leads to occupants having neutral temperatures closer to outdoors and being more tolerant to temperature swings (physiological thermal adaptation). A Post-Occupancy Evaluation (POE) by Deuble and de Dear (2014) of two office buildings of the University in Sydney, one operating with natural ventilation and the other with hybrid ventilation, revealed occupants of the naturally ventilated building were more tolerant with respect to their thermal environment, despite experiencing higher temperatures. The climate change benefit from applying thermal comfort principles in buildings is based on the principles of psychological and physiological adaptation. As represented by the adaptive principals (section 2), increased occupants' exposure to the prevailing outdoor climate or to indoor environments closely connected to outdoors, leads to occupants having neutral temperatures closer to temperatures in those environments, and being more tolerant to natural temperature swings. Physiological adaptation to the prevailing climate in turn leads to higher thermal resiliency, and higher probability that people will enjoy spending more time outdoors. By contrast, if a building is mechanically cooled within narrow temperature bands, occupants will physiologically adapt to it, and will likely want to remain in thermally conditioned spaces within the same narrow comfort bands in other places, such as their car or home. A review study by He et al. (2019) on the impacts of fan use in field studies on thermal comfort, energy conservation, and human productivity, indicates that fan use elevates the neutral temperature and the upper limit of the comfort zone (See also ASHRAE 2017) and reduces the use of air-mechanical conditioning in mixed-mode buildings in summer, while not interfering with occupants' productivity.
3. *Improved usability and thermal satisfaction* – Well-conceived and implemented adaptive opportunities and controls over the thermal environment result in a better use of building thermal environments by occupants and an increased occupant thermal satisfaction (section 4.3). A study by Paciuk (1990) showed that the degree of which employees perceive having control over the thermal conditions at their workspace greatly enhanced their satisfaction with the thermal environment. From a post-occupancy study in eleven buildings, Bordass et al. (1994) show positive relations between perceived control over heating and cooling, and favourable comfort rates. They further show that well designed, with higher perceived degrees of control, and properly managed buildings score higher in comfort and forgiveness with performance shortcomings. According to Bordass and Leaman (1997) "many building deliver less than they promise" (i.e. performance gap) because they appear to under-estimate or ignore physical and human interactions, and due to a lack of attention to detail for occupants'

requirements. From an extensive overview of field studies on human comfort, Mishra and Ramgopal (2013) conclude that buildings lacking adaptive opportunities tend to receive poor comfort ratings. They further conclude that when occupants are not able to exercise their adaptive options, they tend to use power intensive methods to maintain thermal comfort. A field study by Boestra (2016) revealed a positive significant association between perceived controls and comfort perception, as well as overall satisfaction with the indoor environment and self-assessed productivity. Yun (2018) studied perceived control and energy use in seven air-conditioned buildings with operable windows in South Korea. The study revealed a statistically significant relationship between perceived control and the thermal sensations of occupants, with a higher comfort temperature and cooler thermal sensation in summer for a group with high perceived-control, over a group with low perceived-control. In the same study, Yun use simulations to show increasing occupants' perceived control over the thermal environment results in cooling energy reductions without sacrificing comfort.

4. *Health and Well-being* – Indoor temperature fluctuations that are planned by design and operated accordingly, rather than by a malfunctioning or deficient building or HVAC result in more diverse indoor thermal environments that change with the prevailing climate, rather than promote thermal monotony. Ryan et al. (2014) provide review evidence on the positive effects of thermal and airflow variability on health and well-being in the built environment. Kingma (2011) points out that thermal environmental monotony is not necessarily healthy because it accustoms the body to little effort to regulate its temperature, with potential loss of regulatory capacity over time, which may have a causal relation to the development of obesity and pathologies related to obesity (see also section 2.1).

4. Implementing the adaptive principles

4.1. Framework

In order to create buildings based on the adaptive comfort concept, the adaptive principles need to be included in the various building project phases and become part of an integrated (holistic) design process (Hansen and Knudstrup, 2005). Figure 1 presents the framework which was developed to facilitate this process (Hellwig et al. 2019). It includes five main elements, which were identified as those most relevant to the adoption of the adaptive concept in buildings:

(i) the adaptive principles, as the fundamental theory to be implemented in the framework processes (Section 2)
(ii) the building context, which includes the relevant background information of the building in question that determines how adaptive principles apply in that specific case (section 4.2)
(iii) the adaptive responses/actions, which include the possible conscious and unconscious human reactions to different thermal stimuli (section 4.3)
(iv) the planning/design phase, which includes the building and building services design, as well as the design of adaptive opportunities (section 4.4)
(v) the operational planning/operation of the building, which specifies stakeholders' role in ensuring successful implementation of the intended adaptive opportunities (section 4.5.

Figure 3 shows the interlinkages between processes and the iterative nature of the approach, as a decision in one process influences the other. The framework is intended as a complementary process of an integrated building design approach and not as it's replacement. It does not include all necessary design criteria for a holistic design, but focuses on the integration of adaptive principles in the process.

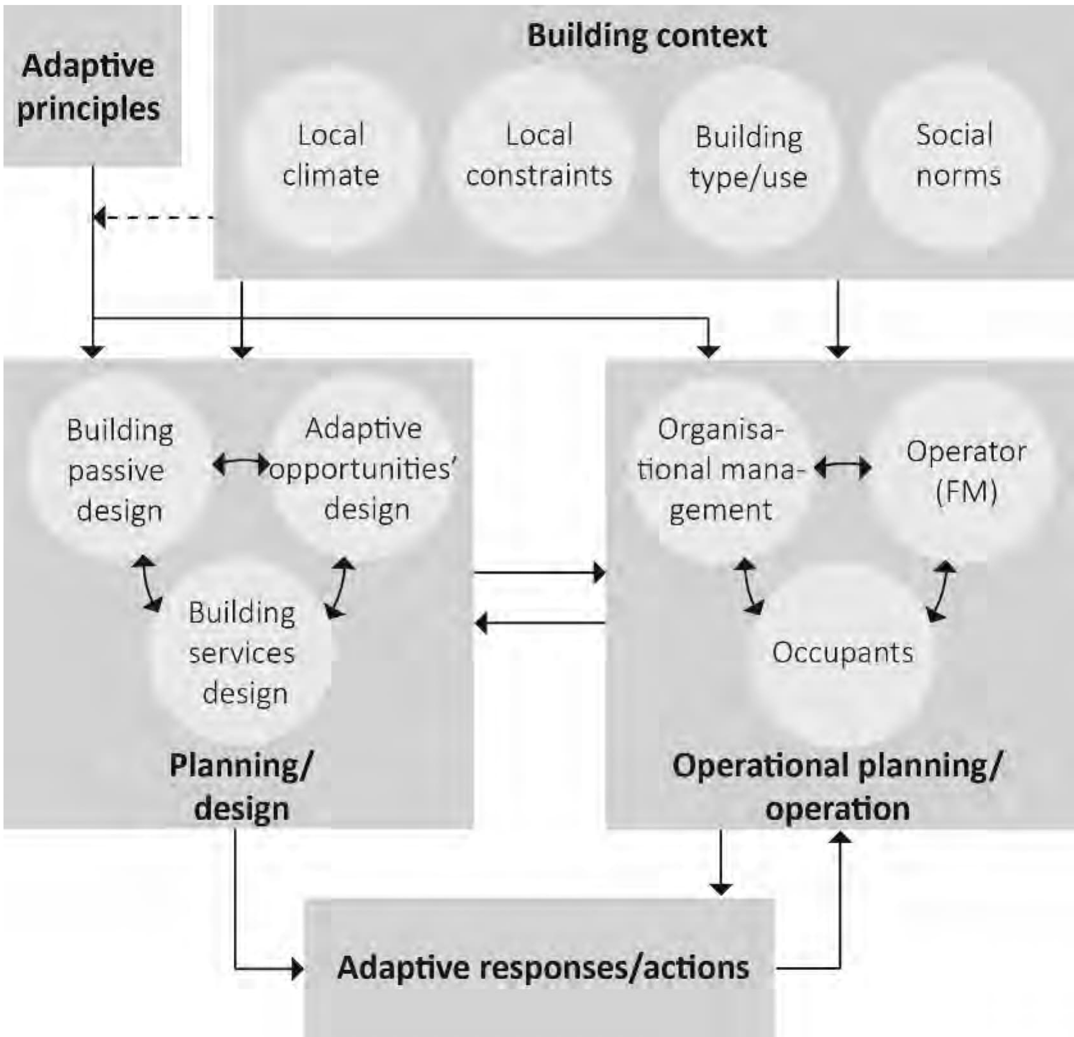

Figure 3: Framework for adopting the adaptive principles in planning and operation of buildings. Reprinted from Energy and Buildings, 205/109476, Hellwig, RT; Teli, D.; Schweiker, M; Choi, JH; Lee, MCJ; Mora, R; Rawal, R; Wang, Z; Al-Atrash, A, (2019), A Framework for Adopting Adaptive Thermal Comfort Principles in Design and Operation of Buildings, Copyright (2019), with permission from Elsevier.

4.2. Building context

The building context is introduced as a set of variables setting the frame for what should be designed. These variables include the local climate, local constraints, building type and use and the human context/social norms. This background information helps to identify the potential of adaptive principles in a specific design case and decide the ways to apply them to a specific building. In this way, building context acts as a moderator between the adaptive principles and the building and operational design. For example, occupants in a warm climate are expected to have become more tolerant to warm indoor conditions (compared to occupants in a cold climate), due to their adaptation to warm climatic context. Such information on the application of the adaptive principles in a specific context can then feed into the building's design and operational planning.

Local climate

The local outdoor climate is the main driver of human adaptation in free-running buildings, where the indoor climate changes with the outdoor climate. The indoor comfort temperature of occupants in such buildings is therefore related to the outdoor temperature they experience (Humphreys, 1978). For example, people who live in cold climates feel comfortable at cooler temperatures compared to people from warm/hot climates (Humphreys and Nicol 1998; van Hoof 2008; Brager and de Dear 1998). People may also have different levels of tolerance to cold or warm indoor conditions depending on their exposure to such conditions in their climate zone. This effect is partly due to physiological adaptation after long-term exposure to non-neutral thermal environments.

Similarly, seasonal changes influence human thermal response as they give people time to adapt to changes in their thermal environment. Research has shown that people’s comfort temperature varies across seasons; e.g. it was higher in summer and spring compared to winter (Wang et al. 2010; 2014). People have also been found to be more tolerant to the cold environment in winter and more tolerant to the hot environment in the summer (Cao et al. 2011). Analysis of thermal comfort studies has shown that within a population seasonal drifts of up to 7 to 8 Kelvin in the indoor temperature can be accepted by people (Humphreys et al., 2016). This means that the indoor temperature doesn’t have to be stable throughout the year but could vary by up to 8 degrees between seasons, depending on the local climate.

Apart from the local outdoor climate, the local indoor climate the occupants typically experience also influences their adaptability. A strong relationship has been found between mean indoor temperature experienced and people’s comfort temperature (Humphreys, 1976; Auliciems 1981a, Ning et al. 2016). This means that people’s comfort temperature adapts to the environment they typically experience. As an example, occupants who lived in unheated homes in the South-east China were found to be more tolerant to cooler indoor thermal conditions than occupants who lived in homes with central heating systems in the North part of China (Li et al. 2018). Occupants who had been exposed to very stable and warm thermal environments in UK social housing apartments were found adapted to these warm conditions (Teli et al., 2016). Sensitivity to temperature variations of subjects in another study was found to be higher at the early heating phase, which gradually changed during the winter season as they adapted to their heated indoor environment (Wang et al. 2018).

It becomes clear that thermal experience in different outdoor and indoor climates affects people's adaptation, which leads to different temperature preferences. Therefore, the local outdoor climate, its seasonal course and the typical indoor climate the occupants experience need to be considered in the building’s design and operational phase. As a guide, adaptive comfort models developed for different climate zones can be used (e.g. Manu et al. 2016, Toe 2018, see examples in Appendix 1).

The characteristics of the outdoor climate and the typical indoor climate in the location in question are parameters for consideration in the design phase, defining people’s adaptation. For example, if the typical indoor climate experienced is centrally controlled and stable throughout the year (e.g. year-round AC), occupants need to be familiarised with the adaptive nature of the new building and their role in achieving comfortable conditions, for example by adaptive opportunities (section 4.3). Operational planning will need to account for ways to ease occupants to more variable indoor conditions. On the other hand, if the dominant indoor climate control practice in the location in question is 'free-running', then application of adaptive principles in the operation of the building will be more straightforward to the occupants.

Local constraints

Local constraints are factors that can limit the opportunities for a functioning adaptive design. Most constraints listed below are related to the potential of window opening. Although challenging to address, there are still ways to overcome- at least partly- and apply the adaptive principles.

Outdoor air pollution and noise. In certain highly polluted and busy urban areas window opening is not considered a viable option, for health and comfort reasons. Although it may be more challenging, it is still possible to plan and design for window opening by considering alternative building and layout configurations. The main source of air pollutions and noise in urban areas is vehicular traffic. Building design should therefore aim to exploit parts of the building away from the source. For example, the courtyard side of the building can be prioritised for window opening in many rooms, e.g. bedrooms, living rooms. Other adaptive actions may be also promoted through the building's design. More details on the design of adaptive opportunities are included in section 4.3.

Urban heat island effect (UHI). Similar to air pollution and noise, the UHI is limiting the potential of natural ventilation. However, the extent to which UHI makes window opening completely ineffective in a certain location should be investigated on a case-by-case basis. For example, it is possible that natural ventilation is not effective due to UHI for parts of the day/year or in specific cases due to the waste heat released by air-conditioners when in use. As above, thoughtful building design should be applied, as well as measures to counteract the UHI effect, e.g. vegetation.

Disease transmitting insects. In certain locations, window opening may be constrained by the presence of insects. In such cases, insect screens/nets may be considered in the design phase, accounting for their impact on ventilation rates.

Security issues. This constraint is particularly relevant to ground floor level spaces. Possible solutions include window restrictors or the use of window types with limited opening, e.g. "tilt and turn" (hopper), "top-hung" etc.

Building planning requirements. Requirements regarding the indoor environment and other building planning aspects e.g. fire safety, may pose challenges in designing based on the adaptive principles. There are different strategies around the world and solutions depending on building size, space and unit size, which need to be considered on a case-by-case basis.

Cultural custom (e.g. dress code). Clothing adjustment is the easiest and fastest way to improve comfort. Adaptation to local clothing habits means that one has a certain variation available due to specific fabrics and clothing combinations used in the location in question. In addition, it is not always possible to use clothing adjustment in its full potential due to dress code restrictions. It is recommended to relax dress code requirements whenever possible.

Space scarcity in highly populated areas. There may be limiting opportunities to design for natural ventilation in dense areas.

Real Estate Company planning. Applying adaptive principles successfully in a building requires the involvement of building occupants as early as in the planning phase. However, this is more difficult to implement when tenants are unknown, e.g. in buildings built on the real estate market. In such cases, the use of 'sample occupants' during the design phase would help to account for the variety of possible occupant types in the planned building. Communication to the occupants of the design intentions related to the building usage and operation can be done in retrospect, e.g. with the use of digital "manuals" made available to occupants straight after building occupation. This approach would not even require the involvement of the real estate owner. The lack of occupant involvement in such building projects would overall require a stronger effort to be placed in the operational phase of the building, together with fine-tuning of the building systems.

Attitudes. There are individual differences in attitudes, and some attitudes are not conducive to adaptive buildings while others are. For example, occupants in green buildings with a stronger environmental concern are more likely to accept conditions that deviate from their "ideal" than occupants who do not share the same environmental concern (Leaman and Bordass 2007; Deuble and de Dear 2012b). Personality, openness to receive information on the building and proactivity in taking action to achieve comfort are different between persons, with varying expectations several factors, such as culture, learnt attitude, habit, or lack of adaptation to the outdoor and indoor climate. In such cases, operational planning and operation should introduce communication mechanisms to inform about the buildings' adaptive design principles, e.g. by highlighting the benefits of thermal adaptation (see section 3) and provide checklists for the different responsibilities of the relevant stakeholders.

Technological challenges. Fixed preferences and persistence with certain technological solutions lead to limited design alternatives which often exclude adaptation. Other technological challenges relate to the way systems are traditionally operated, e.g. typical air-conditioning set-point control based on air-temperature.

Building type and use

The building type does influence occupant's behavioural actions to adapt to their thermal environment. This fundamental mechanism can be adopted as design and environmental design and control principles. In addition, different building types have different context in terms of opportunities for adaptation, social context and interaction, expectation of indoor climate control. For example, public buildings, offices and homes provide different degrees of privacy and opportunity for adaptation. Homes in particular provide a high degree of freedom to occupants, which is conducive to the application of the adaptive approach. As compared to public buildings, offices and facilities, where work productivity and environmental health are more highlighted, adopt numerous opportunities to apply the adaptive approaches to create comfortable conditions. Individual controllability features are well applied in design, i.e., a layout of the workplace.

As such, depending on building typologies, the impacts of comfort temperature controls vary, but are consistently critical to enhancing physiological and environmental benefits at the same time. There may be limited options available in the implementation strategies per building type, but those potentials are high with the help of modern design strategies and advanced technologies for personal environmental controls (section 4.3).

Human context/ Social norms

The human context including social norms is a potential source for significant barriers when applying adaptive principles during the operation of buildings. Therefore, such barriers or constraints need to be envisaged during the design stage. The following three aspects need to be considered with this respect:

Dress codes. Clothing level adjustments are an essential part of thermal adaptation and enable individual modulation of the objective and perceived thermal strain (Morgan and de Dear, 2003; Schiavon and Lee, 2013; Schweiker and Wagner 2017). Dress codes as part of the organizational culture, e.g. the requirement of a suit with tie often found in bank offices and beyond, will largely reduce the behavioural adaptive potential in clothing level adjustments. At the same time, acceptable clothing assemblies are based on societal agreements, e.g. related to the acceptance of men wearing short trousers at work. Organisational measures together with societal discussions related to the need of such dress codes are required to overcome these barriers. Such approach was implemented in Japan with the Cool Biz campaign, suggesting office workers to loosen their dress code in order to be able to feel comfortable with an increased cooling set-point of 28^{o}C. Considering the Japanese social environment, where a typical formal suit is almost required as a dress code in every office workplace, “Cool Biz” allowing wearing sportswear outfits and T-shirts, as well as sandals in such a conventional building type, was a drastic campaign. Such practical advice to occupants and building managers on how to deal with thermal discomfort through clothing and other adjustments would be helpful and can be supported with guidelines, e.g. the guide “How to manage overheating in buildings: a practical guide to improve summertime comfort in buildings” by CIBSE in the UK (CIBSE, 2010).

Shared controls. When controls are shared between individuals, this reduces individual control opportunities and either leads to few dominating “controllers” or requires a consensus among all regarding the chosen state. Related phenomena are known as “temperature wars” or “thermostat wars[1]". A reduction in perceived control leads to a lower thermal and overall satisfaction (Brager et al. 2004; Boerstra et al. 2012; Hellwig, 2015; Schweiker and Wagner 2016), requires tighter temperature bands to satisfy the majority, and leads to an increased energy use for the provision of such tight temperature bands (Hoyt et al. 2015). In addition, shared controls, for example for a joint ceiling fan or window may decrease the amount of usage, because of few individuals opposing to their usage and reducing the behavioural adaptive opportunity for all sharing such control (Schweiker and Wagner, 2016). Politeness of some occupants on one hand and increased power of other occupants on the other hand may lead to diminished perceived availability of adaptive controls. Therefore, the provision of individual control is suggested where possible. Such individual control is preferably provided by means of highly energy efficient personal comfort systems (Rawal et al. 2020) and in case such provisions are not possible, by majority driven aspects using contemporary learning algorithms (e.g. comfy[2], Aguilera et al. 2019) (see also section 4.3).

4.3. Adaptive responses and actions

Fundamental to the adaptive approach is the role of the occupant: "If a change occurs that produces discomfort, people tend to act to restore their comfort." (Humphreys and Nicol 2018). Auliciems (1981b) called this behavioural and techno-cultural adjustments. For the means people use to restore their comfort the word "adaptive opportunity" was introduced by Baker and Standeven (1997). Another term, more often used nowadays is "indoor environmental affordances". Besides the work in this IEA EBC Annex 69, recent activities on international level, e.g. IEA EBC Annex 66 (2019) and IEA EBC Annex 79 (2019) point to the importance of this topic.

The state of the art on occupant behaviour and control perception has been summarised in reviews (Ackerly et al. 2011, Hellwig 2015, Schweiker et al. 2018a,b). Many studies show that the feeling of thermal comfort is correlated with having control over one's indoor environment, e.g. operable windows near the workplace (e.g. Leaman and Bordass 2006, Hellwig, 2005, Choi et al. 2012, Schweiker et al. 2016). Absence of or low personal control can even lead to the sick building syndrome (Bischof et al. 2003, Marmot et al. 2006). Hellwig (2015) integrated the main factors determining the level of personal control perceived by people into a conceptual model (Figure 4). Besides the current physiological and psychological state of a person, are these main factors: Availability, effectivity and responsiveness of control opportunities, both depending on the building's passive design and the building services design but also on the social environment (human context), the occupant's knowledge of the building and its technical systems, their previous experience (e.g. success or failure in previous behavioural control actions in the actual

[1] https://www.businessnewsdaily.com/10964-office-temperature-debate.html; retrieved 25/2/2020

[2] Comfy. ComfyApp. Retrieved May 5, 2018, from https://www.comfyapp.com/, retrieved 25/2/2020

or other buildings), a person’s personality including their indoor environmental related locus of control (control expectation) and indoor environmental related self-efficacy (addressing competences or skills), their expectations, value system and actual preferences.

The occupants’ feeling whether there are adaptive opportunities available to them is driven by social norms, expectation (e.g. Fountain et al., 1996; Brager and de Dear, 2003, Xu et al. 2020). When a building’s design or operation with regard to personal control does not meet an occupant’s expectation, he/she might complain (Bischof et al. 2002). Although probably rooted in the lack of control, these complaints might not address the degree of personal control but instead the indoor climate, i.e. the temperature or the indoor air quality. In order to avoid later disappointment or complaints, giving the occupants sufficient information about the building’s functioning helps the occupants developing realistic expectations which are consistent with the performance of the building after the building is commissioned (Usable Buildings, 2020).

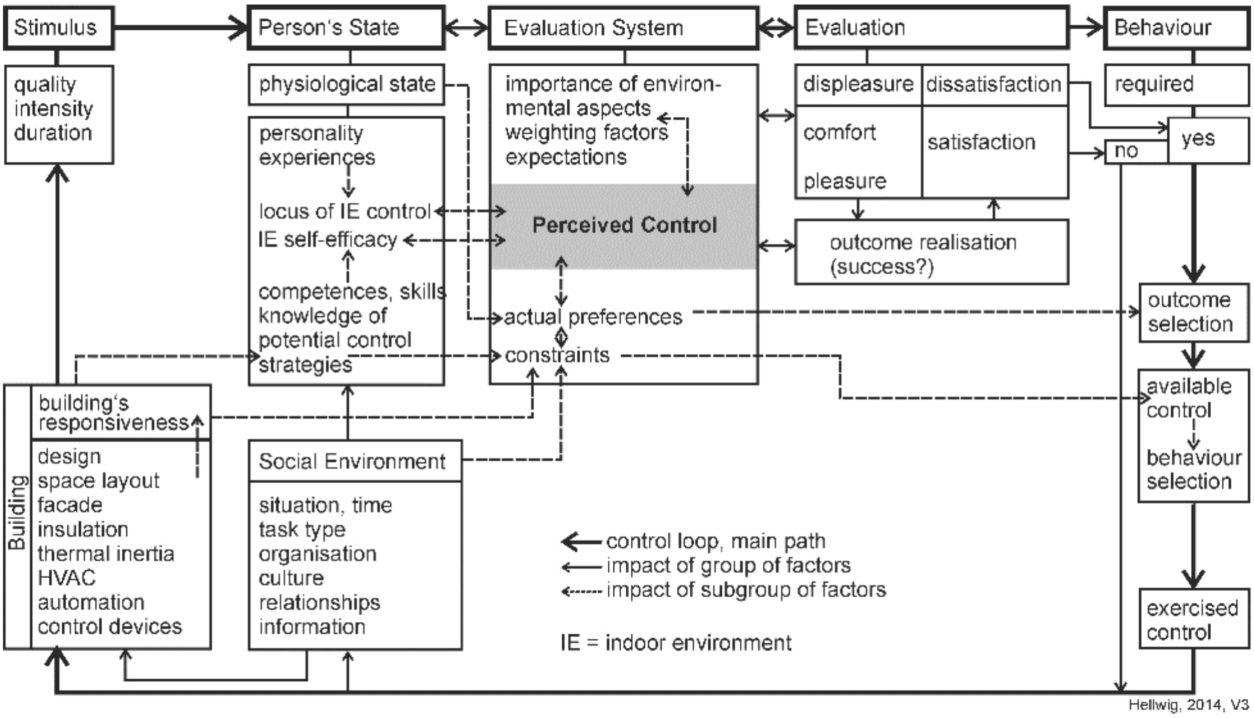

Figure 4: Conceptual model of perceived control, *reprinted from Hellwig, RT (2015): Perceived control in indoor environment: a conceptual approach. Building research and information, 43(3),302-315, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com, Nb.4785810412877).*

Conformity to expectations, which describes the degree of conformity between desired and perceived availability of controls was shown to influence the level of personal control perceived (Al-Atrash et al. 2018). Such a situation might occur when a higher number of persons share the same room and occupants’ satisfaction decreases, rooted in a lower degree of perceived control and higher social interactions necessary (Hedge et al., 1989; Duval, Charles and Veitch, 2002; Marquardt, Veitch and Charles, 2002; Wagner and Schakib-Ekbatan, 2011; Al-Atrash 2018). Available adaptive opportunities on room level like ceiling fans and blinds are used less often in shared offices compared to single person offices. Instead more personal level adjustments through changing of clothing are applied (Schweiker and Wagner 2016). Therefore, designing for appropriate personal control in open-plan offices is challenging due to a generally diminished perception of privacy. This effect can be diminished if occupants can call the facility management which solves the problem quickly (Leaman and Bordass 2006).

