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Guidelines to bridge the gap between adaptive thermal comfort theory and building design and operation practice

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Abstract: Adaptive thermal comfort guidelines have been developed within the work of Annex 69: "Strategy and practice of adaptive thermal comfort in low energy buildings". The guidelines have been established based on a framework for adopting adaptive thermal comfort principles in building design and operation developed by the authors. The guidelines target building practitioners, addressing the critical interrelated role building planners, building operators and occupants play. A successful adaptive thermal comfort design, in which design for human thermal adaptation is foreseen, planned, and carefully embedded in the design and operation intent, is based on broad knowledge and understanding of the multiple quantifiable and non-quantifiable factors influencing human perception, as well as human building interaction. Adaptive building design follows a user-centric integrated design approach and therefore it is critical to consider the occupants' and the operators' role in buildings already in the design phase. This paper focuses on three main challenges identified earlier and how these are addressed in the guidelines, i.e. i) updating prevailing knowledge about human thermophysiology and adaptation, ii) developing a procedure for design of adaptive opportunities, and iii) providing guidance for operational planning and operation of adaptive buildings. The challenge for future research remains to assess the magnitude of how specific design decisions affect particular adaptive mechanisms.

Keywords: Adaptive thermal comfort, Personal control, Building energy efficiency, Climate context, Integrated Design, Occupant, Stakeholder

1. Introduction

Ensuring acceptable indoor temperatures with the minimum required energy use is one of the world's challenges. The adaptive thermal comfort concept originates from the pioneering works of Webbs (1964), Auliciems (1969a, 1969b, 1981b, 1981a), Nicol and Humphreys (1973) and Humphreys (1976, 1978), who established the relationship between human thermal

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comfort and prevailing indoor and outdoor conditions. In contrast to the static view on thermal comfort, they define thermal comfort as a self-regulating[1] system. Their work formed the foundation for the formulation of the three adaptive principles, today known as behavioural, physiological, and psychological (de Dear et al. 1997). Since its development, numerous proofs of the adaptive thermal comfort concept were found in field studies.

Designs that apply the adaptive comfort principles by leveraging on people's natural ability to align with the outdoor climate result in more variable indoor temperatures over time, with the following benefits: 1) Avoid or reduce mechanical energy use, and help mitigate climate change, 2) enhance people's and buildings' resilience to climate change, and 3) increase thermal satisfaction of occupants, and 4) improve occupants' health and well-being (Table 1).

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

	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	Wide and sloped comfort bands dependent on the prevailing local climate, enabling relaxed set points, and reflecting thermal preferences	*Resilience to climate change* - Enhance, rather than impair, physiological adaptation to the local climate, making buildings adjusted to local and enhance their supportive thermal behaviour
3	Designed, well implemented, and well-communicated adaptive opportunities and (objective and perceived) controls	*Improved usability and thermal satisfaction* - Improved operation of the building according to the design intent, improved occupants' thermal satisfaction through increased perceived control
4	Designed passively or actively regulated dynamic thermal environments that fluctuate within the adaptive comfort bands	*Health and well-being* - Improved thermal satisfaction, improved health and well-being, thermal delight

Despite the above benefits and the considerable progress in adaptive comfort research, the manifestation of theory into design and operation practice is far from realisation. The limited examples of successfully adopted adaptive design and building operation in energy efficient building practice point to a need for developing guidance for building planners and operators[2].

For the development of the guidelines, the challenges and gaps in adopting the adaptive principles in practice were identified (Hellwig et al. 2019). The required actions to address these challenges can be summarised as follows:

- updating the understanding of human thermophysiology and supporting a better understanding of adaptation and acclimatisation

[1] This term was coined by Nicol and Humphreys (1973).

[2] In order to bridge this gap, Annex 69: "Strategy and practice of adaptive thermal comfort in low energy buildings" was established in 2015 by international thermal comfort experts under the umbrella of the International Energy Agency's (IEA) Energy in Buildings and Communities Programme (EBC). O One of the major project deliverables is a design guideline on how to use the adaptive comfort concept for lowering the energy use in buildings, including the usage of personal thermal comfort systems (EBC 2018).

- supporting a comprehensive understanding of the adaptive thermal comfort concept among practitioners: explaining the conceptual model behind the equation and the impact of contextual non-quantifiable factors
- interlinking the conceptual model of adaptive thermal comfort with building design beyond using it for determining acceptable temperature ranges
- interlinking the conceptual model of adaptive thermal comfort with operational practice in buildings
- explaining the important role of personal control and how to design for adaptive opportunities
- explaining the importance of dynamic effects in comfort with regards to design
- clarifying terminology used (building conditioning types, building classes)
- addressing the different roles of stakeholders in the process
- enabling planners to further develop their design and adapt their building design for future climate conditions
- indicating solutions for permanently or seasonally conditioned buildings

A framework was subsequently developed (Hellwig et al. 2019), which forms the basis of the guidelines. It emphasises those elements of an integrated design process[3] being most relevant for the adoption of the adaptive principles in practice: the adaptive principles, the building context, the planning and design, the operational planning and operation, and, as the end goal, the adaptive responses or actions of the occupants during building use. Although research has been focussing on office buildings the framework and guidelines apply to all building types/uses and contexts. However, there is certainly a need for well-documented use cases from diverse climates and building types/uses.