Control actions' feedback (outcome realisation, Figure 4) is a psycho-physiological signal sensed by the skin on whether a change in the desired direction was initiated by one's action (Cabanac, 1996). It confirms the perception of high personal control, enhances indoor environmental self-efficacy and control expectation and relaxes comfort expectations (Hellwig, 2015). In so far, high perceived control is necessary for high occupant satisfaction in all conditioning modes.

Behavioural actions might not only help to adapt to a stimulus but also to remove this stimulus, e.g. by using technological means: If the technology used has enough heating/cooling capacity to fully remove or avoid the thermal stimulus physiological adaptation (acclimatisation) to the deviating conditions will not take place (Hellwig 2018). In order to avoid this, energy efficient solutions can be chosen after the building's passive design is optimised in a way that avoids fast changes of the indoor environment under changing outdoor weather conditions (e.g. solar radiation). Provided the occupants are conscious about the "green" performance of their building and understand its importance, the controls are usable and they received factual information on how to make use of certain technological means to adapt, they will be able to use their building in the intended way (Leaman and Bordass 2007; Deuble and de Dear 2012b, Usable Buildings 2020).

Automated control on room level is as such seen as being ambivalent with regard to energy, health and occupants' desire for control (Hellwig et al. 2020a). However, although Building automation systems, IoT and smart solutions allow for usable occupant solutions, planning practice needs to adopt knowledge on personal control and guidance how to implement appropriate personal control options in design and operation (section 4.4).

The factors identified indicate in which manifold way perception of personal control is influenced. At the same time, the identified influencing factors can be used for pro-actively developing design and operation strategies. In order to come to a design proposal and to define how adaptive actions translate into design and operation opportunities a catalogue of conceivable adaptive action is needed. In our framework (Hellwig et al. 2019) we have compiled a collection of conceivable adaptive actions structured according to the following categories:

i) regulation of body internal heat generation,
ii) regulation of the rate of body heat loss,
iii) regulation of the thermal environment,
iv) selection of a different thermal environment, and
v) modification of one's psychological perception.

These five different categories require several main stakeholders' action in the planning and operation of e.g. office buildings: the owner/investor, the building planner, the facility manager, the company manager and the occupant. Table 2 developed in Hellwig et al. (2019) presents an extended collection of adaptive actions sorted according to their effect principles.

Regulation of body internal heat generation**:** it addresses mainly the building occupant as e.g. the fine-tuning of the amount of food and hot or cool drinks consumed. But, it addresses also the company manager to allow for changing or shifting certain activities (Gauthier 2016), if the thermal environment requires this (siesta) or to offer hot or cool beverages.

Regulation of the rate of body heat loss**:** This includes taking on actions like adjusting clothing, selecting clothing material and drinking enough, which are the occupant's responsibility, as well as using a fan. However, the management of a company sets the norms in a working environment, e.g. dress-code which may not allow clothing adjustments or different fabrics used. Since individual adaptive opportunities in open-plan offices are limited, relaxing the dress-code is very important for providing at least this adaptation option to the occupants. As described above, appropriate beverages/ hot drinks offered by the management or allowing the use of desk fans supports that these adaptive actions can be exerted. A management could also offer a variety of office chairs, which have not only different colours or sitting ergonomics but e.g. diverging insulation levels the occupants can choose from.

Regulation of the thermal environment**:** There are too many adaptive opportunities related to the regulation of the thermal environment to mention them all here. Therefore, we mention first the most typical and successful adaptive opportunity: openable windows. Accessible windows, suitable opening types, appropriate size of openable window parts and the perception of occupants that it is OK to use windows are important aspects. Strategies such as night time ventilation require not only the appropriate window design (adjustable opening width, automated control, burglar- and weather-proof design) but it also require that the facility management follows up on the suitability of the control settings and maintenance. The possibility to have still manually openable windows in addition to the automated parts will be conducive to acceptance of automation. An adaptive opportunity to regulate the thermal environment could also be, e.g. in a heat wave, to switch off all heat emitting equipment, which is not needed – this addresses operation, but has a relevance for planning, too: offering centralised printers instead of many decentralised ones requires special printer rooms. Buildings with large open-plan offices cannot provide access to windows for every occupant, which tends to preclude the use of natural ventilation. The large depth of layout plans typically means that heating or cooling is provided by mechanical ventilation, which provides less individual control of the space (Hellwig, 2015). A movable outer shading device in a generally windy area is very restricted regarding its operation time – it might be better to adjust the size of the glazing and combine it with an internal shading device in order to control the amount of sun entering the room. In some regions with high rainfall and humidity, it might even be difficult to have movable outer shading devices for maintenance reasons. In such cases, the passive building design should provide enough self-shading in the façade to compensate for this.

For the *design and operation* of adaptive opportunities, Bordass and Leaman (1997) identified an important capability of adaptive opportunities: the *speed of response*. This means how fast an occupant can feel a change after exerting control (sensed via the skin temperature, see section 2.1). It e.g. includes the response time from the facility management. A short response time gives an immediate (positive) feedback to an occupant and supports his belief that he or she is capable to exert control (increasing indoor environmental self-efficacy as explained in Hellwig, 2015). An example for an ineffective adaptive opportunity could be an openable window that has an insufficient size or unsuitable positioning, so that the air movement or air exchange desired by the occupant is not achieved. This would be an insufficient response to an occupant's need. For controls like thermostats, light switches, shading device switches etc. Bordass et al. (2007) evaluated criteria for usability. These are:

i) clarity of purpose,
ii) intuitive switching,
iii) labelling and annotation,
iv) ease of use,
v) indication of system response/feedback,
vi) degree of fine control.

Placement of such controls should be close to application and close to the desks. For switching off when leaving a space and for switching on when entering, controls should be placed close to the door. Generally, systems meant for occupant interaction should be switched on manually. Switching off can be manual or automatic. Standby settings should be low-energy defaults. They also provide guidance on iconography used and checklists for building designers, control installers and facility managers.

Selection of a different thermal environment: Outdoor places around a building with a certain degree of shelter as e.g. wind protection, shaded places under trees or a building (Figure 5), a sheltered walkway between buildings or non-conditioned indoor transition spaces as e.g. atria would provide the occupants with a short-term exposure to conditions outside thermal neutrality and potential for slow physiological adaptation. They may also serve as places to meet or work (Roetzel et al. 2020).

Figure 5: Outdoor meeting space at a permanently shaded spot integrated on the north side of the Net Zero Energy Building at CEPT University, Ahmedabad, India, semi-arid climate, see Appendix 3, building 05, Photo: copyright Rajan Rawal, CEPT University, India

Investigations have shown that transition from one temperature zone to another zone can elicit positive thermal perceptions (alliesthesia) and can affect the comfort perception after such an experience in a positive way (Parkinson et al. 2016, Ji et al. 2017). Therefore, a building planner may establish different temperature zones in the building’s floor plan and assign different conditioning concepts to these zones. There could be options for spatial temperature differences between workplaces (e.g. different access to the sun). This would require a certain degree of freedom in choosing the individual workplace, which must be facilitated by the company management. Even in cases where a work task does not permit to loosen thermal control at certain workplaces, transitional spaces or other areas with short-term stays such as tea kitchens or printer rooms may offer the opportunity to be less conditioned. This would not just be beneficial for the occupants but contributes also to energy conservation in buildings. The facility management, the company management and the occupants need to know about this design intent, as otherwise the operation of these zones might not work as intended (open doors to conditioned zones, overridden temperature settings, retrofitting of equipment instead). Furthermore, the company culture needs to support having meetings outside, walks and social interaction while having a tea.

Modification of one’s psychological perception: A company’s management should promote and enable a positive psychological perception of the (thermal) environment (Leaman and Bordass, 2007; Deuble and de Dear 2012b). Being supportive of meeting colleagues and have a warm or cool beverage together, provided from the company (Hellwig and Bux 2013, CIBSE 2010) as well as a positive engagement of the company managers with the adaptive concept of the building will affect the occupants’ own perception. If the facility manager receives feedback from the occupants and treats it as feedback instead of complaint, takes it seriously and solves the issue, this will help to provide trust of the occupants in their building (see above about response time) and help to relax their attitude to the indoor environment. Generally, information given to the occupants about the intended functioning of the building and how they can contribute informs them about the design intend and supports them in relaxing and developing trust in the building as well as it helps engaging them in the operation process (section 4.5).

Adaptive opportunities and the related controls should be part of the design intent (section 4.4, Adaptive opportunities design) and therefore documented in the design brief to be able to further communicate the intent during the next phases to the relevant stakeholders: owner, organisational management, suppliers, control installers, facility management and occupants.

To summarise from the above: there is a large potential for behavioural thermoregulatory actions, which employ no operational energy or have a low energy use. Building context and what people are used to (e.g. the most liked adaptive opportunities, Leaman, 2002) determine the adaptive opportunities feasible. Since behavioural thermoregulation is deeply embedded in human thermoregulation and comes natural to people, it comes with the advantage of occupant satisfaction and engagement. There are no excuses for not designing and operating for adaptive opportunities. Constraints may exist, but they might exclude the use of adaptive opportunities only temporarily.

Table 2. Conceivable adaptive actions or responses (adaptive opportunities) to warmer or cooler than previously experienced environments; adopted from Humphreys and Nicol, 1998; Nicol and Humphreys, 2018, Schweiker et al. 2016; Taylor 2014, van Marken Lichtenbelt et al. 2014, further inspiration from R.F. Rupp and N. Brito* and adjusted, re-arranged and amended by the authors. Adaptive actions are seen as predominantly conscious behaviour; adaptive responses (*in italic letters*) are seen as predominantly autonomous, unconscious physiological reactions of the body

categories of adaptive actions or *responses*	**adaptive actions/ *responses* to cooler than previously experienced environment**	**adaptive actions/ *responses* to warmer than previously experienced environment**
regulating the rate of internal heat generation	- increasing the level of activity - relaxing, exposing oneself *to become acclimatised (non-shivering thermogenesis)* - eating a high-caloric or hot meal - increasing muscle tension - drinking a warm beverage - rubbing hands - *shivering thermogenesis (quite extreme and not conceivable)*	- reducing the level of activity - relaxing, slowing down one's life - relaxing, exposing oneself *to become acclimatised (reduced internal heat production, earlier on-set of vasodilation)* - adopting siesta-routine (matching level of activity to diurnal temperature course) - eating less or low caloric food - having cold food
regulating the rate of body heat loss	- *vasoconstriction* - adding clothing or blankets - curling up or cuddling up - selecting different clothing material - closing doors and windows (reducing air movement) - exposing oneself to the sun - sitting close to a heat source (masonry heater, fire, radiator) - relaxing, exposing oneself *to become acclimatised* - having a warm bath or shower - sleeping in family group with the bodies pushed up against each other	- *vasodilation* - taking off some clothing - adopting an open posture - opening a window for getting a breeze - leaning against a cool wall (high thermal inertia) - sitting on a stone bench in the shadow - *sweating* - relaxing, exposing oneself *to become acclimatised (increased sweat rate, redistribution of sweat, lowered sweat on-set temperature)* - drinking more (stay hydrated) - drinking a cup of tea (induces sweating more than compensating for its heat) - drinking cold beverages - using a hand fan - having a cool shower (water at room temperature) - having a bath in the sea or a lake

regulating the thermal environment	- insulating the loft or wall cavities (long-term effect) - improving the windows and doors (long-term effect) - closing windows or doors - letting the sun enter indoors - adjusting or turning the thermostat on or lighting a fire - notifying the facility management	- opening a window - switching off heat emitting equipment not needed - activating shading in front of a window - using night time ventilation - adding shading for walls - wetting the floor - ventilating the attic space - switching on a fan - adjusting thermostat or turning on the air-conditioner - notifying the facility management
selecting a different thermal environment	- finding a warmer spot in the house or going to bed - visiting a friend or going to the library - building a better house (long-term way of finding a warmer spot) - emigrating	- finding a cool spot in the house - sitting under a tree - going for a swim - sleeping outdoors under clear sky e.g. on the roof top - sleeping in the basement - visiting a friend or a shopping centre (hoping for a cooler temperature) - building a better house, e.g. making use of thermal mass or an appropriate window to wall ratio (long-term way of finding a cooler spot) - emigrating
modifying one's psychological perception	- letting the mind adjust so that it becomes used to cooler environments - holding a warm cup of tea *(alliesthesia)*	- letting the mind adjust so that it becomes used to warmer environments

4.4. Planning and design phase

The planning/design phase within the framework includes three interrelated processes, i.e. building passive design, adaptive opportunities' design and building services design (Figure 3, section 4.1).Passive design refers to methods for filtering and moderating weather variability and should be prioritised. Building services design then supplements or enhances the building's passive design if required, with the use of active systems, such as fans and other mechanical systems. The design of adaptive opportunities should take place in parallel to ensure that occupants are able to control their indoor environment. The effectiveness of the adaptive opportunities depends on the building's passive and active design and vice versa. Passive and active design should ensure that an intended adaptive opportunity is made available to the occupants and is perceived as such. The outlined design process is iterative, with every design decision affecting the others.

Building passive design

Passive design strategies aim to maximize the benefit of the outdoor climate for the heating, cooling, ventilation and lighting needs of the building occupants, as well as to moderate its variability whenever necessary. The most important aspects of passive design are summarised below, but readers are referred to dedicated literature on passive design for further details (e.g. Olgay 1963, Santamouris and Asimakopoulos, 1996, Givoni 1998, Hyde 2000, Heywood 2012, Zhai and Previtali, 2010; Kwok and Grondzik 2018, Manu et al. 2019, Manzano-Agugliaro et al. 2015, Cook et al. 2020)

Orientation: Building orientation is a key parameter of passive design strategies that can help minimize active heating and cooling demand. Various approaches depend on the optimum orientation of the building with respect to solar radiation and wind. The integration of active systems also requires appropriate orientation. A suitable orientation of buildings depends on the local climate.

Form: Building shape, form, layout, location of the different functions and façade design determine the building's energy use, the level of comfort achieved, potential for passive cooling, daylight etc. Compact buildings tend to be more efficient in cold climates, as the greater the surface area of the building the more energy is needed to offset the heat losses. However, application of compactness may be chosen with care with regard to climate change scenarios.

Openings: The area of openings affects the amount of solar gains and daylight as well as the effectiveness of natural ventilation.

Shading: Shading is an important design tool for controlling the solar and wind impacts. The sun's path should be taken into consideration to block excess solar radiation in summer and allow it in winter.

Natural ventilation: Natural ventilation refers to the controlled flow of air through different openings (windows, doors, etc.) caused by temperature and wind pressure difference (e.g. Cook et al. 2020).

Hybrid ventilation is an approach which allows to use the advantages of both natural forces and mechanical systems depending on outdoor conditions (Heiselberg, 2002), and is an approach to be found in mixed mode buildings (section 4.5/operation). Providing the occupants with a high level of personal control of properly designed operable windows for natural ventilation and connection to outdoors is key in designing for adaptation. However, it is challenging to implement natural ventilation when the outdoor air is polluted or could cause mist or condensation (Smith and Parmenter, 2016). Such constraints and ways to address them are discussed in section 4.2.

Outdoor spaces: In warm climates, taking advantage of courtyards for passive design is recommended. Shaded courtyards are a good strategy for natural ventilation in summer and for offering spot with diverse thermal conditions.

Building envelope: The building envelope properties should be determined based on the local climate and context. Appropriate insulation can reduce heat losses or gains, while minimising discomfort due to radiant effects (warm/cool surfaces). Building envelope design includes also consideration of airtightness, thermal bridges and appropriate properties of the facade openings.

Vegetation: Green infrastructure contributes to energy use reduction in buildings, increasing the possibilities for free running and mixed-mode operation of buildings, especially in tropical and subtropical climates (Emmanuel et al., 2016).

The potential of a building for free-running operation depends on the combined effect of the implemented passive design strategies and the level of personal control available to the occupants. For example, it is possible to implement natural ventilation in open plan offices, even though individual access to windows might be difficult.

Building thermal inertia: People's clothing adaptation to short-term weather changes has a time-lag of approximately one week (Humphreys 1973, Humphreys and Nicol, 1998) while physiological acclimatisation to sudden changes, such as heat waves, has a time lag of up to two weeks (Taylor, 2014). Therefore, buildings built in accordance with the adaptive principles should provide sufficient buffer for the adaptation of occupants (Hellwig 2018). A building's ability to buffer, hence its thermal mass (Henze et al. 2007) is strongly related to the predictability and reliability of the thermal behaviour of a building, which is an important building property for occupants (Bordass and Leaman 1997) and therefore contributes to the level of control perceived by occupants (Hellwig, 2015).

A successful building design which aims to incorporate the adaptive comfort principles should optimise the use of the building's passive potential. The building should facilitate people's thermal adaptation to changes in outdoor weather conditions, and therefore should be designed in a way that: a) provides sufficient capacity for the regulation of the indoor environment within the building envelope, and b) provide adequate technological opportunities to improve the thermal environment in case what is stated in a) is not adequate.

Adaptive opportunities design

The terms adaptive opportunities, adaptive controls, behaviour opportunities, indoor environmental affordances describe all the means by which occupants can exert behavioural actions as described in section 4.3.

The following paragraphs are reprinted from section 3 in: Hellwig, R. T. et al. (2020c). Guidelines to bridge the gap between adaptive thermal comfort theory and building design and operation practice. In S. Roaf, F. Nicol, & W. Finlayson (Eds.), 11th Windsor Conference - Resilient Comfort, Proceedings, ISBN 978-1-9161876-3-4, pp. 529-545, Copyright (2020) with permission of the authors.

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The adaptive responses and actions of humans are defined as a design goal for a human-centred building design and operation. Designing buildings for adaptive comfort means to provide the necessary opportunities for occupants' adaptation. We have developed a procedure for the development of a *design portfolio of adaptive opportunities* which is displayed in Figure 6.

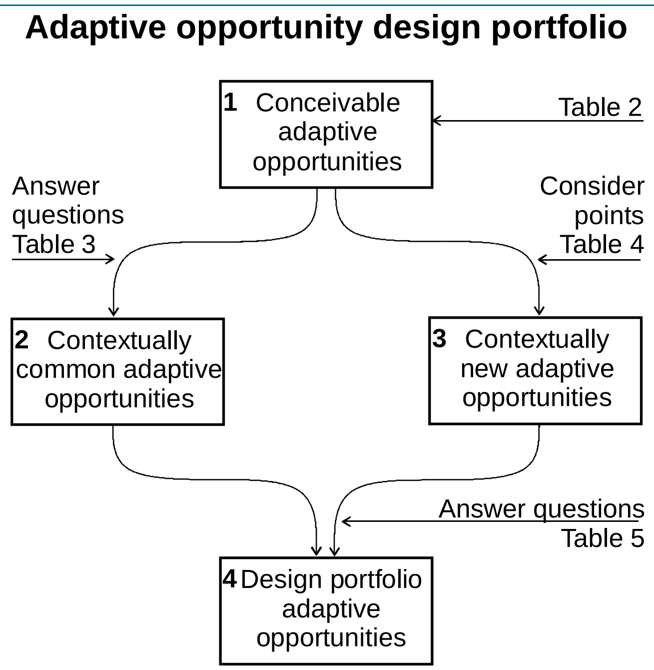

Figure 6: Framework for development of a design portfolio of adaptive opportunities.
This figure is a reprint with adjusted references related to this report. Reprint from: Hellwig, R. T. et al. (2020c). published first at Windsor Conference 2020, Proceedings, Copyright (2020) with permission of the authors.

Step 1

Starting point are all *conceivable adaptive actions and responses,* i.e. *conceivable adaptive opportunities* (Table 2). These are not applicable to all situations buildings are in. Here comes the context the building to be planned is situated in into play.

Step 2

By considering the specialities of the local circumstances the *conceivable adaptive opportunities* are reduced to those common in the actual building's context (section 4.2). Conceivable adaptive opportunities are different in different local climates. For instance, measures such as wetting of walls or floors can be ineffective in warm and humid regions compared to hot and arid climates. Albeit some adaptive opportunities are more suited to a certain season, climate or building type, they may also be applicable in a different context depending on time of the day or occupancy. The building usage/type (e.g. residential, office, classroom etc.) may influence the number and type of conceivable adaptive opportunities as it e.g. may not be appropriate to use a blanket when sitting in a classroom or taking off more clothes in an office environment.

Table 3 shows how these contextual factors drive design solutions and require design actions. Questions raised are exemplary and non-exhaustive. They shall support the planner in analysing the context in which the building is to be designed. [Concrete examples are briefly described in the table's footnotes.] After applying this procedure planners have identified the *contextually common adaptive opportunities*.

Step 3

However, having identified *contextually common adaptive opportunities* may not be sufficient for a contemporary portfolio a planner should have at hand. Therefore, recent or future developments listed in Table 4 should be considered. These additional criteria represent future considerations for the specific location of the building in order to prepare the building for a long-term successful operation. In sight of climate change, adaptive actions previously not used in a certain region may become desirable and appropriate in the future. However, they may be in conflict with some of the common adaptive opportunities. Necessary measures, e.g. for energy efficiency influence the way contextually common adaptive opportunities are to be interpreted. New technologies and actual findings from research provide also information to derive contextually new adaptive opportunities.

Table 3. Contextual factors drive adaptive design solutions and require stakeholder’s action. Questions raised are exemplary and not exhaustive. Illustrative examples are briefly described in the table’s footnotes, which were added to the reprint.

This table is a reprint of table 2 in: Hellwig, R. T. et al. (2020c). published first at Windsor Conference 2020, Proceedings, Copyright (2020) with permission of the authors.

Contextual factor		Question	Design action (responsible actor)
Local climate	Outdoor climate	What is the dominating factors of the climate[1)] (high/low solar radiation, distinct/not distinct seasons, hot and dry, warm and humid, cold etc.)	Identify type of basic design principles / climate adjusted design, (building planner) Identify the type of adaptive need (building planner, operator)
		What is the typical outdoor climate people are adapted to in this region?	Derive occupants’ acceptability of indoor variability and temperature levels (building planner, operator)
	Season	What is the seasonal climate characteristics?[2)]	Derive the main differing seasonal design principles to be met (building planner) Adjust the building operation and elements with seasonal needs (operator) Allow for seasonal varying clothing of your employees (organisational management)
		…	…
Building type/use	Task	Which tasks and activities the occupants are expected to carry out?	Derive level and variation of activities (building planner, operator)
	Building use	Are there building use related requirements which restrict certain adaptive opportunities?	Provide substitute adaptive opportunities, e.g. if a window cannot be opened in a museum with strict temperature and humidity requirements
	Occupant group [5)]	Main occupants’ age and health condition?	Derive ability of occupants for thermoregulation/ unconscious adaptive responses and plan accordingly (building planner, management)
	…	…	..
Human context/ Social norms	Social norms[7)]	Are there adaptive opportunities which cannot be applied due to established norms?	Establish possibility/need to change norm or adjust adaptive action (building planner, operator)
	Indoor climate [3), 4)], previous experience of occupants	Typical indoor climate experienced in buildings of same type? Previous type of indoor climate experienced? (in case of renovation/move to new building)	If new building has different design strategy than previously: develop intense communication strategy already during design phase (building planners, operator) Establish need for modification of expectations/ psychological adaptation (occupant, organisational management) and occupant education (operator, organisational management)
	Assumed knowledge/ common practice	Knowledge/common practice of occupants regarding adaptive opportunities?	Identify need for occupant education and familiarisation to new routines and adaptive strategies (operator)

	…	…	…
Local constraints	Pollution/noise/ UHI/ insects[6)]	Is the building site near a source? (e.g. traffic road)	Establish need to consider orientation/window opening/net protection in relation to source (building planners) and potentially special window operation schedules (operators)
	Security	Are there special security concerns?	Need for adjustment in design, e.g. of windows/restrictors (designer, operator)
Footnotes, added to reprint:			
Examples *1) Dominating climate: high solar radiation, warm and humid → warm discomfort →shielding from solar radiation and air-movement are dominating strategies → need for opportunities for cooler than previously experienced environment → all kind of solar protection and increased air movement* *2) Seasons: cold climate with warm summer → both warm and cool discomfort → need for adaptive opportunities both for cooler and warmer than previously experienced environment* *3) Indoor climate → typical indoor climate experienced? Previous type of indoor climate experienced? (stable/variable, centrally controlled/occupant controlled) → determine need for modification of expectations/ psychological adaptation (occupant) and occupant education (operational management)* *4) Typically AC buildings in location in question → stable, centrally controlled → high need for psychological adaptation and education* *5) Building type/use: main occupants → a) age and health condition? → determine ability of occupants for thermoregulation/ unconscious adaptive responses (designers, operators)* *Old with potential health issues → weak thermoregulation → limited thermoregulatory adaptive opportunities* *Overall healthy adults → normal thermoregulation → no constraints in thermoregulatory adaptive opportunities* *6) Local constraints: Pollution/noise/insects → Is the building site near a source? (e.g. traffic road) → need to consider orientation/window opening/net protection in relation to source (designers) and potentially window operation schedules (operators)* *7) Human context: Behavioural acceptance → are there specific adaptive behaviours which are not perceived as acceptable? → possibility to change norm or adjustment of behaviour*			

Table 4. Considerations of recent and future developments
This table is a reprint of table 3 in: *Hellwig, R. T. et al. (2020c). published first at Windsor Conference 2020, Proceedings, Copyright (2020) with permission of the authors.*

Future developments	**Implications for adaptive opportunities**
Climate change mitigation	necessary measures are e.g. energy efficiency measures, use of renewable energy sources □ need for adjusted ways of designing building which influence adaptive opportunities
Climate change adaptation	expected future changes of the local climate (generally increasing average temperatures, more frequent heat waves) can lead to adoption of adaptive opportunities from other climate zones
Increasing urbanisation	urban heat island effect, challenging certain common adaptive opportunities □ need for design adjustments
Recent technological development of processes or products	new communication strategies, personalised comfort systems (PCS, section 4.4) new types of adaptive opportunities
Recent research results on human perception of indoor spaces	health and well-being through experience of different temperatures → need for adjusted ways of designing building which influence adaptive opportunities (sections 2.1. and 4.6)

Step 4

First, the adaptive opportunities of step 2 and 3 are combined. Table 5 shows a set of questions which support planners in accomplishing a contemporary *design portfolio of adaptive opportunities*. The choice of the *contextually new adaptive opportunities* evokes two challenges: Firstly, the critical point with introducing new behaviour options to a specific location is that all stakeholders in the building: occupants, operators and managers/owners should be provided with information about these new opportunities there are not yet familiar with. Secondly, it appears to be rather risky to rely solely on *contextually new adaptive opportunities* because not all stakeholders may be capable to uptake and embody those new ways of adaptation to the same degree. Therefore, it is strongly recommended to choose a good mixture of *contextually common* and *contextually new* adaptive opportunities, communicate them to and discuss them with all stakeholders.

To summarise from the above: there is a large potential for behavioural thermoregulatory actions, which employ no operational energy or have a low energy use. Local climate and what people are used to (e.g. the most liked adaptive opportunities, Leaman, 2003) determine the adaptive opportunities feasible. *Since behavioural thermoregulation is deeply embedded in human thermoregulation and comes natural to people, it comes with the advantage of occupant satisfaction and engagement. There are no excuses for not designing/operating for adaptive opportunities. Constraints may exist, but they might exclude the use of adaptive opportunities only temporarily.*

For operational planning, commissioning and operation of the building the chosen and documented *design portfolio of adaptive opportunities* is the driver to bring all measure in place which make sure that the planned adaptive opportunities are also those exerted during the building use phase.

Table 5. List of example questions to identify and appropriate mixture of *common* and *new adaptive opportunities.* This table is a reprint of table 4 in: *Hellwig, R. T. et al. (2020c). published first at Windsor Conference 2020, Proceedings, Copyright (2020) with permission of the authors.*

General questions	Have you implemented a variety of common adaptive opportunities which people are familiar with?
	Which are the most liked contextually common adaptive opportunities in buildings in the region?
	When implementation of a new adaptive opportunity is planned: How are the tasks, practices, knowledge, capabilities/skills of the occupant group suitably and sufficiently supported?
	When implementation of a new adaptive opportunity is planned: What is the documented and proven acceptance of this new technology?
	Can an identified new adaptive opportunities replace a common one? When it is one of the most liked common adaptive opportunities, then keep it.
	Are the identified contextually new adaptive opportunities in conflict with the common adaptive opportunities? If they cannot be combined, carefully evaluate the usefulness/ necessity of the new opportunity with regards to future challenges, e.g. climate change.
	When implementation of a new adaptive opportunity is planned: Has the operator of the building sufficient knowledge to operate them?
	Are there special requirements from the operators and the operational management?
	…
New Buildings	If the company moves: Which were the most missed adaptive opportunities in the previous building?
	…
Existing buildings	If the building is renovated: Which adaptive opportunities were available in the building before renovation? Keep them unless there were many complaints about them.
	If the building is renovated: Does the existing building have openable windows? Avoid replacement of previously openable windows by fixed glazing.
	…

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end of reprinted section 3 from: Hellwig, R. T. et al. (2020). Guidelines to bridge the gap between adaptive thermal comfort theory and building design and operation practice. In S. Roaf, F. Nicol, & W. Finlayson (Eds.), 11th Windsor Conference - Resilient Comfort, Proceedings, ISBN 978-1-9161876-3-4, pp. 529-545,

Building Services design

Building service systems aim to control the internal environment of buildings to make it safe and comfortable to occupy. The main goal of these systems is to deliver controlled heating and cooling to spaces for thermal comfort, as well as controlled ventilation to dilute indoor contaminants. When passive design is not sufficient to provide adequate indoor environmental control for adaptive comfort, its capacity can be technologically enhanced with use of innovative technologies and operational strategies that take advantage of the cycling nature of the outdoor climate (IEA-Annex 35 2002, Chiesa et al. 2017). Passive systems need to be carefully planned and building service engineers need to be able to quantify the thermal and airflow dynamics of passive designs, to provide indoor thermal conditions that change only gradually in response to the prevailing outdoor conditions, while remaining within the limits within which people readily adapt to.

The adaptive approach to thermal comfort introduces uncertainties and complexities to the design of building services because it demands shared levels of indoor environmental control with the building occupants, e.g. through interactions with the envelope. For this reason, incorporating adaptive principles and strategies for indoor environmental control adds an entire new occupant-centred dimension to building services design. Occupant-centred design implies that occupants should be involved in the design process "from the ground up". It acknowledges that due to individual differences, a single temperature that is comfortable to all people at all time cannot be recommended (in the meaning of does not exist). With the objective to maximize workers productivity, and minimize liabilities, building service systems have traditionally aimed to provide nearly constant, uniform thermal conditions throughout the building. However, research has demonstrated that the relationship between room temperature, thermal comfort and workers productivity is task-specific (CIBSE 1999, Parsons 2002, Tarantini et al. 2017). Therefore, except for environments requiring nearly constant thermal and ventilation conditions, such as museums, building service designers should strive to fit their designs to the actual requirements of the occupants and their tasks. This principle applies even to design for residences for people with special needs, such as elder or small children.

An occupant-centred approach to design recognizes the diversity and individuality of its occupants by deliberately promoting opportunities for variability in space and time. Environmental variability is materialised by the following aspects.

a) Accommodate spatial thermal variability

Spatially, thermally differentiated zones can accommodate a variety of individual thermal requirements within a building (Deuble and de Dear 2012b). This can be achieved by carefully zoning the building to allow varying servicing and control strategies for different zones of the building. The potential of transitional zones will be discussed in section 4.6.

b) Control to temporal thermal variability

Temporally, indoor temperatures can gradually drift towards outdoor conditions and encourage occupant adaptations such as clothing changes and use of operable windows (Deuble and de Dear 2012b). The adaptive comfort bands limit the inherent temporal variability of temperatures in buildings designed according to the adaptive principles. However, even within these bands temperature fluctuations need to be adequately controlled in both amplitude and frequency of variation (Peeters et al. 2009). Sudden temperature variations will likely provoke discomfort and complaint, "while a similar change occurring gradually over several hours, days or longer, would be compensated by corresponding change in clothing, and would not provoke complaint" (CIBSE 2015). CIBSE Guide A (2015) prescribes acceptable temperature drifts during a day and over several days. Temporal thermal variability will be discussed in section 4.6.

c) Adapt to changing load patterns

Where possible, service systems should aim to be self-balancing and capable of easy adaptation to changing patterns of load by recurrently assessing thermal and ventilation needs, and for example reapportioning ventilation air from areas with low ventilation requirements into highly occupied areas having above-average ventilation requirements, at any particular time of the day (CIBSE 2000).

d) Integrate flexible and usable environmental controls

Acknowledging occupants' individualities and diversity of needs, and reflecting these into a more diverse and thermally variable indoor environment involves new challenges to the design of building service systems. However, the design of building services does not need to be unnecessarily complex or oversophisticated. Careful passive design, may eliminate mechanical systems in certain parts of the building, or will operate selectively. Carefully planning and designing control systems will lead to zones of the building enabling complete control, partial control, or even no environmental control to occupants, e.g. for safety reasons. More importantly, no matter how well engineered and sophisticated control systems are, they will not be successful unless they are user-friendly and intuitive to use by occupants (subsection on adaptive opportunities design). Outcomes of control actions should also be rapid and provide informative feedback, if possible (section 4.3).

An often met requirement today is that building controls should be demand-response. demand response control strategies have demonstrated to save energy and allow cyclical temperature variations, whose magnitude depends on the building characteristics and on the types and strength of the environmental loads (IEA EBC Annex 67). So far those approaches focus on the technical control. However, the term "demand-response willingness" has been introduced recently to indicate how much occupants are willing to deviate from the preferred indoor air temperature for cost/energy savings (Pedersen et al. 2017). Therefore, for this type of buildings a passive-prioritized approach, combined with proper control, can help reduce the use of energy and make the inner building temperature bands fluctuate close to the prevailing outdoor weather. For closer dynamics of the building operation with the prevailing weather, and to save energy, demand response control can integrate weather-feedback, or even better weather-forecast strategies. The principles and recommendations for designing for appropriate adaptive opportunities as described in previous paragraphs still apply and demand-response solutions need to consider them.

However, implementing individual control for all occupants in a building may not always be desirable, or even technically or economically feasible. For design flexibility, levels or degrees of environmental control can be devised dependent on the number of people in the room, the room configuration and the environmental systems available. Kwon et al. (2019) argue that the degree of personal control should be designed and planned to increase satisfaction of individuals and have them agree with compromise on the circumstances. Design for individual control may be challenging in open-plan offices. However, providing means that help to change the environment in an open-plan office, e.g. by contacting facilities and having the request resolved quickly, increases occupant's perception of individual control (Leaman and Bordass, 2006). Cooperative controllers, process and deliver real-time thermal comfort and preference (Lee et al. 2019) feedback from occupants to building management systems (BMS), and optimize energy use. These controllers can handle all facility-related requests from occupants and make decisions on the room conditions based on occupants' votes. By knowing the location where the requests originate, and possibly coupling requests with occupancy detection and counting, the approach permits prioritizing mechanical heating, cooling, and ventilation to the rooms or zones where it is most required (comfy[3]).

Personalised comfort systems

Conventionally, the comfort conditions are maintained within a building using a Total-Volume Conditioning approach, i.e., by heating or cooling the entire built space, irrespective of the occupants' individual thermal/airflow preferences or locations within the built space. The Personal Comfort approach, on the contrary, offers comfort conditions at spots within the built space based on the occupants' individual thermal/airflow preferences and location, while keeping the surrounding, unoccupied zones, in a relatively under-conditioned state. They can be an alternative to high-energy using decentralised split unit systems which - due to their individual control on room or person level – offer personal control and can lead to high thermal satisfaction levels (Al-Atrash et al. 2020). The following considerations summarise more detailed analysis in Rawal et al. (2020a).

The Personal Comfort approach is realized using multiple devices operating on conductive, convective, and radiant heat transfer principles; these devices, along with localized their controls and auxiliaries, are altogether termed as Personal Comfort Systems (PCS).

PCS Devices and Affecting Parameters

PCS Devices are divided into five sub-categories based on the operating principle (Figure 7). Each of these sub-categories include examples of devices which utilize either or all the corresponding modes of heat transfer, as shown in Figure 7. "Heating" and "Cooling" PCS devices utilize conduction and radiation as the modes of heat transfer. These categories include devices such as Air Sleeves, Heated/Cooled Seats, Foot Heaters, Palm Warmers, Heating/Cooling Radiant Panels, etc. "Heating with Ventilation" and "Cooling with Ventilation" PCS devices utilize all three modes of heat transfer - conduction, convection, and radiation. These categories include devices such as Desktop-based Devices, Movable/Fixed Panels, Nozzle-based Devices, Radiant Panels with Fans, Heated/Cooled Seats with ventilation, etc. "Ventilation" PCS devices utilize convection as the only mode of heat transfer and include devices such as Desktop-based Devices, Isothermal Movable/Fixed Panels, Nozzle-based Devices, Mechanical Fans, Ventilated Seats, Ventilated Garments, etc.

[3] Comfy. ComfyApp. Retrieved May 5, 2018, from https://www.comfyapp.com/, retrieved 25/2/2020

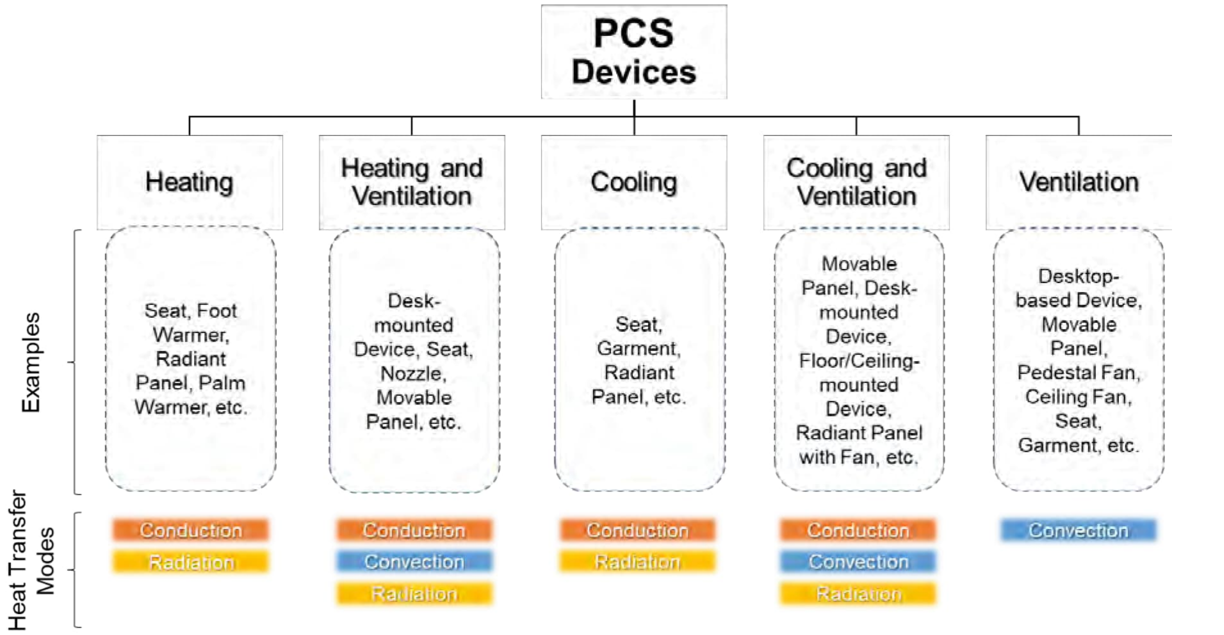

Figure 7: Categorization of Personalised Comfort Systems (PCS) devices

PCS effectiveness

PCSs have been found to increase the occupants' acceptability and satisfaction of their local indoor environment and to decrease the overall heating/cooling energy consumption relative to conventional whole space HVAC operation.

The superior performance of PCSs can be attributed to the aspect of personal control and under-conditioning of the built zones with a low occupancy. PCSs allow the occupants to regulate the temperature, air velocity, direction of the PCS airflow or the temperature of the PCS devices, where applicable. The presence of occupant-controlled PCSs allows the occupants to experience a sense of individual control over their local indoor environment, resulting in enhanced thermal delight (alliesthesia) (de Dear et al. 2011, Parkinson and de Dear 2015, 2016, 2017) which serves as the positive feedback for an successful personal control action enhancing indoor environmental self-efficacy of the person along with high perceived control (Hellwig 2015).

PCSs operation leads to potential energy savings in comparison to conventional whole space HVAC systems (Zhang et al 2015a, Zhang et al 2015b, Kalaimani et al. 2018, Godithi et al. 2019). With PCSs in operation, the conventional whole space HVAC systems have a reduced heating/cooling load due to a relatively 'uncomfortable' set point. Considering the case of a typical office building requiring cooling: the background HVAC system will maintain the air temperature of the entire built volume at, say, 28°C. This will serve as the upper temperature limit for all occupied and unoccupied spaces. The most occupied spaces will be placed with PCS devices, supplying additional coolth through one or all the modes of heat transfer. The occupants can operate and orient their PCS as per their thermal preference if they deem the set point of 28°C as undesirable. A conventional whole space HVAC set point approach, in such conditions would have necessitated a decrease in the overall set point by typically 2 to 6 Kelvin, thereby leading to a higher energy consumption. The PCS approach also allows the building to utilise natural ventilation with a simultaneous PCS operation. Ventilation-based, non-compressive cooling is instrumental in decreasing the overall energy consumption. Radiative and conductive heating/cooling is also effective for simultaneous operation with natural ventilation, therefore potentially increasing the chance of thermal adaptation.

PCS design and operation

The study of PCSs involves understanding the thermal parameters of the ambience, the conditioned zone near the occupant, as well as the device-specific details such as the dimensions or placement of the PCS device. These parameters are necessary to establish a common ground for a comparison between various devices; they are given as:

i) Ambient Room Air Temperature (Troom) for PCS operation,
ii) PCS Air or Surface temperature (TPCS-air or TPCS-surface),
iii) PCS Airflow Velocity (VPCS) at the occupant's body level,
iv) Body parts directly affected due to PCS operation,
v) Position of the PCS device relative to the occupant,
vi) Restriction of occupants' movement due to PCS operation, and
vii) Manually controllable PCS parameters out of Air/Surface Temperature, Airflow Rate, and Airflow Direction.

PCS devices have been researched upon in controlled conditions, field conditions, numerical simulations, etc. to yield a set of device-specific operation conditions, which yield the highest occupant satisfaction. These conditions vary with the PCS category and device type. However, there are a few rules of thumb which are consistent for most of the studied cases (Rawal et al. 2020a), applicable when the activity level below 1.3 met and clothing insulation below 0.7 clo, and are mentioned as follows:

- The difference between the T_{room} and $T_{PCS\text{-}surf}$ should be less than: 23°C for Radiant Heating PCS, and b. less than 10°C for Radiant Cooling PCS (ISO 2006).
- Cool radiant surfaces must remain above the dew-point temperature (as for chilled ceiling).
- The local average difference of T_{air} between the head and the ankle level should always remain under 3°C (ISO 2006).
- For warm or cool air supply, the local average air velocity at the face level should always remain under 0.6 m/s.
- For isothermal air supply with the occupant in control of the air velocity, the local average air velocity at the face level should remain under 1.2 m/s.
- For isothermal air supply with pre-set air velocity settings, the local average air velocity at the face level depends on the T_{room}, but should always remain under 1 m/s.

The PCS Guideline (Rawal et al. 2020b) will offer an insight into each PCS Category with device-specific description of the seven aforementioned parameters along with a note on the possible improvements, limitations, orientation guides to the system. The guideline will also offer 'value-added' content delving upon the experimentation and survey methodology for analysing PCS, and other additional resources. The guideline can serve as a primer for helping choose the appropriate PCS device for context-specific requirements.

The modularity of the PCS approach makes it tangible for nearly every context. PCS devices are diverse as they range from USB-driven fans to Phase Change Garments. They do not necessarily have to be coupled with the building-level PCS and can be used independently, even outside the building environment. This flexibility of use paves the way for a future with radically decentralised demand-driven heating and cooling.

4.5. Operational planning and operation

In this stage, the most important role for the successful adoption of adaptive principles is that of the stakeholders involved in the building's operation. The aim is to incorporate participation of the occupants in the early stage of design and operational planning, which serves two purposes: i) to understand their needs and ii) to familiarise them later on with the building's intended use and system operation.

This stage also requires the development of an operational strategy by the organisational management and operator (facility manager FM) which should involve and encourage adaptive opportunities. The work performed in this stage provides then input back to the design brief for the building, its service systems and the design of the adaptive opportunities. A successful feedback mechanism between stakeholders can guarantee that problems are identified and resolved quickly during operation.

Appendix 3 documents a summary of findings from all case study buildings of Annex 69, Subtask C which address not only design but procurement, commissioning, operation, maintenance and engagement with occupants, please refer especially to case study buildings 02, 09 and 10.

Stakeholders

The main stakeholders who have responsible roles in the adoption of adaptive principles in a building's lifetime include the design team/planners, the building operators and the occupants.

Planners: The planners cover all disciplines necessary during the design phase of the building (integrated design team), i.e. architects, building physics engineers, building service engineers, sustainability certification consultants/ councils, etc. and are the first to integrate adaptive thermal comfort through their design, following the guidelines analysed in section 4.4. A list of criteria that can be incorporated during the design phase of the building to ensure the ability of the building to run in an adaptive mode is included in Appendix 2 in the form of non-exhaustive sample checklist.

Building operators: The term 'building operator' covers all stakeholders involved in the operation of a building, i.e. the organisational management (owners, tenants) and the facility management. These stakeholders are instrumental to implementing the adaptive design principles and strategies, with the aim to achieve occupants' satisfaction and low-energy performance during the building's service life. They are directly responsible for making sure that the design intent is materialised and in order to do so, they need to meet the following requirements: 1) understand the adaptive principles and their role in achieving building performance targets, 2) be well informed on the singularities of the building and its environmental systems, 3) be motivated and proactive, 4) be well trained on the operation and management of the building's environmental systems, 5) be engaged with the occupants, and 6) be properly supported by the higher management and by the building owner. Appendix 2 includes a non-exhaustive sample checklist for the operation level, which refers to the criteria that allow the building to run in adaptive mode during the operation phase and can be addressed by the facility manager.