The building context (local climate, local constraints, building type/use, human context/social norms) determines the way the adaptive principles should be interpreted for a specific building project. In the planning and design phase of a building, it is the building context and the users that direct the possible passive design solutions and the active building systems (building services). Design decisions in both, passive and active design, are paramount to the potential of adaptive opportunities, as they shape which physical adaptive opportunities a building offers to its users, determine how these available opportunities are understood by users and affect the social relations among building users (e.g. small vs open-plan offices). We therefore propose a procedure for the design of adaptive opportunities, suited to climate and users, before deciding on further design parameters. Furthermore, the point to come across is the importance to tie design and operation in thermally adaptive buildings, and the importance of the human context: intended occupants, operators, managers, owners.

The guidelines report will include four main sections, as follows: After an introduction (Section 1), *Section 2* summarises the three adaptive comfort principles, i.e. physiological, behavioural and psychological adaptation supplemented with recent research findings. 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, improved health and well-being. *Section 4* presents the developed framework for adopting the adaptive comfort principles in design and operation of buildings

[3] integrated design: often also called holistic design, whole building design, or collaborative design

(Hellwig et al. 2019). Each of the subsequent subsections includes guidelines to facilitate the integration of adaptive principles. Section 4 ends with 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. *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.

In this paper, we focus on three areas and how they are approached in the guideline: 1) Upgrading prevailing knowledge about human thermophysiology and adaptation, 2) Developing a procedure for design of adaptive opportunities, and 3) providing guidance for operational planning and operation of adaptive buildings.

2. Updating prevailing knowledge about human thermophysiology and adaptation

In our previous work (Hellwig et al. 2019) we identified challenges in understanding the adaptive principles and therefore difficulties of building practice to adopt and apply the concept of adaptive thermal comfort in designing buildings. New findings from neuroscience, molecular biology, health and thermal comfort research support the concept of thermal adaptation:

a) new understanding of human thermoregulation: decentralised thermoregulation principles (independent thermo-effector loops) instead of central body core temperature set-point theory (Werner 1980, 2010, Auliciems 2014, Romanovsky 2007; 2014),
b) consequently, discomfort signals come from the skin instead of coming from body core temperature deviation (Romanovsky 2014, Schlader et al. 2017),
c) positive effects of exposure to temperatures slightly outside the comfort range on health (Hanssen et al. 2015, Schrauwen and van Marken Lichtenbelt 2016, van Marken Lichtenbelt et al. 2017, Pallubinsky et al. 2017) and human adaptability/ resilience in e.g. heat waves (Auliciems 2014), and
d) the rediscovery (de Dear 2011) of the old concept of alliesthesia (Cabanac 1971) and its new interpretation as an important psycho-physiological driver for people's behaviour (Cabanac 1996) and of people's perceived control in buildings (Hellwig, 2015), and future approaches for zoning/conditioning buildings based on transient comfort perception (Parkinson et al. 2016, Zhai et al. 2019).

Figure 1 displays an integrated view on factors, mechanisms and main interrelations forming human thermal comfort perception. Factors influencing the physiological adjustments by thermoregulation determine a human body's heat balance and form the basis for steady-state thermal sensation models. They are accomplished by behavioural adaptation, psychological adaptation and acclimatisation processes (as part of physiological adaptation) and describe together thermal comfort perception in dynamically changing thermal environments.

The heat exchange mechanisms: convection, radiation, conduction and evaporation are not solely the basis to determine a human body's heat exchange balance. They also form a starting point for architectural passive design, which affords opportunities for behavioural adaptation and seasonal acclimatisation and for the choice and design of adaptive opportunities suited to the local climate and habits.