Occupants: The significant role of occupants has been already highlighted in previous sections. The intention is to involve the building occupants in the decision-making processes during all building phases, i.e. from the start of the design process to beyond commissioning. Such a communication strategy contributes to a better understanding and relationship between stakeholders and to active participation by all necessary actors. However, involving occupants from the beginning leads to two important benefits: a) it helps to understand their thermal experiences and needs which leads to better management of their expectations, and 2) it gives the opportunity to educate them about the building they will occupy. Such an approach increases their awareness on the building environmental systems and intended environmental variability, with benefits to the occupants and the environment. It also highlights the role of occupants in adjusting their thermal environment. A better understanding of how the building systems and controls are intended to work can lead to greater tolerance of the occupants when their initial expectations are not met, which has significant implications, i.e. energy savings (Leaman and Bordass, 2007; Brown and Cole 2008). Relevant research has addressed occupant engagement in the design and operational phases of buildings (e.g. Martek et al. 2019, Bull and Janda 2018). In practice, the "Soft Landings" approach, which was developed in the UK, creates feedback loops for occupant involvement (Soft Landings Framework, 2014). Similar initiatives exist in other countries. A non-exhaustive sample checklist for the occupant behaviour level is provided in Appendix 2, which covers parameters that relate to the occupant actions to improve their comfort and may be used together with Table 2 for inspiration on how to inform occupants about possible adaptive behaviours. In addition, we provide the checklists in form of an overview on the stakeholders' responsibilities and necessary actions in design or operation to their successful application.

Operational Planning

Aside from the standard provisions for the operational planning of buildings, planning the operation of thermally adaptive buildings requires particular considerations due to the more interactive and dynamic nature of the building. In particular, the following provisions should be considered.

1. Include in the operation and maintenance (O&M) manual a section on adaptive operation, including explicit sequences of operation of environmental control systems, detailed guidance on

monitoring and verifying performance recurrently, and the roles and responsibilities of the occupants in interacting with the building.

2. Include an occupants' manual with information on what to expect from the indoor thermal environment and its systems, and simple instructions how to interact with the building. Information should include aspects of thermal comfort, indoor air quality, and other relevant environmental aspects such as lighting and noise. Information should be presented in a factual and non-evaluated manner, without formulating restrictions or constraints.

3. Protocols need to be established to engage designers to support and guide the tracking of building performance in line with the design and help tune the building environmental systems accordingly. This will in turn support the uncovering of performance anomalies by building operators, at the early stages of building occupation, and provide feedback to designers so that they can improve future designs.

4. Provisions need to be made to fine tune the building environmental systems and controls as required during the early stages of building operation. This is particularly critical in thermally adaptive buildings because designs include many assumptions on occupants' behaviours and interactions with the building that need to be verified.

5. A protocol for the continuous performance monitoring of the building needs to be established (Post Occupancy Evaluation). It should include the necessary types of data analysis and key performance indicators, including occupants' degree of satisfaction and levels of interactions with the building.

6. To maintain occupants engaged with the good use of the building, a protocol needs to be established indicating provisions for timely feedback to occupants on the performance of the building and how their adaptive behaviours result in good environmental quality and energy savings.

7. A recurrent survey protocol needs to be established to obtain feedback from the occupants on their level of satisfaction with the building, as well as suggestions or ideas to help maintain, tune, or even improve the indoor environment and systems operation.

8. Given that the amount of monitoring data collected may be substantial, to avoid data bottleneck, the management of data needs to be streamlined, analysed recurrently, and used effectively to produce desired performance outcomes and enable proactive operational adjustments.

Operation

Three types of buildings are considered in relation to building operation, which offer different levels of thermal adaptation and indoor environmental control:

- Naturally ventilated/ free-running/ passive buildings
- Mechanically conditioned/ actively conditioned/ air-conditioned buildings.
- Mixed-mode buildings

A recurring issue is that definitions for some of the terms above vary between countries. For example, natural ventilation has often been used to describe the free-running operation of buildings, but in some countries the term is only used to describe the way indoor air is exchanged with outdoor air. International standards also use terms differently. For the application of adaptive comfort, ASHRAE (2017) uses the term *occupant-controlled naturally conditioned space* while EN 15251 (CEN 2007) uses the term *building without mechanical cooling* and specifies that the heating system should not be in operation. *Active cooling* is often used to describe mechanical cooling, including both cooling of air and thermally activated systems (building elements or chilled panels). The term *mixed-mode* is often used for the operation of buildings that combine natural ventilation and mechanical conditioning of air, seasonally or in alternating operation (Kalz and Pfafferott, 2010; Brager and Baker, 2008; Manu et al. 2016). The different terms and interpretations used regionally suggest the need for careful consideration when planning and communicating the building's operation. Here, we focus on the connection of the above three types of operation to adaptive thermal comfort.

Naturally ventilated, free-running, passive buildings: The thermal conditions in free-running buildings depend on the external weather conditions, their passive design and on occupants' adaptive behaviour. All definitions used in relation to adaptive thermal comfort include the requirement for operable windows. ISO 17772-1 (ISO 2017) and EN 16798 (CEN 2019) add that conditioning systems should not be in operation while other standards highlight that systems should not be installed (e.g. Construction and Planning Agency Taiwan, (2018)). Other requirements for free-running operation include flexible clothing policies (ASHRAE 2017, ISO 2017, CEN 2019) and ceiling fans, especially in climates where air-movement is desirable for improving comfort (Construction and Planning Agency Taiwan, 2018, National Building Code India, BIS 2017).

Mechanically conditioned, air-conditioned, and actively conditioned buildings: These buildings are heated or cooled with water- or air- based systems. Their operation is either centralised or decentralised. Centralised operation typically offers the lowest degree of personal control.

Mixed-mode buildings: Mixed-mode ventilation can be seen as a "bridge" between natural ventilation and air-conditioning, which helps to avoid all-or-nothing options (CIBSE, 2000). However, there is currently no generally accepted definition for mixed mode operation. According to Brager (2006), a mixed-mode building combines natural ventilation with manually or automatically controlled operable windows, and mechanical systems with air distribution and refrigeration equipment. This definition, however, does not cover other cases, such as heating in general or predominantly radiative systems for heating and cooling. Hybrid ventilation is a special case of a mixed mode building, mainly described for building cases in Europe (Heiselberg, 2002). The mixed-mode operation types for the cooling case were described by Brager (2006), based on how the two modes are combined, i.e. in space and time (Table 6). For the heating case, the wide-spread operation mode of central, western and northern European buildings would then be 'concurrent': heating and windows operating in the same space at the same time. Implementation of window contacts which stop heating (close the radiator's thermostatic valve) would formally result into 'change over/ permanently alternating' mode. Some national codes define mixed-mode as operating AC only during extreme outdoor conditions (National Building Code India, BIS 2017) and in the unfavourable orientations (Construction and

Planning Agency Taiwan, 2018). Overall, mixed-mode buildings require a suitable façade design which considers the building context (see section 4.2). CIBSE (2000) explains in detail the principles and best practices in the design of buildings for mixed-mode ventilation, emphasising a “fabric-first” approach. In order to minimize energy consumption without compromising air quality and thermal comfort, mixed-mode ventilation requires appropriate control systems that alternate automatically between natural and mechanical modes (Heiselberg, 2002; Deuble and de Dear, 2012a).

Table 6. Types and characteristics of mixed-mode operation for the cooling case (AC – air-conditioning) (Brager, 2006). Similar classification can be applied to the heating case.

Types of mixed-mode operation		Characteristics
Concurrent		AC and windows operating in the same space at the same time
Change-over/	Permanently alternating	AC and windows operating in the same space but at different times during the day
	Seasonally alternating	AC and windows operating in the same space but at different seasons
Zoned		AC and windows operating at the same time but in different spaces

Being a ‘bridge’ between natural and mechanical ventilation, a question arises as to whether the adaptive comfort concept applies in mixed-mode buildings. Research evidence suggests that the adaptive approach is suitable to evaluate the performance of mixed-mode designed buildings (Brager and Baker, 2008; Luo et al., 2015; Kim et al., 2019).

Apart from the operational considerations related to the building’s systems, building operation should also support in other ways the adoption of adaptive principles. Following the order of activation of adaptive principles described in section 2.4, building operation needs to offer opportunities for physiological adaptation. On the one hand, less tight control of the indoor climate in workplaces could support physiological adaptation. Even in case the work done does not permit to loosen thermal control, transit areas such as gangways or other areas with short term stay, such as tea kitchens or copy machine rooms, may have the opportunity to be less conditioned and offering the occupants a short exposure to conditions outside thermal neutrality and potential for physiological adaptation.

In relation to behavioural adaptation, it is important to encourage occupants to take control actions. Occupants may have to be informed or reminded about their opportunities, the effects they can expect by specific measures such as window opening and the benefits of less tight conditions with respect to energy use and health in order to manage their expectations and increase their satisfaction.

Building operation should also try to minimize constraints to adaptive opportunities. Measures include rethinking of strict dress codes or searching for solutions, which enable night-time ventilation through operable windows, while satisfying requirements with respect to protection against burglaries, rainfall or animals entering the building. Further measures already important to be considered during the design phase are for example sufficient storage space for documents, so that piles of documents on the windowsill restricting window opening can be reduced.

4.6. Adaptive comfort in conditioned buildings

Current standards distinguish between free-running (naturally ventilated), mixed-mode, and conditioned buildings (heated, cooled, air-conditioned or radiation based condition systems). While the application of adaptive comfort principles is rather straight forward in free-running buildings, questions arise, why the adaptive comfort principles and models should not be also valid to conditioned buildings or mixed-mode buildings. On the one hand, standards such as ASHRAE (2017) or CEN (2019) clearly state that the heat-balance approach (PMV) should be applied to conditioned buildings. On the other hand, it is worth looking at the underlying mechanisms in order to decide on the applicability of adaptive principles (section 2) to any type of building or conditioning mode after which we explore temperature and energy-use-related practices and solutions.

Adaptive principles

Nicol (2017), Humphreys et al. (2013) and Parkinson et al. (2020) present a wide variation of individual temperatures within and between climates, season, culture, building types and rooms. They also confirm in their publications the early findings of Humphreys (1978) of a strong correlation between *prevailing temperatures experienced* and comfortable temperatures. It can be interpreted that people are normally satisfied with what they experience every day as long as it does not cause high physiological effort. Therefore, adaptation, which follows closer the outdoor weather conditions is likely higher for occupants of naturally ventilated buildings as these buildings follow more closely the seasonal swing of the outdoor temperatures – buffered in a way, which is a building's purpose. Less so do mixed mode buildings when in conditioning mode or conditioned buildings – also according to initial purpose of conditioning: to ease those outdoor conditions which would require high physiological effort. However, correlation between *prevailing* indoor temperature and comfort temperature is high in such buildings, also, as presented above.

Adaptation to *prevailing indoor temperatures* explains the effect observed in long-term conditioned buildings: gradually increasing/decreasing heating/cooling temperatures, within seasons (e.g. Wang et al. 2018) or over decades (e.g. Hellwig et al. 2020b). They contribute to rebound effects in energy efficient new and renovated buildings (e.g. Sunnika-Blank and Galvin, 2012). This effect could be called *indoor exposure rebound* (Hellwig, 2019). Temperature requirements in standards tend to follow the general practices elicited by new technologies: a new temperature range has become prevailing practice. The separation of requirements for buildings with different conditioning modes goes along with it.

Physiological adaptation: Immediate vasomotor adaptation helps to regulate close to the thermo-neutral zone, hence small thermal variations. Occupants can manage wide ranges (between 10 to 35°C, e.g. Nicol 2017, Parkinson et al. 2020) and find these ranges acceptable – which is not manageable by vasomotor adaptation alone. Shivering or sweating regulate larger deviations from the thermo-neutral zone. Because this would require higher physiological effort, the body employs first behavioural adaptation *(see below)*. Only if the range of experienced temperatures shifts for longer periods, the body acclimatises, for example gradually as with seasonal changes. Depending on how conditioned spaces are operated, exposure to a wide range of temperatures may still exist, which depends on who controls the range and which attitude those controlling exhibit.

Behavioural adaptation is a conscious action taken to support the body to restore comfort without employing too much physiological effort. In section 4.3 we described the manifold adaptive opportunities and the mechanisms. The wide range of temperatures recorded in one building over time tend to occur more often in individually controlled spaces like homes where personal control is high (despite possible financial constraints).

Psychological adaptation comprises experiences, attitudes/ values, expectations, etc. which contribute among other factors to the degree of personal control perceived. High perceived control relaxes comfort expectations (section 4.3). Because of their prevailing technical design, conditioned spaces tend to limit personal control. Societal expectation towards specific dress-codes can further limit behavioural opportunities. They tighten comfort expectations because behavioural adaptation - as the *first conscious line of defence* of adaptation - is restricted.

Therefore, it can be concluded that the adaptive principles do well explain thermal perception phenomena and measured temperature ranges in all kind of spaces. In principle, adaptive comfort models should therefore be applicable to all kinds of condition modes (Humphreys et al. 2013, Nicol, 2017, Parkinson et al. 2020). Design and operation practice as well as social attitudes and established practices which are to be linked to conditioning modes, might constrain the applicability of adaptive models.

Temperature and low energy-use-related practices and solutions[4]

Which temperature and low energy-use-related practices can be observed in conditioned indoor spaces and how could they be employed for enhancing adaptation? Design and operation strategies for mixed-mode or conditioned buildings should first of all rely on traditional, common every-day practice in conditioned buildings.

Temperature and energy-related practices in buildings have been divided into the following strategies: a) temperature regime (conditioning extend), b) conditioning schedules, c) spatial conditioning, and d) behaviour (Hellwig 2019). Interpreting the adaptive principles towards those (formerly) established design and operation practices and combining them with new practices and technologies, may unlock energy conservation potential.

Temperature regime (level)
Widening temperature dead bands, hence lowering the heating or increasing the cooling base-temperature would be a suitable strategy (Brager, 2013) expanding the time in which a building is

[4] The following text is based on work in Hellwig, R.T., Teli, D., & Boerstra, A. (2020b) but has been extended here.

neither heated nor cooled, but free-running. In heated, energy-efficient residential buildings in central/northern European climate, the heating base temperature was expected to decrease from formerly 15°C to 10°C due to theoretically decreased transmission and ventilation losses. However, this theoretical potential does not materialise fully as monitoring results show: indoor temperature set-points increase in countries with active heating far above 20°C (Hacke, 2016, Hansen et al. 2018, Teli et al. 2018). Indoor temperature reductions to about 20°C in those countries would achieve 14% energy conservation or more (e.g. Mata et al. 2013). A rule of thumb gives about 10% energy use saving per 1 Kelvin lowered heating temperature. According to Hoyt et al.(2015) the same applies for the cooling case. Energy savings from extending indoor temperature set-points were estimated for the US based on simulation at 32-73% depending on climate (Hoyt et al. 2015). Multi-objective optimisation of HVAC set-points resulted in up to 60% energy savings, depending on climate, based on widening the static set-points (Papadopoulos et al. 2019). This potential seems to be based on the fact that established practices that are not even compliant to *"any standard" (*Parkinson et al., 2020).

Established conditioning practice varies. An operation mode for active cooling (air-conditioning, chilled ceiling) has been used for decades controlling the room temperature following the outdoor temperature (latest version: DIN 1994, officially not applicable anymore): The indoor temperature set point is adjusted continuously during an outdoor temperature rise (20°C to 32°C) from 20°C to 26°C, called summer compensation to avoid too large temperature differences between room and outside temperature. In addition, the cooling energy expenditure is thereby substantially reduced. It is still in use.

Implementing advanced control algorithms based on adaptive models for conditioned buildings is another option. A first example is the initial version of the adaptive comfort model developed in the Scats project (McCartney and Nicol, 2002). By using an adaptive set-point instead of a static set-point in an air-conditioned building in the UK resulted in 30% energy savings. Yun et al. (2016) used an adaptive model developed for air-conditioned buildings and estimated an energy conservation of about 22% by using the adaptive model instead of a static set-point of 23°C. The Indian Model for Adaptive Comfort (IMAC, Manu et al. 2016) is another example for an adaptive model for partly conditioned buildings (here: mixed mode buildings).

Individualised conditioning practice could be a way to allow the indoor temperature of the space to be closer to the prevailing outdoor temperature, an effect called corrective power of personalised comfort systems (Zhang et al. 2015a). Personalised Comfort Systems (PCS) (respective paragraph in section 4.4) are means of individualised condition practice and offer at the same time high levels of personal control contributing to psychological adaptation as described above. As with such systems, the *local* environment around an occupant is now conditioned and therefore the whole-space temperature can be increased by 1 to 6 Kelvin (cooling) or decreased by 2 to 10 Kelvin (heating) (Zhang et al. 2015 a). Local fan use can reduce the whole space temperature by about 2 to 3 Kelvin (ASHRAE, 2017). In typical heating cases 1 K decrease in indoor temperature typically corresponds to 5 to 15% of energy conservation, leading to reported absolute energy savings of 5 to 60%, whereas in cooling cases energy savings of 5 up to 50% are reported (for more detail see

Rawal et al. 2020). PCS concepts have to go along with a general energy-efficiency approach, i.e. limiting the power of such devices, as otherwise the conservation potential will not materialise (Schiavon and Melikov, 2008).

Indoor temperature increase that has been observed over decades, seasonally or in energy-efficient buildings, could be a result of people habituating to indoor temperatures in conditioned buildings, especially in those seasons during which people spend least time outdoors and show lower activity levels (summary in Hellwig et al. 2020b, Wang et al. 2018). The following two practices: varying conditioning schedule or varying spatial conditioning might offer strategies to diminish the effect of slowly increasing (heating) or decreasing (cooling) temperatures indoors.

Conditioning schedule

Typical practices are within-day temperature variations, e.g. in residential building through night set-back or shut-offs (Huebner et al.2015, Teli et al 2018, Nicol, 2017) in cold/temperate climate as well as night activation of cooling in bedrooms in warm/hot climates. In energy efficient buildings, due to the larger time constant, the margin of the temperature decrease through night set-back (heating) would be small. Therefore, and before the background of the steady-state temperature postulate and the limited heating power of low exergy systems, in operation practice, it is common recommendation that night set-backs or shut-offs are to be avoided/not necessary in new buildings. However, even small deviations from the standard set-point might be supportive to diminish indoor temperature adaptation and hence, avoid increasing heating temperatures. Similar approaches may apply for the cooling case.

For people arriving at their office after commuting to work, hence showing an increased metabolic rate, it was shown in Danish transition season in a simulated typical summer outdoor condition that a cooler starting temperature of 20°C (instead of 23°C as the lower edge of the cooling comfort band in ISO 2006) provides a suitable comfort (laboratory study, Bourdakis et al. 2018). It is reasonable to operate passive night cooling strategies with natural ventilation until lower temperatures are reached in order to gain more capacity in the building to take up excess heat during the coming day. People also commute to work in other seasons, and it could be as well reasonable to employ more night set-backs and start with conditioning a room upon arrival of the occupant.

Most non-residential buildings rely on ICT systems (building automation/management systems, IoT) which provide potential to employ conditioning schedule following demand control (see above under ‘temperature regime’).

Spatial condition

In residential buildings, practices, like spatial conditioning, have been disappearing with technological development leading to different operation practice but as well to different design practice, as for example temperature zoned floor plans (unconditioned vestibules, staircases) which have been replaced by large connected spaces of mixed use (Grytli and Støa, 1998). This applies not only for newly designed buildings but also for building renovation (Vogler, 2014). The design postulate of homogeneous temperature all over a heated dwelling has led in practice to a large group of occupants *requesting differing temperatures* in their dwelling, especially lower temperatures for bedrooms (e.g. Berge et al. 2017, Nicol, 2017, Hacke, 2016). One aspect is for example that the mechanical balanced ventilation technology pre-dominantly used in residential mechanical ventilation does not allow for temperature zoning as the recovered heat is distributed to all supply air rooms, independent on the demand of air. Another aspect is the availability of room separating elements, e.g. doors, wall, which are seldom to be found contemporary floor plan layouts. Georges et al. (2019) tested the impact of changed control/distribution strategies and construction options for temperature zoning in passive houses with mechanical ventilation with heat recovery, which point towards new design strategies for dwellings.

Even in mechanically conditioned non-residential buildings there is potential to introduce a certain degree of thermal adaptation e.g. if the building is properly zoned. Spatial variation in conditioning in office buildings (cooling case) has shown benefits for thermal comfort perception and for energy conservation (Zhai et al. 2019, Parkinson et al. 2016). As explained in section 4.3, transition from one temperature zone to another zone can elicit positive thermal perceptions (alliesthesia) and can affect the comfort perception after such an experience in a positive way (Parkinson et al. 2016, Ji et al. 2017). Frequent exposures to conditions outside thermal neutrality will start adaptive processes, such as physiological adaptation (section 2.1). Research on the necessary frequency and length of necessary exposures is still required. Transition spaces suitable could be entrance spaces, corridors, tea kitchens or rooms for work breaks. These rooms could be conditioned in such a way that their thermal conditions are closer or equal to outdoor conditions in the heating case. For summer transitions from outside to inside and at the same time transition from walking exertion to sedentary activity, Arens (2020) argues that the "..need for comfort begins when they come indoors". In order to dissipate the stored body heat increased air-movement could be provided especially in entrance areas.

Another option would be to offer outdoor spaces around the building or in courtyards, which offer parts of the year comfortable spaces to meet up (Figure 5) or to work (Roetzel et al. 2020) or to have a break. Semi-outdoor spaces, as for instance free-running atria, serving often as connectors between building parts support also such processes. Such spaces can be combined with small canteens or coffee areas. All these practices exist already, they only need to be employed more systematically.

Behaviour

Adaptation by means of clothing depends strongly on organisational aspects and societal agreements or norms, which – as shown by the CoolBiz example from Japan – can be changed. Clothing adaptation as such is independent of the conditioning mode; it can take place in free-running, mixed mode, and conditioned buildings. Although standards such as ASHRAE (2017) or ISO (2006) incorporate tables highlighting the compensation potential of clothing of up to 2 Kelvin for indoor space related clothing, this option has been used less often in recent years in conditioned buildings. Enhanced promotion of such behaviour is needed.

Other behavioural adaptive processes not directly addressable by the a*daptive comfort equations* are the increase in air speed, which is relevant at higher outdoor temperatures. Increasing air speed is possible under all types of conditioning modes: in free-running and mixed mode buildings by opening windows and/or running a table or ceiling fan. In mixed mode and conditioned buildings (with active conditioning “on”), however, it is energetically not meaningful to open the window at these times, so that the option of table or ceiling fans remains. Already today standards such as ASHRAE (2017) offer models for incorporating increased air-speed in the design of buildings which lead to higher set-point temperatures for cooled spaces by employing ceiling fans or desk-top fans (Schiavon et al. 2015) or can mitigate the implementation of active cooling technology to spaces. The important consideration hereby is that the fan speed is under control of the occupants in order fully benefit from alliesthesia (Parkinson and de Dear, 2017).

Climate change implies that increased air-speed will be applicable and useful in the warm season also in formerly temperate/cold climate zones. However, the learnt attitude of people from these climates that increased air-speed is causing draft (which is a relevant concern in cooler environments) is a serious barrier towards implementation and requires therefore a careful discussion on changed thermal comfort practice in these regions (see Table 4). It seems to be important to start this discussion now as energy-intense cooling technologies penetrate into areas which traditionally used the free-running mode for operating their buildings in the warm season.

In conditioned buildings, personal control can be increased by means such as Personalised Comfort Systems (see under “temperature regime” and section 4.4).

In section 4.4 (Adaptive opportunities design, Figure 6) we presented a methodology *how to design for adaptive behaviour intentionally*, which is not limited to buildings in free-running mode and can well-applied especially to mixed-mode buildings and conditioned buildings. If sufficient adaptive opportunities are afforded, perceived control will be high which relaxes comfort expectations and supports high rates of satisfaction. Hence adaptive comfort models may be suitable to be applied for whole-space (background) conditioning.

From the above argumentation, and supported by analysis (Nicol 2017, Humphreys et al. 2013, Parkinson et al. 2020, Arens/ Arens and Zhang 2020), it can be concluded that the adaptive principles can well applied for all type of building conditioning modes, and if designed according to these principles - first of all with appropriate personal control - adaptive comfort requirements following outdoor temperatures can be applied also for conditioned or mixed-mode buildings. However, more research would be needed to define specific beneficial conditions in more detail.

5. Future directions for use of the adaptive principles in low energy designs

5.1. Executive summary

In order to overcome challenges and barriers in the adoption of adaptive principles and models identified in practice (section 1, page 3) and in education (Teli et al. 2020) we have summarised relevant research findings to support a clear communication of the adaptive comfort approach describing:

- WHAT the adaptive principles are,
- WHY it is beneficial to use the adaptive principles,
- HOW the adaptive principles can be translated into design and operation of buildings, and
- WHOM should be addressed for enhanced implementation of the adaptive principles (Teli et al. 2020).

WHAT - One comprehensive understanding of thermal perception in buildings

Our description of the adaptive principles in section 2 (page 6) aims to explain the importance of a comprehensive understanding of thermal perception in buildings which is determined by the physical environment, represented by quantifiable factors, but to a large degree by contextual factors described qualitatively. For this reason diversity of thermal perception is highly diverse (Gauthier et al. 2020).

We start with an introduction of the three adaptive comfort principles, namely, behavioural, physiological, and psychological adaptation. Second, the effectiveness and order of adaptive responses is explained. The limited number of studies looking at these aspects individually suggest that the largest effect have the clothing level adjustments, followed by physiological adaptation. In terms of order, vasomotor responses are first to be activated, followed by behavioural actions. Third, few adaptive comfort models, which summarize thermal adaptation as the relationship between outdoor climatic conditions and comfort temperature, have been adopted in international standards and thus form the current legal basis for the planning and operation of building concepts based on adaptive principles (Appendix 1).

WHY - Benefits of adaptive occupancy

Following the introduction on the adaptive principles, this report identifies four benefits from applying them in buildings: energy conservation, resilience to climate change, usability and thermal satisfaction, and health and well-being.

Low energy occupancy

Energy conservation results from widening and sloping the thermal comfort bands consistent with the prevailing local climate, enabling relaxed set points on mechanical cooling or free-running operation. Case study evidence from mechanically cooled buildings demonstrate that when the thermostat is set to vary according to the local outdoor temperature, energy savings are achieved as well as peak energy reductions.

Resilient occupancy

Thermally adaptive buildings are more resilient to climate change simply because they are inherently more connected to outdoors than entirely mechanically conditioned buildings. The benefits of such connection are two-fold: buildings design to local context inhering a supportive thermal performance in buffering outdoor weather events without the use of energy, enhance, rather than impair, physiological adaptation of occupants to extreme weather events.

Usable occupancy

Improved usability and thermal satisfaction are achieved in thermally adaptive buildings due to occupants perceiving that they have control over their thermal environment and being able to exercise control over their thermal environment when necessary to restore comfort. Usability and thermal satisfaction are achieved not only by planned design and operation, but also through proper communication and engagement with occupants on the adaptive opportunities and controls available.

Healthy occupancy

Indoor temperature fluctuations that are planned by design and operated accordingly, lead to indoor thermal fluctuations that benefit occupants' health and well-being, as research evidence shows.. Researchers also point out that thermal environmental monotony may be detrimental to our regulatory capacity over time.

HOW – Integrate adaptive principles in building design and operation

Framework

A framework has been introduced, which aims to facilitate the adoption of the adaptive approach in the relevant phases of a building's lifetime and consists of five main elements (Figure 3, page 14):

- adaptive principles,
- building context (local climate, building type/use, human context/social norms, local constraints),
- planning and design phase (building passive design, adaptive opportunities design, building services design),

- operational planning and operation (occupants, organisational management, operator/facility management)
- adaptive responses and actions

Central to the framework is the positioning of occupants‘ adaptive responses and actions as design goal. A collection of conceivable adaptive opportunities (actions and responses) is provided (Table 2, page 26). The aim of design and operation is to ensure that both conscious behaviours and autonomous/ unconscious body reactions are elicited by the design intentionally, for which purpose we propose a qualitative design procedure for intentionally design of adaptive opportunities (see further down).

Central to the framework is also, that it describes the *adaptive principles* as a *generalised design portfolio*. Building context (beyond *site* as the spatio-climatic, classic context in architectural design) *filters* suitable adaptive opportunities. The planning and design phase is an iterative, integrated design process which needs to integrate a building's passive design (maximizing the benefits of the outdoor climate and minimising its unfavourable elements), the adaptive opportunities and the building service systems (supplementing or enhancing the building's passive design if needed). Only when passive design along with the adaptive opportunities are not sufficient to provide adequate indoor comfort, their capacity can be technologically enhanced with use of active systems (building services design).

Incorporating adaptive principles in indoor environmental control means introducing a new occupant-centred dimension to building services design. Such an approach considers the diversity and individuality of its occupants. Strategies to address this are proposed in this guide, i.e. accommodating spatial and/or temporal thermal variability, adapting to changing load patterns and integrating flexible and usable environmental controls. (For operational planning and operation aspects, see further below: WHOM)

Intentional design and operation of adaptive opportunities

The adaptive responses and actions are the design goal of the proposed framework (Figure 3). The aim of design and operation is to ensure that the conditions are met so that both conscious behaviours and autonomous/unconscious body reactions can take place successfully. The *design portfolio of adaptive opportunities* is a new process proposed by Activity B2 of this IEA EBC Annex 69 work group (4.4, Adaptive opportunities design, Figure 6, page 30). The process includes four steps:

1) conceivable adaptive actions,
2) contextually common adaptive actions,
3) contextually new adaptive opportunities, and
4) adaptive opportunity design portfolio.

In order to approach each step in the process, additional material is provided serving as inspiration and is by far not exhaustive. In order to facilitate the generation of a design proposal and to define how adaptive actions translate into design and operational strategies, a collection of conceivable adaptive opportunities (actions and responses) is provided (Table 2, page 26), which is structured based on five categories: regulation of body internal heat generated, regulation of the rate of body heat loss, regulation of the thermal environment, selection of a different thermal environment and modification of one's psychological perception. The Building context, as defined in our framework, facilitates the subsequent steps. It is a qualitative process which helps to raise awareness and can be used for different building contexts. This way, adaptive opportunities are introduced as a design target and embedded into the design brief. The proposed design procedure can be included in design guides or standards.

Personalised Comfort Systems (PCS)

Personal Comfort Systems (PCS) are presented as one possible design strategy. The aim of PCS is to condition the immediate ambience of the occupant using specialised devices, with the conventional HVAC system operating at a relaxed setpoint as a background conditioning strategy. This allows the unoccupied or transitional zones to be maintained at a relatively 'under-conditioned' state, while the occupants' immediate ambience is moderated as per the occupants' preference. PCS offer to the occupants an immediate control over their thermal environment. They allow the occupants to regulate the temperature, air velocity, and direction of the PCS airflow or the temperature of the PCS devices, where applicable and therefore have the potential to enhance thermal comfort and save energy due to the relaxed cooling/heating setpoints of the central HVAC systems.

WHOM - Stakeholder roles in adaptive building operation and design

Already before the start of operation the operational planning involves relevant stakeholders in order to include operational aspects as drivers for the design in the planning phase.

This report recognises operational planning and operation as equally - if not more - important as the design phase. Three groups of stakeholders, who have responsible roles in the adoption of adaptive principles in a building's lifetime, are identified as the design team/planners, the building operators and the occupants. The low-energy and occupants' satisfaction targets of a building can only be achieved through the commitment of these groups of stakeholders to collectively develop and implement plans, consistent with the design intent, to operate the building. Aside from the actual designers and planners, emphasis is made on the importance to engage building operators and occupants as early as possible, from the early phases of the design process. This involvement will ensure not only that they are well informed, but most importantly that their feedback is considered.

After describing the roles of the stakeholders in the adoption of the adaptive principles in low-energy thermally adaptive buildings, the operational planning provisions are outlined. These provisions intend to provide systematic tools to embed the adaptive design intent in the everyday operational practices of the building. The intent of these tools is to develop a proactive culture of continuous performance monitoring that permits early anomalies detection and timely fine-tuning of systems, as well as maintains occupants' engagement through their recurrent operational feedback.

Acknowledging that specific standards and guidelines are available on the actual operation of buildings depending on their type of conditioning, this guideline focuses on the unique adaptive aspects that are not covered by those standards and guidelines. Three general types of buildings are considered in their different relation to design for adaptive thermal comfort: 1) Naturally ventilated, free-running, passive buildings, 2) Mixed-mode buildings, and 3) mechanically conditioned, actively conditioned, air-conditioned buildings. Currently, these types of buildings offer occupants different degrees of thermal adaptation and thermal environmental control, and therefore, individual guidance is provided for each building type, according to the planning provisions. For each building type, challenges are identified. The potential for adaptive comfort especially in conditioned buildings is discussed in section 4.6 (page 47) and conclusions from this discussion will be addressed in the following section.

5.2. Future directions for enhanced adoption of the adaptive principles

"...too much emphasis on comfort provision may deny occupants simple facilities for discomfortalleviation, so creating a dependency culture in which people have to rely upon management to solve problems which they could have taken care of themselves." (Bordass and Leaman (1997, p. 192)

Education and Training

We identified challenges and barriers in the adoption of adaptive principles and models in practice (section 1, page 3) and in education (Teli et al. 2020). These lie in an incomplete view on the manifold quantifiable, but especially qualitative influencing factors determining (positive) thermal perceptions, partly rooted in missing guidance on how to integrate qualitative factors in building design as thermal comfort standards focus on quantifiable factors. In addition, building professionals' education and training seldom covers *the human factor* and focusses on quantifiable factors. Diversity of thermal perceptions among occupants is rather seen as a mysterious challenge than as an opportunity for resilient sustainable design. For these reasons, thermal perception in the built environment is still not treated in the necessary, comprehensive way and as a result the translation into a human-centred sustainable building design and operational concepts incomplete.

A change in mind-set is required and it starts with educating young professionals. Qualitative factors of human thermal perception need a place in teaching such as quantifiable factors have already.

Four important learning outcomes have been defined for teaching the adaptive comfort approach, summarised as: WHAT – WHY – HOW – WHOM (Teli et al. 2020).

The framework, developed in this report (section 4.1, page 13) supports such education and training activities. Proposals on how to reach these learning goals were made in this report (see above executive summary). A human-centred design procedure to intentionally design for adaptive opportunities was developed (section 4.4, page 30) for teaching, for training but also for design practice. Finally, young professionals need to be educated leaving the silos of separated disconnected disciplines and instead learning how inter-disciplinary and integrated design works and to which (good) results it can lead.

Adaptive building design paths

Include qualitative factor to thermal perception in the design process

The point has be discussed above under 'education and training' already. There is no need to repeat the issue here in detail, but to make it clear that qualitative factors influencing thermal perception are essential part of an integrated and successful design process for adaptive comfort, resilience and energy efficiency.

Adaptive design is first of all climate-adjusted passive design

As outlined in this report, design for resilience has to address how the health of the occupants is addressed in a design which does moderate (buffer) extreme weather events for occupants rather than trying to fully eliminate such challenges to the risk of system failure (e.g. by full dependency on energy). For such a design approach the adaptive principles offer a lot: moderating seasonal gradual changes as well as sudden extreme events and preparing for predicted global temperature increase with a dynamic approach to comfort assessment always related to prevailing outdoor temperature conditions, and hence, naturally embedded in the building context. The first means for this purpose is passive design. Therefore, the connection between thermal comfort standards and passive building requirements should be closer. For example, the perception of personal control is – as described in section 4.3 (page 19), among others driven by predictability of the thermal performance of the building, and this way, personal control as a qualitative factor can be influenced by designing the dynamics of the building performance.

Design and operate for diversity

Occupants' needs and preferences vary inter- and intra-individual with time, space, task, hence a variety of contextual factors (Gauthier et al. 2020, Roetzel et al. 2020). Such a colourful palette needs answers in design, which may not lie in addressing individual need precisely with one solution (this might even fail as the best solution of *now* might not be the right one for *tomorrow*) but with an evenly colourful palette of adaptive opportunities. They can reach from solutions on person level (encouragement to climate responsive clothing) and passive affordances as operable windows or spatial variation of thermal conditions to more advanced technical solutions (Lessons learned from case study building in Appendix 3). A proposal, how to develop such a portfolio of adaptive opportunities was made in this report (see above). Stakeholders' roles in keeping adaptive opportunities properly operating during a building's life time are provided in Appendix 2. Documentation in the building manual is necessary part of it. Another lesson learnt is to prepare buildings for future increasing occupancy and involve the facility management when changes in the layout are planned.

Shaping dynamic thermal building performance

Future design and operating solutions for climates with distinct seasons have to strengthen seasonally varying condition modes by affording targeted seasonal solutions. The adaptive comfort approach offers the potential to intentionally design for all distinct seasons as it provides means to design also the transition between those seasons. To be more precise: It helps to design buildings in a way that allows to operate them as long as possible in free-running mode and shows ways to address divers conditioning modes.

In design practice, dynamic thermal building simulation has been used in order to determine e.g. excess temperatures or to show compliance with acceptable temperature ranges. There is a need to use the *dynamic feature* of dynamic thermal building simulation more intentionally:

Humphreys (1973) suggested to distinguish time periods at which clothing changes occur: within-day, day-to-day and week-to-week or seasonal variation in clothing behaviour, which indicate differentiated temperature changes assigned to these time periods. Extended analysis of existing data from several buildings types show that the temperature ranges found comfortable in conditioned buildings are much wider than standards imply (Humphreys et al, 2013, Nicol, 2017). However, those ranges seem to apply for week-to-week/seasonal differences and for individual levels of temperatures. People are more sensitive to within-day changes (Humphreys et al. 2013). Translating Humphreys' results into practical application of today's building design: One planning focus should be the limitation of within-day changes. Maximum within-day changes can be derived from the sensitivity of 0.5 units on the 7 point scale per Kelvin as recommended for planning by Humphreys et al. (2013). Whereas day-to-day changes and week-to-week changes can be derived making use of the changing comfort band depending on the running mean outdoor temperature. Designing for limitations of within-day and day-to-day variations requires first of all climate adjusted passive design (section 4.4) as it prevents the need for installing fast reacting and energy-intense mechanical systems for whole space conditioning. The knowledge of the mean of the adaptive comfort band informs refining the passive design (day-to-day and seasonal). The magnitude of those changes depend on the local climatic conditions and has been discussed as being represented by the choice of the constant *alpha* in the exponentially-weighted running mean outdoor temperature (McCartney and Nicol, 2002; ASHRAE, 2017).

Consider adaptive principles for all conditioning modes

As discussed in section 4.6, research results support that there is no reason to apply the adaptive principles only for free-running buildings, they apply well in mixed-mode and conditioned buildings. The design means to reach adaptive comfort perception in occupants may differ in detail. Essential part, again, is the integration on appropriate control on individual level and a suitable communication strategy between building operators and occupants. Building management/automation systems or more recent IoT systems (see section 4.6) offer fantastic opportunities to integrate adaptive control algorithms controlling the indoor temperature by following the outdoor conditions. Starting the design from the assumption of an outdoor weather appropriate clothing behaviour of the occupants is a first important contribution, facilitating the transition between conditioning modes. Implementation of personalised comfort systems or individual fans may be another option, integration with the central HVAC system is recommended (Arens and Zhang, 2020).

Integrated design and operation (Holistic design and operation)

Designing buildings for resilience and energy efficiency is facilitated by the adaptive comfort approach. However, the amount of diverse influencing factors, of opportunities for technical solutions, and the interdisciplinary nature of it, can only be solved sufficiently, when the relevant actors in such a process get involved in an active way, when planning disciplines interact and engage with each other, when the process is designed and followed as an iterative optimisation process (Hans and Knudstrup 2005, Hellwig, et al. 2019, Arens and Zhang, 2020). Some education and planners follow already such approaches in their work, with some success.

Standards

Extend the scope

As explained above, there is a need to raise awareness to qualitative factors influencing comfort perception. Currently CEN (2019) provides "…input parameters to the design of building envelope, heating, cooling, ventilation…" A factor not mentioned in a standard, does literally not exist. For instance, there is almost no mentioning of the importance of control (just for elevated air speed control). By implementing a new definition of what satisfaction with the thermal environment means, that it includes the feeling of comfort but also the feeling of pleasure after a successful behaviour action to restore comfort (Hellwig, 2015), this way, personal control by means of adaptive opportunities could be added as a design goal.

Redefine the meaning of the classes/categories

The comfort classes/categories as defined in the standards (A, B, C or I, II, III) have been causing some misunderstandings among building planners. Although defined as level of expectation they are often interpreted as level of quality, with tight indoor climate control seen as most desirable. As described in Hellwig et al. (2019) sustainability rating systems as used in Germany or Denmark, allocate more credits for class A/category I buildings. Class A/ category I stands for high expectation and is meant to be applied for very sensitive people, vulnerable groups who might be sick or restricted in their possibilities to adapt, either because of missing ability to sense temperature or because of disability in changing clothing without the help of others (CEN 2007, 2019). However this does not reflect real comfort/satisfaction performance of buildings in practice as Arens et al. (2009)

showed: Class A indoor environments did not show higher satisfaction than other classes. Therefore, is was proposed, that the level of personal control could be expressed with those classes (Boerstra 2010, Hellwig, 2015), partly found in the Dutch adaptive comfort standard (Boerstra et al. 2015). Arens and Zhang (2020) state that "..Adaptive environments will be true 'Class A' environments..."

Formulation of global adaptive comfort temperature requirements

In section 4.6 it was concluded that potentially, the adaptive model can be applied for all kind of buildings. Therefore, standards should include advice how to support exploitation of the adaptive approach's benefits for all type of buildings and conditioning modes. Inclusion of qualitative factor, e.g. personal control, is one contribution. Another would be to provide condition mode specific expressions of the comfort temperature/ prevailing outdoor relation of the form ($T_c = a * T_{trm} + b$). Parkinson et al. (2020), based on the global ASHRAE database II, found condition mode specific formulations (Task A of this IEA EBC Annex 69). One difficulty is that with prevailing conditioned buildings correlation with outdoor temperature is very low – those buildings have not been designed for adaptation, and hence may not be appropriate to serve as good examples. They remark in addition, that there might be the need to adjust additionally for regions and propose to use the incept for such adjustments but keep the gradient.

Meaning of comfort bandwidth

When the classes/categories would be redefined, according to level of personal control, then there would be the need to define one reasonable comfort bandwidth, as discussed under '*Shaping dynamic thermal building performance', above.* Standards do not yet involve guidance on acceptable within-day changes explicitly. Supplementing such information on the meaning of the acceptable indoor temperature band and limit within-day variations would support building designers to employ dynamic building simulation's full potential. For hot and humid climates, Nicol (2004) proposes an adjusted comfort bandwidth of +/- 1 Kelvin.

Default clothing design assumption

Instead of designing detailed for extreme conditions (winter/ summer clothing), design should incorporate the underlying assumption that people dress according to the outdoor climate. This is implicit in the approach of the outdoor running mean temperature. Providing comfort temperature requirements in the form of the current adaptive model ($T_c = a * T_{trm} + b$) would make it an underlying assumption for all conditioning types. Examples of typical local clothing could be given, but are not necessary. Required would be a communication strategy to the occupants stating that seasonally adjusted clothing is expected. If dress-code would be conditional for specific tasks, than alternative measures on individual level could be taken, e.g. personalised comfort systems.

Include advice how to design for adaptive opportunities

To make designing for adaptive opportunities essential part of designing for occupant satisfaction, requires that basis guidance on how to so is given. A qualitative design procedure for intentional designing adaptive opportunities, as proposed in this report, could be provided in form of a technical document supplementing indoor environmental quality standards. Including reference and basic principles/procedure (not specific requirements) of adaptive opportunities design and operation (see above) can be supplemental.

Designing buildings according to the adaptive principles requires an occupant-centred and climate-centred approach that realises synergistic building-occupant controlled indoor environments in response to the prevailing outdoor weather. Implementing this approach involves many challenges and complexities that demand a collaborative effort between the several building disciplines towards a common goal: achieving comfortable, satisfying indoor environments sustainably.

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Appendix 1: Adaptive comfort models

For the evaluation of naturally ventilated buildings, ASHRAE Standard 55 (2017) includes the adaptive model developed based on ASHRAE RP 884 worldwide database (de Dear et al. 1997). Based on the surveys within the European SCATs study (McCartney and Nicol, 2002), EN 15251:2007 (CEN, 2007), its imminent successor EN 16798 (CEN, 2019) and ISO 17772-1 (ISO, 2017) include a similar model for buildings not mechanically heated or cooled (free running). The terms, models and criteria used in these international standards are summarised in Table 7. Table 8 provides the same information for national standards that have adopted the adaptive approach using the above or other adaptive models.

Climate- or location- specific adaptive models have been developed through field studies around the world. Examples of existing models are provided in Table 9.

Table 7. Terms, thermal comfort models and criteria used in current international standards for different building operation modes

Standard	Building operation mode		
	Free-running	Mixed-mode	Conditioned
ASHRAE Standard 55 (2017)			
Term	- Occupant-controlled naturally conditioned spaces	- Not defined	- Any space
Model	- Adaptive model		- Heat balance model
Criteria	- No mechanical cooling system installed - No heating system in operation - Near sedentary physical activities with metabolic rates ranging from 1.0 – 1.3 met - Avoid strict clothing policies inside the building - Prevailing mean outdoor temperature is: 10°C<T_{rm}<33.5°C - Operable windows to the outdoors operated by the occupants - Mechanical ventilation with unconditioned air may be utilized in addition to operating windows		- Applicable for all buildings - No specific criteria defined
ISO 17772-1 (2017)/ prEN 16798 [superseding EN 15251 (2007)]			
Term	- Buildings without mechanical cooling	- Not defined	- Heated and/or mechanically cooled buildings
Model	- Adaptive model	- Heat balance model and adaptive model seasonally alternating	- Heat balance model
Criteria	- No mechanical cooling or heating in operation - Operable windows or comparable facade components operated by the occupants - Mechanical ventilation with unconditioned air may be utilized in addition to operating windows - Other low-energy methods of personal control such as fans, shutters, night ventilation etc. - Near sedentary physical activities with metabolic rates ranging from 1.0 – 1.3 met - Avoid strict clothing policies inside the building - Running mean outdoor temperature is: 10°C<T_{rm}<30°C	- Common planning practice: combining the heat balance model for the heating period and the adaptive approach for the non-heating period, e.g. in German sustainability certification systems	- Applicable for all buildings - No specific criteria defined

Table 8. Terms, thermal comfort models and criteria used in current national standards for different building operation modes

Standard	Building operation mode		
	Free-running	Mixed-mode	Conditioned
Dutch ISSO 74			
Term	- Not defined	- Alpha	- Beta
Model		- Heat balance model (heating) and adaptive model (non-heating) seasonally alternating	- Heat balance model (heating), adaptive model (transition), heat balance model (cooling)
Criteria		- Criteria set through the use of a flowchart - With occupant control - Free-running conditions in non-heating period with operable windows and other adaptive opportunities - Non-strict clothing policy - Actively cooled spaces, cooling not clearly perceivable by occupants	- Criteria: set through the use of a flowchart - Without or low occupant control - Spaces/zones heated in winter or actively cooled spaces, cooling clearly perceivable by occupants
Chinese GB/T50785-2012			
Term	- Free-running buildings	- Not defined	- Heated or cooled spaces
Model	- Two options: a) adaptive models for different climate zones or - b) adaptive predicted mean vote (aPMV)		- Heat balance model
Criteria	- The adaptive model can be used for two groups of climate zones: 1) severe cold area and cold area, 2) hot summer - cold winter, hot summer - warm winter, and temperate area - Adaptive predicted mean vote (aPMV) conditions are available for climate zones according to 1) and 2) as well - Proper natural ventilation measures should be used		- When using centralised air-conditioning, the outdoor air volume should comply with the relevant national standards

	- Mechanical ventilation/fans can be used but no heating or cooling devices		

(National Code) National Building Code 2017 India, Energy Conservation Building Code 2017 India based on Indian IMAC

(Voluntary Program) GRIHA – Green Building Rating System based on Indian IMAC

Term	- Naturally ventilated (NV)	- Mixed mode	- Air-conditioned (AC)
Model	- Adaptive model for NV buildings based on Indian data	- Adaptive model for mixed mode buildings based on Indian data	- Heat balance model based on ASHRAE St. 55
Criteria	- No mechanical cooling or air-conditioning systems installed - Ceiling fans and operable windows available	- AC is operated only during extreme outdoor conditions	- AC always in operation

Table 9. Adaptive comfort models in different locations/climates.