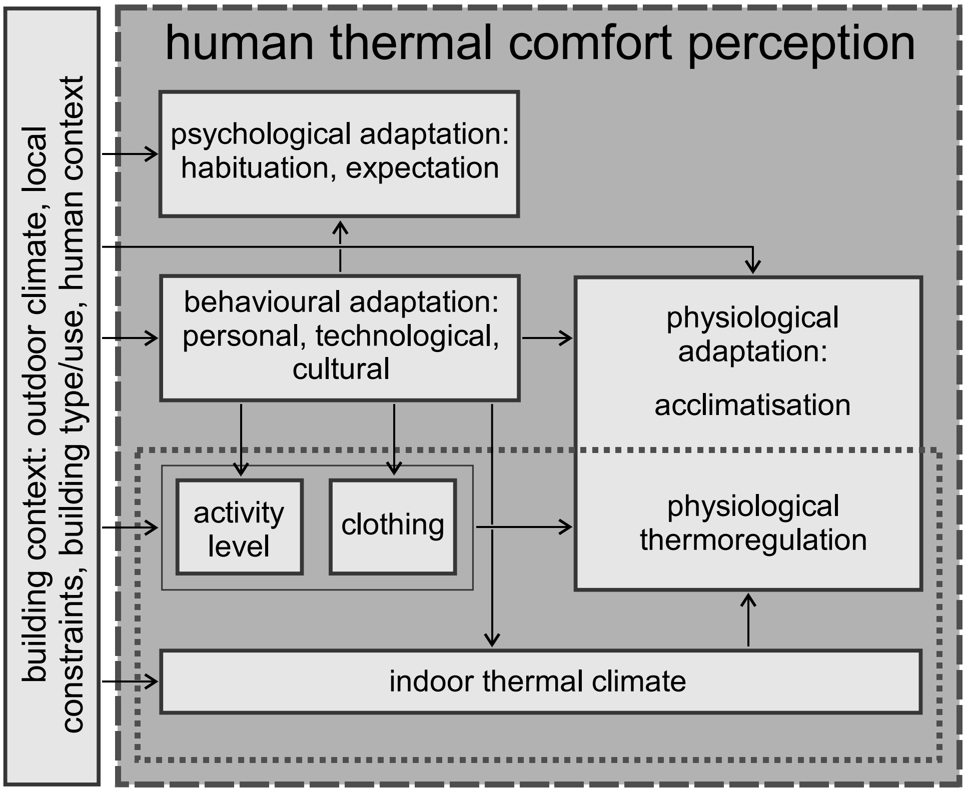

Figure 1. Integrated view on factors, mechanisms and main interrelations constituting human thermal comfort perception. Factors influencing the physiological adjustments by thermoregulation determine a human body's heat balance, and form the basis for thermal sensation models (dotted line rectangle). 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.

A word on acclimatisation: A non-physiologist might start doubting when physiologists call a slowly increasing temperature, e.g. seasonal outdoor temperature change, as mild "heat strain/stress" (Taylor 2014), whether it should be "allowed" to be reflected indoors and whether it would then cause complaints. However, in everyday life such a change in outdoor temperature would be perceived as a natural change, as proven in numerous field studies, summarised in databases with data from all over the world (de Dear 1998, McCartney and Nicol, 2002, Földvary et al. 2018). However, gradual temperature changes should be separated from extreme and rapid temperature changes as e.g. in heat waves – with the two latter being the stress test whether a building's buffering and filtering capabilities are sufficient.

The human body has several strategies to detect and then respond or react to changing thermal conditions of the environment. The first response, activated autonomously, is the vasomotor response (vasodilation and vasoconstriction). The second response is behavioural thermoregulation (e.g. clothing, going to a different location, opening/closing a window). Comfort (or better discomfort) perception hereby serves as the driver to initiate behavioural adaptation before sweating or shivering, as the third thermoregulatory responses, are activated (e.g. Schlader et al. 2017, Figure 2). The psycho-physiological feedback signal to a person, i.e. whether a behavioural adjustment was successful in restoring comfort (Cabanac 1996), comes from the skin temperature at the point in time when a change in the "right" direction is detected (Romanovsky 2014). This has implications on the design of adaptive opportunities, especially of the active systems, and requires consideration when using energy-efficient low-temperature heating or low-temperature cooling systems as they tend to have a longer response time.

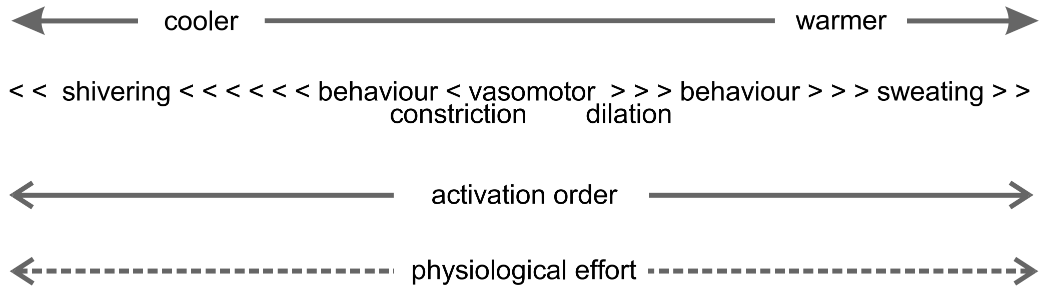

Figure 2. Hierarchy of activation of physiological autonomous (vasomotor, shivering, sweating) and behavioural body responses (simplified from Vargas and Schlader 2018, based on Schlader et al. 2017).