Source	**Standard/ Project/ Climate**	**Adaptive thermal comfort model ($T_c = C * T_{a, out} + D$)**	**Country**
ASHRAE 55, 2017	ASHRAE Standard 55, 2017 based on ASHRAE database I	$T_{op} = 17.8 + 0.31 * t_{pma\ (out)}$	Global field surveys, naturally ventilated
EN 15251, 2007	EN 15251, 2007 based on Scats	$T_{op} = 0{,}33\ T_{rm} + 18.8$	European field surveys and the results of the SCATs project
Humphreys, 1978	world-wide	$T_c = 0.534 * T_{mm} + 12.9$	free-running
McCartney & Nicol 2002.	The Smart Controls and Thermal Comfort (SCATs) project	$T_c = 0.302 * T_{rm} + 19.39$ for $T_{rm} > 10°C$	London in the UK, Athens in Greece, Lisbon/Porto in Portugal, Lyon France and Malmö Gothenburg in Sweden.
		$T_c = 0.206\ T_{rm} + 21.42$	France
		$T_c = 0.205\ T_{rm} + 21.69$	Greece
		$T_c = 0.381\ T_{rm} + 18.12$	Portugal
		$T_c = 0.051\ T_{rm} + 22.83$	Sweden
		$T_c = 0.168\ T_{rm} + 21.63$	UK
Nguyen et al. 2012	South-East Asia, hot-humid, ASHRAE database I	$Tc = 0.341T_{a;out} + 18.83$	Naturally ventilated and air-conditioned
Indraganti et al. 2014	hot-humid climate, India	$T_c = 0{,}26\ T_{rm} + 21{,}4$	naturally ventilated
		$T_c = 0{,}15\ T_{rm} + 22{,}1$	mixed mode
Manu et al. 2016	several climates of India	$T_n = 0.54\ T_{rm(30\ days)} + 12.83$	India, naturally ventilated buildings
		$T_n = 0.28\ T_{rm(30\ days)} + 17.87$	India, mixed mode buildings

Toe, 2018	hot–humid climates ASHRAE database I	$T_{neutop}=0.57_{Toutdm}+13.8$	range: 19.4-30.5°C daily mean outdoor temperature
Al-Atrash et al. 2020	hot summer Mediterranean climate	$T_c = 0.524 * T_{rm} + 13.3$	Amman/Jordan 6°C ≤ T_{rm} ≤24°C (free running building)
		$T_c = -0.07 * T_{rm} + 28.32$	Amman/Jordan 24°C < T_{rm} ≤28.5°C (free running building)
Parkinson et al. 2020	ASHRAE database II, worldwide	$T_c = 0{,}122 * T_{mm} + 21$	air-conditioned
		$T_c = 0{,}242 * T_{mm} + 19.5$	mixed mode
		$T_c = 0{,}282 * T_{mm} + 19.7$	naturally ventilated

T_c: comfort temperature °C; $T_{a, out}$: outdoor air temperature °C; C and D are constants; tpma (out) is the prevailing mean outdoor air temperature; T_{op} is the operative temperature (°C); T_{mm}: mean monthly outdoor temperature; T_n: neutral temperature; T_{neutop} : Neutral operative temperature; T_{outdm} is daily mean outdoor air temperature (°C), i.e., the 24-h arithmetic mean for the day in question; Trm is the running mean outdoor over the previous seven days (°C).

Appendix 2: Identifying adaptive opportunities in buildings

Below is a list of examples of parameters that can help identify if a building is functioning based on adaptive thermal comfort or whether it has the potential to do so. The list is divided in three levels 1) Design level, 2) Operation level and 3) Behaviour level.

- The items in design level are the parameter that can be incorporated by the integrated design teams during the design phase of the building to ensure that the building can run in adaptive mode.
- The operation level items are the parameters that help the building run in adaptive mode during the operation phase and should be addressed by the facility manager/operator
- The behaviour level includes the parameters that relate to the occupant actions/responses that change according to the changes in the thermal environment (occupant adjustment).

Design Level Checklist

☐ Design for free-running mode of the building, hence for natural ventilation whenever possible, or at least for mixed mode operation

☐ Passive solar design to allow exposure to solar radiation when needed

☐ Appropriate thermal mass design

☐ Window shading design for solar protection under warm conditions

☐ Day/night-time ventilation with appropriate windows design for easy operation by occupants (e.g. operable windows)

☐ Movable furniture to provide opportunities to move to cooler/warmer spots

☐ Integrate active systems which can be adjusted by occupants (e.g. low energy ceiling fans)

☐ Integrate personalised comfort systems for individual occupant adjustments in open plan spaces

☐ Design active systems that operate at variable set points to allow for the experience and adaptation to variable indoor conditions

☐ Design spaces with different indoor climates for use by occupants at different times based on thermal preference

☐ Design of shaded outdoor spaces for use when too hot

☐ Design of spaces for consumption of beverages/food

…to be continued

Operation Level Checklist

☐ Maintain facilities and spaces for relaxation/ consumption of beverages/food

☐ Ensure good operation and maintenance of HVAC systems, controls, shading systems

☐ Check suitability of control settings on window control

☐ Switch off heat emitting equipment when necessary

☐ Prepare feedback system for ensuring easy access of occupants to the facility manager

☐ Flexible timing of building operation

…to be continued

Behaviour Level Checklist

☐ Occupant control over windows

☐ Occupant control over fan speed

☐ Occupant control over fan direction

☐ Occupant control over set point

☐ Occupant control over shading

☐ Changing the location
☐ use of hand fan
☐ Clothing flexibility
☐ Changing activity level
☐ Having hot/cold beverage at desk
☐ Having hot/cold food at desk
☐ Acclimatizing the body
☐ Adjusting body posture
…to be continued

The effectiveness of the implemented adaptive opportunities can be assessed through Post Occupancy Evaluation (POE) to help make necessary adjustments and/or improvements. A POE typically involves both quantitative (e.g. environmental measurements) and qualitative (e.g. questionnaire surveys) techniques. Guidance on evaluation methods can be found in Appendix K of ASHRAE standard 55 (ASHRAE, 2017), ISO 17772-1 (ISO, 2017) and CIBSE Guide A ‘Environmental design’ (CIBSE, 2015).

This table assigns responsibilities for adaptive opportunities related actions to the different stakeholders and can be seen as a complementary presentation of the previous checklists. This table does not intend to be complete and can be used as inspiration to identify responsibilities and necessary actions in design and operation of buildings for all types of adaptive opportunities (adaptive control, indoor environmental affordances)

Table 10. Enabling adaptive opportunities for occupants: Exemplary design and operation actions by stakeholder, slightly adjusted

The first version of this table is a reprint of table 3 in: Hellwig, R. T. et al. (2020c). published at Windsor Conference 2020, Proceedings, Copyright (2020) with permission of the authors.

Examples of adaptive opportunities	Stakeholder responsibility			
	Integrated design team	Organisational management	Operator	Occupant
Adaptive opportunities available	*Design context adjusted adaptive opportunities* *Inform operation*	*Inform the design team* *Facilitate use* *Inform the occupants*	*Inform design and maintain context adjusted adaptive opportunities* *Prepare user and operator manual*	*Take information up and use adaptive opportunities*
Consumption of food and hot or cool drinks	Create/design dedicated spaces	Offer hot or cool beverages as appropriate	Maintain facilities	Having hot/cold food/ beverage
Adjust activity level and metabolic rate	-	Allow/encourage for shifting of certain activities, siesta		Walk around while thinking, take a siesta
Adjust clothing/clothing material	Design with relaxed seasonal dress-code	Relax dress-code	-	Dress for clothing adjustment
Use of ceiling fan and other active systems	Integrate active systems which can be adjusted by occupants	-	Maintain facilities	Make use of the offer
Use of personalised comfort systems (desk fans, warmers, etc)	integrate PCS	Allow/provide PCS	Maintain facilities	Make use of the offer
Use furniture with different insulation levels	Selection of furniture ranges for different thermal experiences	Offer a variety of office chairs/furniture of different colour, sitting ergonomics, etc	Manage change requests	Make use of the offer
Exposure to sun/ use shading	Passive solar design, shading design	with usable shading devices	Ensure good operation and maintenance	Activate/deactivate shading
Window control	Day/night-time ventilation design with appropriate window design (adjustable opening width, manual/ automated control, burglar- and weather-proof design); Address local constraints, e.g. pollution/ noise/insects (insect screens, windows at appropriate building side, etc)	Choose a building with operable windows, passive and climate adjusted design	Suitability of the control settings and maintenance	Open/close window

Control internal heat from equipment (e.g. printers)	Design centralised printer rooms	-	Switch off heat emitting equipment if necessary (heat wave)	Print only when necessary
Thermostatic control	Select HVAC systems with appropriate, accessible controls	-	Ensure the controls are usable/operable	Use controls
Move to a cooler/warmer location	Design different microclimates/ spaces with a variety of conditions	Allow employees to select their work location	Ensure the intended design of variable indoor climates is implemented	Find a location with the preferred indoor climate
Resort to outdoor spaces	Design dedicated outdoor spaces with shading etc	Allow employees to extend their working environment outdoors	Maintain/clean and ensure good state	Work outside
…	…	…	…	…

Appendix 3: Documentation of buildings investigated in Annex 69, Subtask C

IEA EBC Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C: Case studies - Practical learnings from exemplary adaptive buildings

Lead: Richard de Dear, University of Sydney, Australia
Co-Lead: Stephanie Gauthier, University of Southampton, UK; Jungsoo Kim, University of Sydney, Australia,
Disclaimer: recommendations from case-studies are partly context dependent: usage, climate, previous experience

<u>Content</u>:

- Table 8. List of buildings investigated in Annex 69, Subtask C
- Lessons learnt
- Documentation of buildings C01-C14

Table 11. List of buildings investigated in Annex 69, Subtask C

ID	Country	City	Typology	Climate
C01	Australia	Wollongong (Sydney)	University research office	Cfa
C02	Canada	Vancouver	Office building	Cfb
C03	China	Shenzhen	Office building	Cwa
C04	China	Tianjin	Office building	Dfa
C05	India	Ahmedabad	University research office	Bsh
C06	Jordan	Amman	Office building	Csa
C07	Jordan	Amman	Office building	Csa
C08	Korea	Seoul	Office building	Dwa
C09	United Kingdom	Southampton	University research offices	Cfb
C10	United Kingdom	Southampton	University research office	Cfb
C11	United States	Alameda, CA	Small office building	Csc
C12	United States	Los Angeles, CA	Office building	Bwk
C13	United States	Los Angeles, CA	Office building	Bwk
C14	United States	Irvine, CA	Office building	Bsk

IEA EBC Annex 69
Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

Case study buildings

C01 to C14

Please refer to the 14 case-study descriptors for the following information: the contributors, the building description, the occupant type, a description of the dataset, the data collection methods, the data and models availability, a summary, key findings, lessons learned and recommendations for "adaptive" building design (operation and refurbishment), energy performance data and related publications

Summary of findings

Recommendations from 10 case-study buildings have been summarized by themes and described as follows:

- **Design** of the building: adopt passive design principles to reduce the use of mechanical systems.
- **Design** of the spaces: allow for future increase in occupancy and changes in layout.
- **Design** of HVAC systems: ensure that draught is mitigated, in particular to spaces near atrium and vents (inlet/outlet and fan). In some cases, ceiling fan may be a better option than pedestal/desk fans.
- **Design** of HVAC systems: radiant cooling is preferred over convective cooling solutions (e.g. VRF).
- **Design** of double skin façade with windows to the internal glass pane: successful solution to buffer wind, solar gain and external temperature/humidity, while enhancing natural ventilation
- **Design** of blinds and/or solar shading solutions to mitigate glare and solar gains.
- **Design** of BMS systems: ensure that the BMS allows real-time feedback and historic data access/visualisation. BMS to enable better fault detection and forecasting of fault.
- **Design** of control systems: minimize (or even eliminate) actuators, to ease the maintenance of the building.
- **Design** of control systems: ensure appropriate number and location of sensors for operation and maintenance. Ensure individual fell empower over their thermal environment while minimizing conflict in operation mode (i.e. one zone heating and another zone cooling). Design to enable adjustment to meet individual needs and preferences.
- **Specification** of building systems and components: ensure a robust supply chain to all devices, equipment and parts. This will ease the commissioning process and maintenance of the building.
- **Procurement** of HVAC systems: ensure that the mechanical systems and the BMS are under a single contract, to avoid mismanaged interfaces.
- **Commissioning** of control systems: ensure appropriate level of control to all automated system (e.g. manual override, timer and daylight sensor to blinds/shading)
- **Operation** enable a range of adaptive opportunities (i.e. from building controls to dress code)
- **Maintenance** of HVAC systems: ensure seasonal reviews of the set-points (heating and cooling)
- **Engagement** with occupants: introducing a building user guide for lighting and thermal systems (i.e. how does a double skin facade works? How does the chilled beams work? how to set a thermostat? etc.)
- **Engagement** with occupants: introduce a comfort-based smart window and thermostat signaling system (e.g. if energy is wasted, a signal turn red)

IEA EBC Annex 69

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C

Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C01

Contributors

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When and where

06/2017 – 04/2018
University of Wollongong, Australia.

Building(s) description

- Owner type: University
- Building type: Office and research lab building
- Total floor area: 2,600 m^2
- Number of stories: 2 stories, mixed-mode
- Location (city; country): Wollongong, Australia

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	5 minutes	SAMBA*	±0.5 °C
Mean radiant temperature	5 minutes	SAMBA	±0.5 °C
Globe temperature	5 minutes	SAMBA	±0.5 °C
Relative humidity	5 minutes	SAMBA	±3 % RH
Mean air velocity	5 minutes	SAMBA	±0.05 m/s
Outdoor air temperature	30 minutes	Weather station (Australian Bureau of	-
Outdoor relative humidity	30 minutes	Weather station (Australian Bureau of	-

*More information about instrumentation: Parkinson et al. (2019) Continuous IEQ monitoring system: Performance specifications and thermal comfort classification, Building and Environment, 149, 241-252

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; Height; Weight; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City lived in before moving to residence; Country lived in before moving to residence; Köppen-Geiger classification of place living before place of residence; City and Country of origin; Köppen-Geiger classification of place of origin; Perceived control of door, window, curtain/blinds, heating system, cooling system and fan; Reported adjustment of door, window, curtain/blinds, heating system, cooling system; Type of Work

and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation).

- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Thermal acceptability; Air Movement sensation; Draught acceptability; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This study investigated how different modes of operation in the mixed-mode building - air-conditioning (AC) and natural ventilation (NV) - affect indoor thermal environmental conditions and occupant perceptions of thermal comfort. Continuous indoor environmental quality (IEQ) data and building operational data such as HVAC system and windows states were collected, alongside right here right now occupant comfort surveys. Time-and-place matching of these objective and subjective data streams enabled analysis of the relationships between building operational modes, indoor thermal environments, and occupant perception of comfort. The results indicate that the mode of ventilation influenced comfort responses of occupants beyond the direct effects of different thermal conditions. The occupants of the case study mixed-mode building were more tolerant of, or adaptive to, the indoor thermal conditions when the building was in the NV mode of operation compared to the AC operational mode.%.

Key Findings

- Longitudinal field observation made in mixed mode (MM) ventilation building
- Mode of ventilation (NV vs. AC) influenced occupant thermal comfort
- Occupants more tolerant of indoor thermal variations during NV operation
- Clothing prediction model developed and compared against the ASHRAE model
- Adaptive comfort standard can be applied to MM buildings

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

The SBRC Building has overcome some comfort issues, particularly cold in winter, however many of the problems causing these were not due to its design as a low energy adaptive comfort building. In fact the passive design elements within the building have lessened the impact of these problems on comfort. There are four key learnings from the SBRC for future buildings:

- Firstly, problems were caused by commissioning of the Building management System (BMS) and Mechanical Services, contributing to this was the contractual arrangement used in construction. The BMS and Mechanical services were delivered under separate contracts by different firms. This led to mismanaged interfaces between the two systems causing problems with building operation. Whereas if they were under a single contract these interfaces would likely have been better managed.
- Secondly, problems arose as Living Building Challenge certification for materials supply (e.g. composition, or distance from factory to site) often forced contractors to use devices and equipment that were out of normal supply chains. This caused difficulty during installation and commissioning as devices and equipment were often unfamiliar to them, or without the usual parts and service support.
- Thirdly for natural ventilation the SBRC uses hundreds of mechanically actuated windows, each actuator is a maintenance burden and

potential point of failure casing problems with natural ventilation. Designs that minimise (or even eliminate) actuators and allow for easy maintenance are strongly advised.

- Finally, the SBRC is a research testbed that included a number of systems and subsystems purely for research and testing purposes that sometimes included duplication of purpose (e.g. hydronic slab and air conditioning). Future buildings would only need a subset of those systems in the SBRC to successfully operate as an advanced mixed mode adaptive comfort building.

Energy performance/data

The surveyed building is a net-positive energy building comprising a number of office and laboratory areas, which is powered entirely by electricity. The 160 kWp photovoltaic solar array on the roof of the building generates approximately 240 MWh/yr of renewable electrical energy, while the electricity consumption of the building as a whole amounts to approximately 140 MWh/yr, which is 8 MWh/yr less than the design target. The total energy consumption was designed to be less than one third of that for similar conventional buildings at the time of construction. The actual annual electrical energy demand of the HVAC system has been metered as approximately 48 MWh/yr.

Related publications

[1] Kim J., Tartarini F., Parkinson T., Cooper P., de Dear R. (2019) Thermal comfort in a mixed-mode building: Are occupants more adaptive?, *Energy and Buildings,* 203, 109436. https://doi.org/10.1016/j.enbuild.2019.109436.

IEA EBC Annex 69

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C

Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C02

Contributors

Rodrigo Mora & Rohit Upadhyay, Building Science Graduate Program, British Columbia Institute of Technology (BCIT), Vancouver, Canada.

When and where

11/2017 – 10/2018
BCIT, Vancouver, BC, Canada.

Building(s) description

- Owner type: Institute of Technology
- Building type: Office building
- Total floor area: 6,860 m2
- Number of stories: 3 stories, mixed-mode, large 3-storey atrium
- Location (city; country): Vancouver, BC, Canada

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	10 minutes	ONSET HOBO MX1102	± 0.21°C
Mean radiant temperature	10 minutes	ONSET HOBO U12-013 (external sensor)	±0.35°C
Globe temperature			
Relative humidity	10 minutes	ONSET HOBO MX1102	±2 % RH
Mean air velocity	≈ monthly	SensoAnemo series 5100LSF transducer	±0.02 m/s
Outdoor air temperature	10 minutes	MX2301	+/- 0.2C°
Outdoor relative humidity	10 minutes	MX2301	±2.5 % RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Dress code; Approximate distance between weather station and place of survey in [km]; HVAC (thermostat), desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; Height; Weight; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City lived in before moving to residence; Country lived in before moving to residence; Köppen-Geiger classification of place living before place of residence; City and Country of origin; Köppen-Geiger classification of place of origin; Perceived control of door, window, curtain/blinds, heating system, cooling system; Reported adjustment of door, window, curtain/blinds, heating system, cooling system; Workspace arrangement (e.g. pre- allocated workstation vs. no pre-allocated workstation).
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Thermal Acceptability; Air Movement sensation; Draught acceptability; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.

- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study enabled office occupants' comfort and behavior to be researched in a LEED Gold office building built in 2011. The study includes data from open and individual/private offices. Some open-office areas and several private offices have windows with interior blinds. A double-skin façade (DSF) is located in front of all windows except for those in the first floor. Designed for thermal and noise buffering, the façade includes dampers and fans for controlled and enhanced air circulation in warm days and enclosed condition in cool days. Heating, cooling and ventilation is provided by low-energy active chilled beams (ACB) in offices areas and a radiant floor heating system in the central atrium. A high-efficiency ground-source heat pump provides cooling in offices and zones with high cooling loads and heating in offices with high heating loads simultaneously, while rejecting excess heat either to the ground or to the atmosphere.

Key Findings

- The building is high-performance from mechanical and energy efficiency points of view. Adaptive design opportunities are mainly provided to occupants in individual/private offices: operable windows buffered by a DSF, interior blinds, and an individual heating and cooling thermostat. However, except for the blinds, few of them took advantage of those opportunities.
- Except for a few exceptions, windows were generally not opened. After asking occupants, it is hypothesized that the reason is that occupants felt no need to do so since the concurrent MM heating and cooling was continuously providing adequate thermal conditions for comfort.
- The few occupants that opened windows did so mainly to feel sensation of fresh air and air circulation.
- In general, occupants with private offices were satisfied with their office environment. However, occupants in open offices were in general less satisfied. Many occupants in open offices had portable heaters and fans; some voiced complains related to excessive noise from their colleagues.
- Even though most occupants in individual/private offices did not take advantage of the adaptive design opportunities provided by their office, it can be hypothesized that the reason they were in general more comfortable and satisfied with their office environment than occupants in open offices, is the higher level of perceived control they experienced over their office environment.

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

Lessons from "adaptive" building design:

- The efficient simultaneous cooling, heating, and heat dissipation operation of the GSHP made the designer and the facility manager interviewed complacent about the energy efficient delivery of mechanical cooling and heating energy, which does not need to be further saved or avoided. Relying on this idea, designers thought that there was no need control or promote window operation to save energy in MM operation, except for strict humidity control to avoid condensation on the ACBs, i.e. the ACB is turned off when the humidity is high if a window is open.
- Consequently, the building was so "efficiently" mechanically heated and cooled that most occupants in offices with windows saw little need to open windows for thermal comfort, but mainly to "get fresh air". Curiously, observing chilled beam operation of adjacent private offices an inconsistent pattern was observed: it was noted that while in one office the ACB was cooling, in the adjacent office the ACB was heating. This

does not seem to be an energy efficient approach to operate indoor climate systems.

- Despite not being fully exploited for natural ventilation, the double-skin façade (DSF) performs efficiently in buffering wind and ambient temperature fluctuations, and enhancing use of natural ventilation. This was confirmed with temperature and humidity data collected from the DSF, not reported in this study, and a sensation of calm airflows when opening windows to collect façade data regularly.
- In future projects, to encourage occupants to operate windows and thermostats wisely, a comfort-based smart window and thermostat signaling system can be installed that warns occupants when energy is wasted (red), and prompts occupants to open windows and change thermostat settings to save energy when conditions are suitable (green). Such system should be coupled with the building management system to coordinate the operation of windows and ACBs.
- Unfortunately, the mechanical cooling operation cannot be shut down completely in this building because the core building areas still need cooling most of the year, but most importantly computer and data rooms also need to be maintained cool. Furthermore, the GSHP needs to provide enough cooling for the building to prepare the ground for the heating season.
- In conclusion, a building designed to be operated according to the adaptive thermal comfort principles requires that these principles be applied literally "from the ground up", with the selection of energy sources and the design of the mechanical plant taking place with adaptive thermal comfort principles in mind. If possible, occupants should participate in the design process, and be well educated about the possibilities and benefits of adaptive thermal comfort design.

Lessons from operation:

- An important lesson from this study is that the occupants were not educated on the climate system and ventilation in their offices. Furthermore, they were not educated on the energy penalties of improper interactions with the building, or given best practices of building interactions to make the building run more energy efficiently.
- Occupants were completely unaware of the environmental and energy benefits of operating windows, the double-skin façade, and setting the thermostat adequately.
- Occupants were not aware that the chilled beams supplied fresh outdoor air. Some opened the windows even in cold days to get fresh air. One occupant used to crack-open the office window in cold days, while operating a portable heater.
- In many cases, occupants in private offices did not know how to set the thermostat and set it wrongly.
- Occupants in open offices were not even aware of the presence of a thermostat. In one open office with two thermostats, these were wrongly set: the one closer to the window was set for core office conditions and vice versa.

Energy performance/data

According to utility data of the years from 2015 to 2017, the energy use intensity (EUI) of the surveyed building is 217 ekWh/m^2, which is low, compared to the mean value of Canadian offices of 335 ekwh/m^2; and 287 ekWh/m^2, the mean value in offices in the Greater Vancouver area. Which indicates that the building is more energy efficient than the average office building in the same climate zone.

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C03

Contributors

Bin Cao, Jérôme Damiens, Min Li, Maohui Luo, Borong Lin, Yingxin Zhu. Department of Building Science, Tsinghua University, China.

When and where

08/2012 – 08/2013
Shenzhen, China.

Building(s) description

- Owner type: Architectural and Engineering Office
- Building type: Office building
- Total floor area: 18,000 m^2
- Number of stories: 12 stories, mixed-mode
- Location (city; country): Shenzhen, China

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	15 minutes	TJHY WSZY-1	±0.5°C
Mean radiant temperature			
Globe temperature	Random test	TJHY	±0.5°C
Relative humidity	15 minutes	TJHY WSZY-1	±3 % RH
Mean air velocity	Random test	TJHY	±5 % m/s
Outdoor air temperature	1 hour	TJHY WSZY-1	±0.5°C
Outdoor relative humidity	1 hour	TJHY WSZY-1	±3 % RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building; Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Number of people sharing the office room; Age of the participants; Sex; City and Country of residence; Type of Work.
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD).

Data and models availability

- Data availability: The Data analysis is shown in the paper: [Maohui Luo, Bin Cao, Jérôme Damiens, Borong Lin, Yingxin Zhu. Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. Building and Environment, 2015, 88:46-54.]. The original data is not available online.

- Model availability: 'Calculated / derived variables' where derived using the ASHRAE standard 55.

Summary

This study was conducted in a MM office building in Shenzhen, China from August 2012 to August 2013. Through statistical analysis of occupants' thermal responses during air conditioning (AC) and NV periods, considerable differences in occupants' perceived comfort were observed. The results show that occupants' actual thermal sensation and acceptance of thermal conditions both varied when the building changed from AC to NV mode, or vice versa. Compared to the steady state comfort model (i.e., PMV), the adaptive model was found to be more applicable to MM buildings, especially when NV was being utilized. These findings provide support for a more flexible applicability of the adaptive comfort model in the real world, and can serve as a valuable reference for the design and operation of MM buildings.

Key Findings

- In MM buildings, occupants' actual thermal sensation and acceptance of thermal conditions varied when the building changed from AC mode to NV mode, or vice versa.
- The adaptive comfort model was found to be applicable to MM buildings, especially in NV mode.
- In some current comfort standards, the application of the adaptive comfort model is still conservatively constrained to pure NV spaces, which limits MM buildings to operating within more restricted indoor thermal conditions

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

In the design stage, how to make full use of natural conditions to meet the thermal requirement should be considered seriously so as to reduce the energy consumption of the air conditioning in some mixed-mode buildings.

Energy performance/data

This building adopts an integrated design method and over 40 sustainable building design technologies with low energy consumption and low cost. The actual energy intensity of the project is 63 kWh/ m^2 per year, which is significantly lower than the energy consumption of general commercial buildings from 90 to 200kWh/ m^2 per year. The project has been awarded the China's green building three stars logo and the LEED gold certification.

Related publications

[1] Maohui Luo, Bin Cao, Jérôme Damiens, Borong Lin, Yingxin Zhu. Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. Building and Environment, 2015, 88:46-54.

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C04

Contributors

Wenjie Ji, Di Mou, Xinyu Jia, Bin Cao, Yingxin Zhu, Department of Building Science, School of Architecture, Tsinghua University, China.

When and where

10/2017 – 11/2018 & 03/2019 – 06/2019
Tianjin, China.

Building(s) description

- Owner type: Architectural and Engineering Office
- Building type: Office building
- Total floor area: 5,700 m^2
- Number of stories: 6 stories, mixed-mode
- Location (city; country): Tianjin, China

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods 10/2017 – 11/2018

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	5 minutes	TJHY WSZY-1	±0.5°C
Mean radiant temperature			
Globe temperature			
Relative humidity	5 minutes	TJHY WSZY-1	±3 % RH
Mean air velocity			
Outdoor air temperature	1 hour	Getting historical value from nearest weather	
Outdoor relative humidity	1 hour	Getting historical value from nearest weather	

Table 2 Data collection methods 03/2019 – 06/2019

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	5 minutes	TJHY WSZY-1	±0.5°C
Mean radiant temperature			
Globe temperature	5 minutes	TJHY HQZY-1	±0.3 °C
Relative humidity	5 minutes	TJHY WSZY-1	±3 % RH
Mean air velocity	Monthly	TJHY WFWZY-1	±0.05 m/s
Outdoor air temperature	1 hour	Getting historical value from nearest weather	
Outdoor relative humidity	1 hour	Getting historical value from nearest weather	

Description of the datasets

10/2017 – 11/2018 dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Number of people sharing the

office room; Age of the participants; Sex; City and Country of residence; Type of Work.

- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Relative humidity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

03/2019 – 06/2019 dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* , Number of people sharing the office room; Age of the participants; Sex; Height; Weight; City and Country of residence; Period lived at current place; Type of Work.
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Thermal acceptability; Air Movement sensation; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: The data haven't been published in any article yet, thus they are currently not available from the network.
- Model availability: 'Calculated / derived variables' where derived using the ASHRAE Database II validated comfort calculator "IEQ Lab Comfort Index Calculator.xlsm".

Summary

This case study was conducted in a MM office building in Tianjin, China from November 2018 to October 2019. Through statistical analysis of physical parameters and occupants' thermal responses during AC and NV periods, considerable differences in thermal environment and occupants' thermal perception were observed. Occupants' actual thermal sensation differed greatly from PMV in AC and NV modes, indicating that the adaptive model was more applicable in MM buildings than PMV-PPD model. This study provides support for a more flexible applicability of the adaptive model in MM building, and can be used as a reference for the design and operation of MM buildings.

Key Findings

- Occupants perceived thermal comfort varied during AC and NV periods.
- PMV deviated from occupants' actual thermal sensation votes significantly during AC and NV period.
- The adaptive comfort model was found to be more applicable to mixed-mode buildings

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

When designing such buildings, designers should apply passive natural cooling strategies， such as operable windows, ceiling fans, internal blinds, a planted roof, and so on. These strategies should be available to occupants in order to provide adaptive opportunities for occupants to keep a better thermal perception.

Energy performance/data

The tested building received a National Three-Star Green Building Certification after the renovation in 2013. The energy consumption of per unit of area of the building is 47.5kWh/(m^2·a), and the energy demand of HVAC system is 19.6kWh/(m^2·a). The limit value specified in China's GB/T 51161 was 73 kWh/(m^2·a) in the same climate zone in China. Therefore, the building's energy consumption is significantly lower than the similar conventional buildings in the same climate zone.

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C

Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C05

Contributors

Rajan Rawal & Himani Pandya, Centre for Advanced Research in Building Science and Energy, CEPT University, Ahmedabad, India.

When and where

01/2017 – 04/2018
CEPT University, Ahmedabad, India.

Building(s) description

- Owner type: University
- Building type: Research facility
- Total floor area: 800m^2
- Number of stories: 4 stories, mixed-mode
- Location (city; country): Ahmedabad, India

Occupant type

- Research Staff, Administration Staff and Students in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	15 minutes	HOBO ZW-006 and ZW-007 data node with TMC6-HD, TMC20-HD, TMC50-HD temperature sensors	±0.2°C
Mean radiant temperature	1 hour	HOBO U12-012 data logger with TMC1-HD temperature sensor	±0.2°C (MRT Calculated)
Globe temperature	1 hour	HOBO U12-012 data logger with TMC1-HD temperature sensor	±0.2°C
Relative humidity	15 minutes	HOBO ZW-006 and ZW-007 node with DBT-RH sensors	±2.5 % RH
Mean air velocity	One-time	VelociCalc Multi-function Ventilation Meter Model 9565 with 964 Thermoanemometer straight probe	±0.015 m/s
Outdoor air temperature	1 hour	HOBO RX3000 Automatic Weather Station with 12-bit temperature/relative humidity smart sensor	±0.2°C
Outdoor relative humidity	1 hour	HOBO RX3000 Automatic Weather Station with 12-bit temperature/relative humidity smart sensor	±2.5% RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; Height; Weight; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City lived in before moving to residence; Country lived in before moving to residence; Köppen-Geiger classification of place living before place of residence; City and Country of origin; Köppen-Geiger classification of place of origin; Perceived control of door, window, curtain/blinds, heating

system, cooling system and fan; Reported adjustment of door, window, curtain/blinds, heating system, cooling system; Type of Work and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation).

- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Thermal acceptability; Air Movement sensation; Draught acceptability; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study enabled office occupants' comfort and behavior to be researched. The learned thermal comfort, acceptance, and sensation leading to occupant behaviors and preferences contributed to two different studies. In publication [1], a statistical relationship between energy generation-consumption, indoor-outdoor temperature, and thermal comfort is documented. Observed patterns of survey responses show that more than 98% occupants have accepted the thermal environment at the time of survey. The case study building is operated based on India Model for Adaptive (Thermal) Comfort (IMAC). In publication [2], results show when the building is operated at 80% acceptability band of IMAC, more than 90% of the occupants are comfortable and find thermal environment as acceptable with no change in preference to increase or decrease the indoor ambient temperature.

Key Findings

- Passive design strategies help reduce external and internal heat loads and provide an opportunity to operate the building in the naturally ventilated mode as per the need.
- Regular thermal comfort surveys are an effective way of engaging the occupants in the operation of the Net Zero Energy Building (NZEB).
- The hourly average indoor air temperature in a summer typical week experienced a temperature fluctuation of 10 °C with HVAC consumption as high as 25 kWh whereas it did not undergo a significant variation in winter typical week with below 5 kWh HVAC consumption.
- The Energy Performance Index (EPI) of the NZEB was 29.1 kWh/m2/yr in 2017 out of which 70% share was of HVAC systems

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

- Building provide enough adaptive opportunities
- Ceiling fans would have better options over pedestal – desk fans as desk fans makes more noise
- Radiant cooling is preferred option over VRF

Energy performance/data

The surveyed building is a net-positive energy building comprising an office and research laboratory areas, which is powered entirely by electricity. The 30 kWp photovoltaic solar array on the roof of the building generates approximately 42 MWh/yr of renewable electrical energy, while the electricity consumption of the building as a whole amount to approximately 23 MWh/yr, which is 9 MWh/yr less than the design target. The total energy consumption was designed to be less than one sixth of that for similar conventional buildings at the time of construction. The actual annual electrical energy demand of the HVAC system has been metered as approximately 16 MWh/yr.

Related publications

[1] Rawal, R., Manu, S., & Shah, A. (2017). A Report on Net Zero Energy Building - A Living Laboratory, CEPT University, Ahmedabad. Ahmedabad. Retrieved from http://www.carbse.org/a-living-laboratory/.

[2] Rawal, R., Pandya, H., Desai, A., Vardhan, V., Shukla, Y., Manu, S., … Ranjan, A. (2019). Energy & Thermal Comfort Performance Evaluation of Net Zero Energy Building in Hot Dry Climate – A case study. In Proceedings of the 1st International Conference on Comfort at the Extremes: Energy, Economy and Climate (pp. 418–439). Heriot Watt University, Dubai.

IEA EBC Annex 69
Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C06

Contributors

Farah Al-Atrash, School of Architecture and Built Environment, German Jordanian University, Jordan. Runa Hellwig, Department of Architecture, Design and Media Technology CREATE, Aalborg University, Denmark. Andreas Wagner, Building Science Group, Karlsruhe Institute of Technology (KIT), Germany.

When and where

04/2016 – 01/2018
Amman, Jordan.

Building(s) description

- Owner type: Corporate
- Building type: Office building
- Total floor area: 4,095 m^2
- Number of stories: 4 stories, mixed-mode
- Location (city; country): Amman, Jordan

Occupant type

- Office workers in single, shared and open office spaces

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	2 minutes	HOBO U12	±0.35°C from 20° to 30°C
Mean radiant temperature	-	-	-
Globe temperature	2 minutes	external NTC. 10K 3470 temperature sensor probe connected to HOBOs	±0.35°C
Relative humidity	2 minutes	HOBO U12	±2.5 % RH
Mean air velocity	at the time of the questionnaire	Testo 480, thermal flow velocity probe Ø 3 mm	±0.03 m/s
Outdoor air temperature	Hourly	wunderground.com	-
Outdoor relative humidity	Hourly	wunderground.com	-

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; City; Year of construction; Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office roo; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City and Country of origin; Perceived control of door, window, curtain/blinds, heating system, cooling system and fan; Reported adjustment of door, window, curtain/blinds, heating system, cooling system; Type of Work and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation).

- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study enabled office occupants' comfort and behavior to be researched. The results of the loess regression revealed that the adaptive thermal comfort equations resulting in an almost constant temperature of 23.5°C and showing independency from the outdoor temperature conditions. Between the individual offices, the temperature differences were up to 6 K in the same season. Perceived control showed a positive significant correlation with thermal comfort and air quality perception during all seasons. No significant differences in perceived control level with regard to season were found, although the median of perceived control in spring was one scale point lower compared to the other seasons. Perceived control in single offices was the highest.

Key Findings

- The mean and median temperatures were around 23 to 24°C during all seasons.
- The clothing value of the occupants followed the outdoor temperature conditions of the seasons. The ASHRAE clothing value model seems to underpredict the clo-values at lower outdoor temperatures but represents quite well the clothing insulation at temperatures around 2 to 7°C. Since the maximum clo-values we found alter only slightly with season, cultural aspects could play a role.
- The clothing behaviour observed in the two mixed mode buildings indicate an adaptive behaviour too, but the observed indoor temperatures speak for overcompensation of outdoor summer conditions indoors through the availability of thermostat control in each office. The comfort temperatures measured would not be well-represented by and the adaptive approach
- Perceived control correlates positively with both thermal comfort and air quality perception across all seasons.
- No significant differences in the general perceived control level with regard to season were found
- Operable windows are a highly desired feature of workspaces. Buildings should therefore preferably be designed with operable windows, if external environmental conditions are suitable for that
- New variables have been introduced in this study: consistency of perceived and objective availability, and conformity to expectation

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

- Non-operable windows were found in three shared offices. This is surprising, as the building is a LEED certified, aiming for high occupant comfort and satisfaction. Operable windows should be provided in all offices especially that external environmental conditions in Amman/ Jordan are suitable for that.
- Adaptive opportunities should be equally accessed in shared and open offices. Indoor environmental quality is a main section of the LEED scorecard which includes the category of providing controllability over thermal comfort systems. Furthermore, the single offices of the surveyed buildings offered more objectively available control options compared to shared and open-plan offices.
- Providing more external shading devices especially horizontal ones to the south facade.

Energy performance/data

Solar photovoltaic panels are used for exterior lighting. The renewable energy produced 2.5% out of the total energy consumption of both the building and site. Energy efficient lighting techniques were applied, through the use of energy efficient lamps and implementation of a lighting control system which used sensing devices to switch the lights in some spaces. The building design provides 90% of the spaces with daylight and views. Examples of water efficiency management are the rainwater harvesting systems which are used to capture roof and hardscape run-off, and also collect the water condensed from the AC Units. The collected water is stored in special tanks for use with high efficiency irrigation systems and toilet flushing. The project captures and treats 90% of the annual rainfall. The HVAC design provides each space with a separate thermostat. It also has interior shading elements and double-glazed windows. The glazing characteristics are as follows: transmittance (34%), reflectance out (13%), reflectance in (28%), solar energy transmittance (17%), solar energy reflectance (8%), shading coefficient (0.32), U-Value Summer 1.66 W/m^2 K. It used overall, including air-conditioning and lighting, 99 kWh/m^2.a in 2016 and 74 kWh/m^2.a in 2017 where the average consumption for commercial building in Jordan is 200 kWh/m^2 according to the ministry of energy and mineral resources, which is approximately 50% less than the design target. According to commercial buildings energy consumption survey in the USA (Krizmane, 2014), LEED buildings show an average energy use of 82 kWh/m^2.a and range between 35 and 290 kWh/m^2.a.

Related publications

[1] Al-Atrash, F., Hellwig, R. T., & Wagner, A. (2018). Personal control over indoor climate in office buildings in a Mediterranean climate - Amman, Jordan. Windsor conference Proceedings 'Rethinking Comfort', April 2018, 269-314.

[2] Al-Atrash, F. Z. (2018). Adaptive thermal comfort and personal control over office indoor environment in a Mediterranean hot summer climate – the case of Amman, Jordan. (Dissertation). Karlsruhe Institute for Technology (KIT). DOI: 10.5445/IR/1000088485

[3] Al-Atrash, F., Hellwig, R. T., & Wagner, A. (2020). The degree of adaptive thermal comfort in office workers in a hot-summer Mediterranean climate. Energy and Buildings, 223, paper 110147, pp 14, DOI: 10.1016/j.enbuild.2020.110147

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C07

Contributors

Farah Al-Atrash, School of Architecture and Built Environment, German Jordanian University, Jordan. Runa Hellwig, Department of Architecture, Design and Media Technology CREATE, Aalborg University, Denmark. Andreas Wagner, Building Science Group, Karlsruhe Institute of Technology (KIT), Germany.

When and where

04/2016 – 01/2018
Amman, Jordan

Building(s) description

- Owner type: Private Sector
- Building type: Office building
- Total floor area: 25,600 m^2
- Number of stories: 14 stories, mixed-mode
- Location (city; country): Amman, Jordan

Occupant type

- Office workers in single, shared and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	2 minutes	HOBO U12	±0.35°C from 20° to 30°C
Mean radiant temperature	-	-	-
Globe temperature	2 minutes	external NTC. 10K 3470 temperature sensor probe connected to HOBOs	±0.35°C
Relative humidity	2 minutes	HOBO U12	±2.5 % RH
Mean air velocity	at the time of the questionnaire	Testo 480, thermal flow velocity probe Ø 3 mm	±0.03 m/s
Outdoor air temperature	Hourly	wunderground.com	-
Outdoor relative humidity	Hourly	wunderground.com	-

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; City; Year of construction; Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City and Country of origin; Perceived control of door, window, curtain/blinds, heating system, cooling system and fan; Reported adjustment of door, window, curtain/blinds, heating system, cooling system; Type of Work and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation)

- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study enabled office occupants' comfort and behavior to be researched. The results of the loess regression revealed that the adaptive thermal comfort equations resulting in an almost constant temperature of 23.5°C and showing independency from the outdoor temperature conditions. Between the individual offices, the temperature differences were up to 6 K in the same season. Perceived control showed a positive significant correlation with thermal comfort and air quality perception during all seasons. No significant differences in perceived control level with regard to season were found, although the median of perceived control in spring was one scale point lower compared to the other seasons. Perceived control in single offices was the highest.

Key Findings

- The mean and median temperatures were around 23 to 24°C during all seasons.
- The clothing value of the occupants followed the outdoor temperature conditions of the seasons. The ASHRAE clothing value model seems to underpredict the clo-values at lower outdoor temperatures but represents quite well the clothing insulation at temperatures around 2 to 7°C. Since the maximum clo-values we found alter only slightly with season, cultural aspects could play a role.
- The clothing behaviour observed in the two mixed mode buildings indicate an adaptive behaviour too, but the observed indoor temperatures speak for overcompensation of outdoor summer conditions indoors through the availability of thermostat control in each office. The comfort temperatures measured would not be well-represented by and the adaptive approach
- Perceived control correlates positively with both thermal comfort and air quality perception across all seasons.
- No significant differences in the general perceived control level with regard to season were found
- Operable windows are a highly desired feature of workspaces. Buildings should therefore preferably be designed with operable windows, if external environmental conditions are suitable for that
- New variables have been introduced in this study: consistency of perceived and objective availability, and conformity to expectation.

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

- The majority of occupants (75%) worked in an open-plan office environment. Restrictions in accessing the available control options obviously appeared in shared and open-plan offices. This is related to the nature of these office types, as many individuals with different personalities and needs had to work close to each other. Furthermore, some occupants were sitting relatively far away from the control options. The design should enable adjustments to meet individual needs and preferences as well as providing comfort system controls for all shared multi-occupant spaces to enable adjustments that meet group needs and preferences. As well as reducing the percentage of open-plan offices.
- Non-operable windows were found in three shared offices and in two open-plan offices. This is surprising, as the building is a LEED certified,

aiming for high occupant comfort and satisfaction. Operable windows should be provided in all offices especially that external environmental conditions in Amman/ Jordan are suitable for that.

- Adaptive opportunities should be equally accessed in shared and open offices. Indoor environmental quality is a main section of the LEED scorecard which includes the category of providing controllability over thermal comfort systems. Furthermore, the single offices of the surveyed buildings offered more objectively available control options compared to shared and open-plan offices.

Energy performance/data

20% of the materials were manufactured regionally. Grey water reuse and rainwater harvesting have allowed the building to achieve a 50% reduction in potable landscape water use, a reduction of 40% in indoor water use, and a 50% reduction in wastewater generation. Thermal comfort design refers to design heating, ventilating and air conditioning (HVAC) systems and the building envelope to meet the requirements of one of ASHRAE standard 55-2004 or EN 15251: 2007. The energy consumption data are not available for this building.

Related publications

[1] Al-Atrash, F., Hellwig, R. T., & Wagner, A. (2018). Personal control over indoor climate in office buildings in a Mediterranean climate - Amman, Jordan. Windsor conference Proceedings 'Rethinking Comfort', April 2018, 269-314.

[2] Al-Atrash, F. Z. (2018). Adaptive thermal comfort and personal control over office indoor environment in a Mediterranean hot summer climate – the case of Amman, Jordan. (Dissertation). Karlsruhe Institute for Technology (KIT). DOI: 10.5445/IR/1000088485

[3] Al-Atrash, F., Hellwig, R. T., & Wagner, A. (2020). The degree of adaptive thermal comfort in office workers in a hot-summer Mediterranean climate. Energy and Buildings, 223, paper 110147, pp 14 DOI: 10.1016/j.enbuild.2020.110147

IEA EBC Annex 69

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C

Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C08

Contributors

Chungyoon Chun & Suhyun Kwon, Department of Interior Architecture and Built Environment, Yonsei University, KR.

When and where

07/2016 – 03/2017
Seoul, KR.

Building(s) description

- Owner type: Corporate Office
- Building type: Office building
- Total floor area: 25,000 m^2
- Number of stories: 7 stories, mixed-mode
- Location (city; country): Seoul, KR

Occupant type

- Office workers open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	10minutes	Sensirion SHT21	±0.3 °C
Mean radiant temperature			
Globe temperature	10minutes	S+S Regeltechnik RPTF-2	±0.2 °C
Relative humidity	10minutes	Sensirion SHT21	±2 % RH
Mean air velocity	10minutes	TSI TA465	±0.2 m/s
Outdoor air temperature	1 minutes	AWS(Automatic Weather Station, Korea Meteorological Administration)	±0.2 °C
Outdoor relative humidity	1 minutes	AWS(Automatic Weather Station, Korea Meteorological Administration)	± 2 % RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; Height; Weight; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City lived in before moving to residence; Country lived in before moving to residence; Köppen-Geiger classification of place living before place of residence; City and Country of origin; Köppen-Geiger classification of place of origin; Perceived control of door, window, curtain/blinds, heating system, cooling system and fan; Reported adjustment of door, window, curtain/blinds, heating system, cooling system; Type of Work and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation).
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location;

Thermal sensation; Thermal comfort; Thermal preference; Thermal acceptability; Air Movement sensation; Draught acceptability; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.

- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study enabled office occupants' comfort and behavior to be researched. Complaint index were compared between the typical office building and green building. Complaint index was calculated using complaint frequency and exposure time to each temperature. The complaint index of the green building office showed very low level and the difference of complaint frequencies between the seasons were small. The largest difference was observed in summer. Even in the same temperature, occupants in typical office complained overcooling but not in green office. [1]

Key Findings

- In green building, occupants complained less even in the same temperature environment.
- Overcooling in summer time was not observed in green building

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

The building's façade was a curtain wall structure which allowed the daylight to come inside the office. However, the daylight caused glare and warmed up the space in not intentional way. Blinds or some kind of system that could control the daylight would be needed. The office was an open office space with few control points of the thermostat system. Controlling one big zone of the office resulted in affecting the other nearby areas and individuals with different thermal state or work type. More thermostat that able the control of more small zones or encouraging the occupants to use more personal devices could be one solution.

Related publications

[1] Kwon, Suh-hyun, Yoonhee Lee, Chungyoon Chun (2018) The comparison of thermal discomfort between a typical office and a green building office. In 15th *international Conference on Indoor Air Quality and Climate*.15rh International Conference on Indoor Air Quality and Climate, 2018

IEA EBC Annex 69
Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C09

Contributors

Stephanie Gauthier & Leonidas Bourikas, Energy & Climate Change Group, Faculty of Engineering & Physical Sciences, University of Southampton, UK.

When and where

07/2017 – 06/2018
University of Southampton, Southampton, UK.

Building(s) description

- Owner type: University
- Building type: Office and research lab building
- Total floor area: 10,650 m^2
- Number of stories: 7 stories, mixed-mode, atrium level 3 to 7
- Location (city; country): Southampton, UK

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	5 minutes	Extech Instrument model SD800	±0.8 °C
Mean radiant temperature	5 minutes	Mindset mini temperature data logger 161-357	±0.5 °C
Globe temperature	-	-	-
Relative humidity	5 minutes	Extech Instrument model SD800	±4 % RH
Mean air velocity	Bi-monthly	DeltaOhm HD32.3	±0.2 m/s
Outdoor air temperature	5 minutes	Oregon Scientific WMR500	±1 °C
Outdoor relative humidity	5 minutes	Oregon Scientific WMR500	±5 % RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City lived in before moving to residence; Country lived in before moving to residence; Köppen-Geiger classification of place living before place of residence; City and Country of origin; Köppen-Geiger classification of place of origin; Perceived control of door, window, curtain/blinds, heating system; Reported adjustment of door, window, curtain/blinds, heating system.
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.

- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

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- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

The learned windows opening behaviors contributed to two different studies. The results of the first study [1] established a relationship between window opening behavior, indoor ambient and radiant temperature and CO_2 levels. Observed patterns of window opening behaviour did not match the building's design strategy as users acted differently from what BMS advised. This will have a substantial impact on energy performance in summer. The second study [2] aimed to quantify occupants' window behaviour impact to the energy performance gap. The study showed that window opening behaviour increased heading load by 17%.

Key Findings

Longitudinal comfort surveys in mixed mode building

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

Recommendations from the facility manager were as follows:

- Design and commissioning of the HVAC system: Draught should be mitigated in the open plan office, in particular with the working spaces around the atrium and with the floor inlets from the displacement ventilation system.
- Design of HVAC controls: some operation mode may be over-complicated, while other do not enable changes. For example, east facing external shadings are controlled by daylight sensors (not timer). This control strategy causes overheating in summer. Further issues are with the access of the controls/actuators (e.g. scaffolding or abseiling) and the maintenance of parts (e.g. maintenance by specialist contractors only, actuators within window frames, manufacturer ceasing trading, etc.).
- Design of internal spaces: allow for future increase in occupancy and changes in layout. For example, cellular offices were introduced, which impacted on the air flow. Mechanical systems had to be introduced to ventilate these new offices.

Energy performance/data

The case study building received BREEAM certification Very Good at completion. The building maximizes passive design measures of orientation, shading, super-insulation and exposed thermal mass. A mixed-mode ventilation system with automated and user operated windows uses the lightwell as a solar stack and mechanical assistance with heat recovery for peak conditions. Renewables included a biomass boiler. The building uses low energy lighting throughout. The 2019 display energy certificate shows a G rating (195). The annual energy demand for heating was 166 kWh/m^2/year, which is only 72% of the heating demand of a typical office building in the same climate zone. However, the annual electricity demand was 215 kWh/m^2/year, or 270% of the electricity demand of a typical office building. This large electricity demand is attributed to the laboratories in the building, including transgenic glasshouses and neuroimaging suite.

Related publications

[1] Giakoumis, George and Gauthier, Stephanie (2016) Understanding window behaviour in a mixed-mode buildings and the impact on energy performance. In Proceedings of the 6th Masters Conference: People and Buildings. London, UK, 23rd September 2016. Network for Comfort and Energy Use in Buildings.

[2] Pradana, Muhamad, Gauthier, Stephanie and Bourikas, Leonidas (2017) Close the energy performance gap, a window at a time. In Proceedings of the 7th Masters Conference: People and Buildings. London, UK, 22th September 2017. Network for Comfort and Energy Use in Buildings.

IEA EBC Annex 69

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C

Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C10

Contributors

Stephanie Gauthier & Leonidas Bourikas, Energy & Climate Change Group, Faculty of Engineering & Physical Sciences, University of Southampton, UK.

When and where

08/2017 – 06/2018
University of Southampton, Southampton, UK.

Building(s) description

- Owner type: University
- Building type: Office and research lab building
- Total floor area: 6,160 m^2
- Number of stories: 5 stories, mixed-mode, atrium level 3 to 5
- Location (city; country): Southampton, UK

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	5 minutes	Extech Instrument model SD800	±0.8 °C
Mean radiant temperature	5 minutes	Mindset mini temperature data logger 161-357	±0.5 °C
Globe temperature	-	-	-
Relative humidity	5 minutes	Extech Instrument model SD800	±4 % RH
Mean air velocity	Bi-monthly	DeltaOhm HD32.3	±0.2 m/s
Outdoor air temperature	5 minutes	Oregon Scientific WMR500	±1 °C
Outdoor relative humidity	5 minutes	Oregon Scientific WMR500	±5 % RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; City and Country of residence; Period lived at current place; Köppen-Geiger classification of place of residence; City lived in before moving to residence; Country lived in before moving to residence; Köppen-Geiger classification of place living before place of residence; City and Country of origin; Köppen-Geiger classification of place of origin; Perceived control of door, window, curtain/blinds, heating system, cooling system; Reported adjustment of door, window, curtain/blinds, heating system, cooling system.
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.

- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

The longitudinal comfort surveys contributed to two different studies. In the first study [1], thermal comfort surveys contributed to a review of the value of alpha as defined in BS EN 15251. In the second study [2], the longitudinal data from this case study together with another five buildings' dataset was used to clustering of individual thermal sensation votes to identify four thermal sensation traits. Besides, this study introduced a person-centric thermal zone (Zt) to inform adaptive building strategies.

Key Findings

Longitudinal comfort surveys in mixed mode building

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

Recommendations from the facility manager were as follows:

- Inform the occupants by introducing a building-users' guide, explaining how thermal and lighting systems operate; for example, it may answer the following questions: How to dim the lights? How to switch on the heating? This will avoid windows being opened when HVAC systems are on.
- Design and commissioning of the controls: ensure that the occupancy sensors are located appropriately.
- Design and commissioning of the HVAC system: ensure that the building management system (BMS) allows real-time feedback and historic data access/visualization. Are the systems working as they should? If not, where is the fault? BMS system should enable better fault detection and forecasting of fault.
- Commissioning and maintenance of the HVAC system: ensure that a review of the set-points is undertaken as the start of every seasons (2 to 4 times per year).

Energy performance/data

The case study building received BREEAM certification Excellent at completion. The building maximizes passive design measures of shading, super-insulation and exposed thermal mass. A mixed-mode ventilation system with automated and user operated windows uses mechanical assistance with heat recovery for peak conditions. It is heated and powered by a CHP plant. The 2019 display energy certificate shows a D rating (98). The annual energy demand for heating was 102 kWh/m^2/year, which is only 44% of the heating demand of a typical office building in the same climate zone. However, the annual electricity demand was 123 kWh/m^2/year, or 153% of the electricity demand of a typical office building. This large electricity demand is attributed to the laboratories on the ground floor of the building.

Related publications

[1] Pasalidou, S., Gauthier, S. and Bourikas, L. (2018) Revisiting the adaptive control algorithm to UK office buildings. In Proceedings of the 8th Masters Conference: People and Buildings. London, UK, 21st September 2018. Network for Comfort and Energy Use in Buildings.

[2] Gauthier, S., Bourikas, L., Al-Atrash, F., Bae, C., Chun, C., de Dear, R., Hellwig, R.T., Kim, J., Kwon, S., Mora, R., Pandya, H., Rawal, R., Tartarini, F., Upadhyay, R. and Wagner, A. The colours of comfort: From thermal sensation to person-centric thermal zones for adaptive building strategies. Energy and Buildings, under review.

IEA EBC Annex 69
Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C11

Contributors

Center for the Built Environment, UC Berkeley, USA.

When and where

10/2011 – 10/2012
Alameda, CA, USA.

Building(s) description

- Owner type: Privately owned
- Building type: Small office building
- Total floor area: 260 m^2
- Number of stories: 2 stories
- Location (city; country): Alameda, CA, USA

Occupant type

- Office has two rooms and open office spaces

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	5 minutes	Onset U-12 hobo data loggers	±0.35 °C
Mean radiant temperature	-	-	-
Globe temperature	-	-	-
Relative humidity	5 minutes	Onset U-12 hobo data loggers	±2.5 % RH
Mean air velocity	-	-	-
Outdoor air temperature	5 minutes	Onset U-12 hobo data loggers	±0.35 °C
Outdoor relative humidity	5 minutes	Onset U-12 hobo data loggers	±2.5 % RH

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Perceived control of door, window, curtain/blinds, heating system, cooling system and fan; Reported adjustment of door, window, curtain/blinds, heating system, cooling system.
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Perceived Air Quality; Ensemble clothing insulation of the subject (clo); Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity; Outdoor air temperature and Outdoor relative humidity.

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

The aims of this study are to how occupants exercise various adaptive control opportunities to meet their comfort needs in the absence of a mechanical HVAC system. The building provided acceptable thermal conditions for 98% of the survey period, covering an indoor temperature range of 16–28 °C. Occupants opened windows when the outdoor temperature was above 15 °C, with window opening often occurring at the occupant's arrival and proportional to outdoor temperature. Fan use was by indoor temperature, typically being turned on during summer at indoor temperatures above 25 °C. Heaters were turned on in winter more than an hour after arrival and commencement of sedentary activity. With these adaptive control behaviors, occupants were thermally neutral and satisfied from 18 to 27 °C. Their satisfaction exceeded that predicted by ASHRAE Standard 55 or PMV-based ISO standards.

Key Findings

- In the Alameda building, a knowledge-worker occupancy aware of naturally ventilated design principles uses windows and fans very effectively to achieve thermal comfort throughout the year in a building with no HVAC.
- The windows opening/closing patterns are heavily driven by occupancy.
- The measured acceptability results from this study provide evidence that PMV-based classification system, and particularly the narrow 'class I' classification, is inappropriate for the adaptive comfort design and operation in this building

Related publications

[1] Yongchao Zhai, Anoop Honnekeri, Margaret Pigman, Edward Arens. Use of adaptive and its effects on human comfort in a naturally ventilated office in Alameda, California. Energy & Buildings 203(2019)109435.

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Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C12

Contributors

Kyeongsuk Lee, Schoo of Architecture, University of Southern California, USA; Joon-ho Choi, Marc Schiler & Selwyn Ting, Faculty of Architecture, University of Southern California, USA; Heidi Creighton, AIA, LEED AP BD+C, O+M, WELL AP, Buro Happold Engineering, USA.

When and where

01/2018 – 11/2018
Los Angeles, CA USA.

Building(s) description

- Owner type: Corporate: Privately Held
- Building type: Office building
- Total floor area: 15,000 m^2
- Number of stories: 16 stories
- Location (city; country): Los Angeles, CA, USA

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	Bi-monthly	USC's e-BOT, HOBO	±0.7 °C
Mean radiant temperature	Bi-monthly	Hand-held sensors, HDR camera	±1 °C
Globe temperature	-	-	-
Relative humidity	Bi-monthly	e-BOT, HOBO	±3% RH
Mean air velocity	-	-	-
Outdoor air temperature	-	-	-
Outdoor relative humidity	-	-	-

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; City and Country of residence; Type of Work and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation).
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Draught acceptability; Perceived Air Quality; Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative

temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study investigated office occupants' comfort and satisfactions as a function depending on IEQ measurement time and IEQ quality. The results indicated that the occupants had different environmental perceptions, even when their IEQ conditions were constant, or only slightly changed. Moreover, human factors, such as age and gender, also had an impact on human perceptions of the environment. This resulted in variations in the IEQ satisfaction of each individual, depending on the season and/or month. These findings suggested that multiple-time data collection is required to generate a robust environmental design solution by increasing understanding of the relationship between humans and environmental factors. This study also confirmed potential parameters to be considered to define environmental comfort, i.e., thermal comfort condition.

Key Findings

- This study was conducted using two office buildings located in Southern California, U.S.A.
- This study revealed there is a possible impact of IEQ measurement time on user satisfaction.
- While actual IEQ conditions were almost the same, the user groups reported different environmental satisfaction levels.
- The inconsistent environmental satisfaction levels were observed in a certain age and gender group.
- The results of this study have potential for being adopted in user-centered environmental control with consideration of the effects of season and/or time of day.

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

- If you have an option to choose to maximize between energy efficiency and occupants' comfort, which one would you put more weight for decision?
- What is the ideal frequency to check the occupants' environmental comfort and building operational performance in reality?

Energy performance/data

The case-studied building has been certified as a LEEE-Gold in performance, and the interior was certified as a WELL Building -Platinum. Unfortunately, the energy performance was not accessible to collect.

Related publications

[1] Choi, Joon-ho, Loftness, Vivian and Aziz, Azizan (2011) Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines. Energy and Buildings, 46, 167-175.

[2] Choi, Joon-ho and Moon, Jahyun (2017) Impacts of human and spatial factors on user satisfaction in office environments. Building and Environment, 114, 23-35.

[3] Choi, Joon-ho and Lee, Kyeongsuk,(2018) Investigation of the feasibility of POE methodology for a modern commercial office building. Building and Environment, 143, 591-604.

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Subtask C
Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C13

Contributors

Kyeongsuk Lee, Schoo of Architecture, University of Southern California, USA; Joon-ho Choi, Marc Schiler & Selwyn Ting, Faculty of Architecture, University of Southern California, USA; Heidi Creighton, AIA, LEED AP BD+C, O+M, WELL AP, Buro Happold Engineering, USA.

When and where

01/2018 – 11/2018

Los Angeles, CA USA.

Building(s) description

- Owner type: Corporate: Privately Held
- Building type: Office building
- Total floor area: 33,600 m^2
- Number of stories: 62 stories
- Location (city; country): Los Angeles, CA, USA

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	Bi-monthly	USC's e-BOT, HOBO	±0.7 °C
Mean radiant temperature	Bi-monthly	Hand-held sensors, HDR camera	±1 °C
Globe temperature	-	-	-
Relative humidity	Bi-monthly	e-BOT, HOBO	±3% RH
Mean air velocity	-	-	-
Outdoor air temperature	-	-	-
Outdoor relative humidity	-	-	-

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
- *Participants' variables, gathered from participants' survey, including:* Average number of hours per week spent in the office; Number of people sharing the office room; Age of the participants; Sex; City and Country of residence; Type of Work and Workspace arrangement (e.g. pre- allocated workstation vs. no pre- allocated workstation).
- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Draught acceptability; Perceived Air Quality; Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

Reference: [All the authors of Subtask C] Case studies - Practical learnings from exemplary adaptive buildings (2019) Available at: https://osf.io/z8vnp/?view_only=c265738c4ba0491baf991b13c861973d (Accessed: 7th September 2019)

- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study investigated office occupants' comfort and satisfactions as a function depending on IEQ measurement time and IEQ quality. The results indicated that the occupants had different environmental perceptions, even when their IEQ conditions were constant, or only slightly changed. Moreover, human factors, such as age and gender, also had an impact on human perceptions of the environment. This resulted in variations in the IEQ satisfaction of each individual, depending on the season and/or month. These findings suggested that multiple-time data collection is required to generate a robust environmental design solution by increasing understanding of the relationship between humans and environmental factors. This study also confirmed potential parameters to be considered to define environmental comfort, i.e., thermal comfort condition.

Key Findings

- This study was conducted using two office buildings located in Southern California, U.S.A.
- This study revealed there is a possible impact of IEQ measurement time on user satisfaction.
- While actual IEQ conditions were almost the same, the user groups reported different environmental satisfaction levels.
- The inconsistent environmental satisfaction levels were observed in a certain age and gender group.
- The results of this study have potential for being adopted in user-centered environmental control with consideration of the effects of season and/or time of day.

Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

- If you have an option to choose to maximize between energy efficiency and occupants' comfort, which one would you put more weight for decision?
- What is the ideal frequency to check the occupants' environmental comfort and building operational performance in reality?

Energy performance/data

The case-studied building has been certified as a LEEE-Gold equivalent in performance. Unfortunately, the energy performance was not accessible to collect.

Related publications

[1] Choi, Joon-ho, Loftness, Vivian and Aziz, Azizan (2011) Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines. Energy and Buildings, 46, 167-175.

[2] Choi, Joon-ho and Moon, Jahyun (2017) Impacts of human and spatial factors on user satisfaction in office environments. Building and Environment, 114, 23-35.

[3] Choi, Joon-ho and Lee, Kyeongsuk,(2018) Investigation of the feasibility of POE methodology for a modern commercial office building. Building and Environment, 143, 591-604.

IEA EBC Annex 69

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Subtask C

Case studies - Practical learnings from exemplary adaptive buildings

Case study building

C14

Contributors

Kyeongsuk Lee, Schoo of Architecture, University of Southern California, USA; Joon-ho Choi, Marc Schiler & Selwyn Ting, Faculty of Architecture, University of Southern California, USA; Heidi Creighton, AIA, LEED AP BD+C, O+M, WELL AP, Buro Happold Engineering, USA.

When and where

01/2018 – 11/2018
Irvine, CA USA.

Building(s) description

- Owner type: Corporate: Privately Held
- Building type: Office building, Mixed -Use
- Total floor area: 8,500 m^2
- Number of stories: 11 stories
- Location (city; country): Irvine, CA USA

Occupant type

- Office workers in cellular and open office space

Table 1 Data collection methods

Variables	Collection frequency	Data collection equipment specification	Accuracy of readings
Indoor air temperature	Bi-monthly	USC's e-BOT, HOBO	±0.7 °C
Mean radiant temperature	Bi-monthly	Hand-held sensors, HDR camera	±1 °C
Globe temperature	-	-	-
Relative humidity	Bi-monthly	e-BOT, HOBO	±3% RH
Mean air velocity	-	-	-
Outdoor air temperature	-	-	-
Outdoor relative humidity	-	-	-

Description of the datasets

The dataset has four types of variables, described as follows:

- *Buildings' variables, established by the researcher(s), including:* Köppen-Geiger classification of place of case study; Country; City; Year of construction; Year of major refurbishment (e.g. façade, HVAC system, etc.); Type of building (occupying organisation); Operation mode (AC, MV, MM, NV, or undefined); Heating strategy; Cooling strategy; Presence of personal system (blind, shade, fan); Dress code; ID of closest weather station used by weather underground; Approximate distance between weather station and place of survey in [km]; Type of weather station and Control by individual occupant of operable window, HVAC (thermostat), ceiling/pedestal/desk fan, external shade and blind.
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- *Thermal comfort surveys' variables, including:* Completion date and time; Season; Location; Thermal sensation; Thermal comfort; Thermal preference; Air Movement sensation; Draught acceptability; Perceived Air Quality; Average metabolic rate of the subject (Met); Indoor air temperature; Mean radiant temperature; Relative humidity; Mean air velocity.
- *Calculated / derived variables from other variables of the comfort surveys:* Operative

temperature (Top); Predicted mean vote (PMV); Predicted percentage of dissatisfied (PPD) and Standard Effective Temperature (SET).

Data and models availability

- Data availability: All data records listed above are available from the project page on Open Science Framework (OSF) (European server) and can be downloaded without an OSF account. The following information were removed, as they can serve to identify an individual participant: age, height, weight, cities of residence, before residence and origin.

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- Model availability: 'Calculated / derived variables' where derived using the R code form the comf package.

Reference: Schweiker, M. et al (2017) comf: Functions for Thermal Comfort Research. Available at: https://github.com/marcelschweiker/comf (Accessed: 7th September 2019)

Summary

This case study investigated office occupants' comfort and satisfactions as a function depending on IEQ measurement time and IEQ quality. The results indicated that the occupants had different environmental perceptions, even when their IEQ conditions were constant, or only slightly changed. Moreover, human factors, such as age and gender, also had an impact on human perceptions of the environment. This resulted in variations in the IEQ satisfaction of each individual, depending on the season and/or month. These findings suggested that multiple-time data collection is required to generate a robust environmental design solution by increasing understanding of the relationship between humans and environmental factors. This study also confirmed potential parameters to be considered to define environmental comfort, i.e., thermal comfort condition.

Key Findings

- This study was conducted using two office buildings located in Southern California, U.S.A.
- This study revealed there is a possible impact of IEQ measurement time on user satisfaction.
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- The inconsistent environmental satisfaction levels were observed in a certain age and gender group.
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Lessons learned and recommendations for "adaptive" building design; operation and refurbishment

- If you have an option to choose to maximize between energy efficiency and occupants' comfort, which one would you put more weight for decision?
- What is the ideal frequency to check the occupants' environmental comfort and building operational performance in reality?

Energy performance/data

The case-studied building has been certified as a LEEE-Gold in performance. Unfortunately, the energy performance was not accessible to collect.

Related publications

[1] Choi, Joon-ho, Loftness, Vivian and Aziz, Azizan (2011) Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines. Energy and Buildings, 46, 167-175.

[2] Choi, Joon-ho and Moon, Jahyun (2017) Impacts of human and spatial factors on user satisfaction in office environments. Building and Environment, 114, 23-35.

[3] Choi, Joon-ho and Lee, Kyeongsuk,(2018) Investigation of the feasibility of POE methodology for a modern commercial office building. Building and Environment, 143, 591-604.

Appendix 4: Publications and presentations related to this activity B2

1) Papers published/accepted by the Special Issue of "Adaptive Thermal Comfort" in Energy and Buildings

Runa T. Hellwig, Despoina Teli, Marcel Schweiker, Joon-Ho Choi, M.C. Jeffrey Lee, Rodrigo Mora, Rajan Rawal, Zhaojun Wang, Farah Al-Atrash (2019): A Framework for Adopting Adaptive Thermal Comfort Principles in Design and Operation of Buildings, Energy and Buildings, 2019, 109476, https://doi.org/10.1016/j.enbuild.2019.109476

Al-Atrash, F., Hellwig, R. T., & Wagner, A. (2020). The degree of adaptive thermal comfort in office workers in a hot-summer Mediterranean climate. Energy and Buildings, [110147]. http://www.scopus.com/inward/record.url?scp=85085490807&partnerID=8YFLogxK (Appendix 3, case study buildings 06 and 07)

2) Papers published/accepted by other issues or journals, but the papers mention their relevance to Annex 69, activity B2 (in the acknowledgement or other sections).

Runa T. Hellwig (2019): On the relation of thermal comfort practice and the energy performance gap. IOP Conference Series: Earth and Environmental Science, Vol 352, 1, 8 pp. https://iopscience.iop.org/article/10.1088/1755-1315/352/1/012049

Hellwig, R. T., Despoina, T., Schweiker, M., Choi, J-H., Lee, J. M. C., Mora, R., Rawal, R., Wang, Z., Al-Atrash, F. (2019). Applying adaptive principles: Developing guidance for planning practice. I S. Roaf and W. Finlayson, eds., Comfort at the Extremes: Energy, Economy and Climate (CATE). [online] Dubai (s. 262-276)

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3) Papers published/accepted which do not mention the Annex, but the topic of the paper is highly relevant to Annex69, Activity B2 (adaptive thermal comfort).

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Al-Atrash, F., Hellwig, R. T., & Wagner, A. (2018). Personal control over indoor climate in office buildings in a Mediterranean climate - Amman, Jordan. I Proceedings of 10th Windsor Conference: Rethinking Comfort Cumberland Lodge, Windsor, UK, 12-15 April 2018. London. [paper 0132] Network for Comfort and Energy Use in Buildings, http://nceub.org.uk, http://windsorconference.com/proceedings/.

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4) Workshops on Annex 69, Activity B2

Workshop Harbin at International Symposium on heating, Ventilation and Air Conditioning ISHVAC, July 2019: Adaptive thermal comfort for low energy buildings (IEA-EBC Annex69), Chairs: Bin Cao, Runa T. Hellwig
Talk No 5 Hellwig, R.T. et al.: Applying the adaptive thermal comfort concept for lowering the energy use in buildings

Workshop Indoor Air 2020: Guidelines on adaptive thermal comfort application in building design and operation. 16th Conference of the International Society of Indoor Air Quality & Climate (Indoor Air 2020) Seoul, Korea 2-4th November 2020, Live-Zoom discussion on 4th November 2020, 09:30 AM CET- 11:00 AM, 25 Participants

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ANNEX 69

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Energy in Building and
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