That behavioural thermoregulation is *activated by body signals* is a way building designers should pay careful attention to. Similar to autonomous thermoregulation, behavioural thermoregulation is a *natural biological body reaction*, and insofar it is in the building designers', planners', investors', and operators' responsibility to account for this natural and basic need for appropriate control. As physiologists have proven, behavioural thermoregulation is a basic underlying principle of ergonomics and numerous field studies have proven this to be a basic need of occupants.

While literature exists, that explains adaptive mechanisms (Humphreys and Nicol 1998, Nicol et al. 2012, Humphreys et al. 2016), identifies how to better operate buildings (Usable Building Trust, Wagner et al. 2015), or how to prepare buildings for climate change, e.g. by addressing the issue of overheating in buildings (CIBSE 2010[4], Hellwig, 2018), the above mentioned new findings contribute to better explaining results on thermal comfort evaluation from field studies (e.g. de Dear 1998, McCartney and Nicol 2002, Földvary et al. 2018) and to inform future adaptive building design and operation guidelines.

3. Developing a procedure for the design of adaptive opportunities

The availability of appropriate adaptive opportunities is fundamental to occupants' ability to restore thermal comfort by physiological, behavioural and psychological adaptation (see above). Adaptive opportunities and the related controls should be part of the design intent 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.

Within our framework, we have provided a table with conceivable adaptive actions from diverse climates and contexts structured according to five categories (Table 3 in Hellwig et al. 2019).

i) regulation of body internal heat generated,
ii) regulation of the rate of body heat loss,
iii) regulation of the thermal environment,

[4] As one example for guidelines on overheating avoidance by design and operation, which exist in other countries.

iv) selection of a different thermal environment, and
v) modification of one’s psychological perception.

In order to enable these conceivable adaptive actions, various stakeholders in the planning and operation have to take action: the owner/investor, the building planner, the operator/facility manager, the company manager and the occupant, (**Error! Reference source not found.** in Appendix). 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 3.

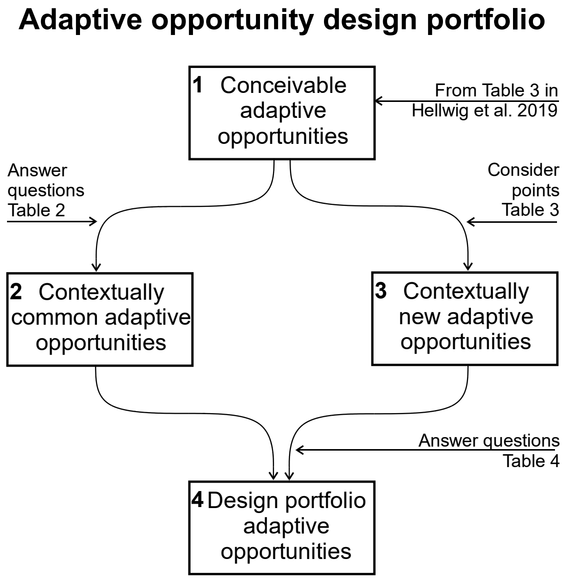

Figure 3. Procedure for development of a design portfolio of adaptive opportunities.

Step 1: Starting point are all conceivable adaptive actions and responses, i.e. *conceivable adaptive opportunities* (refer to Table 3 in Hellwig et al. 2019, see summarised five categories above). These are not applicable to all situations buildings are in. Here comes the context the building 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. *Conceivable adaptive opportunities* are different in different local climates. For instance, measures such as wetting of walls or floors would 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 reduce 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 2 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. After applying this procedure, planners have identified the *contextually common adaptive opportunities.*

Table 2. Contextual factors drive adaptive design solutions and require stakeholder's action. Questions raised are exemplary and not exhaustive.

Contextual factor		Question	Design action (responsible actor)
Local climate	Outdoor climate	What are the dominating factors of the climate [1)] (e.g. 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 are 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 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
	User 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[6)]	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 users	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 users regarding adaptive opportunities?	Identify need for occupant education and familiarisation to new routines and adaptive strategies (operator)
	…	…	…
Local constraints	Pollution/noise/ UHI/ insects[7)]	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)
	…	…	…

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 3 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 *contextually 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. Considerations of recent and future developments

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) → 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

Step 4: First, the adaptive opportunities of step 2 and 3 are combined. Table 4 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 they 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.

Table 4. List of example questions to identify an appropriate mixture of common and new adaptive opportunities

General questions	Have you implemented a variety of common adaptive opportunities which people are familiar with?
	Which are the most preferred 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 user 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 opportunity replace a common one? If it is one of the most liked common adaptive opportunities, then rather 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.
	…

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.*

4. Operational planning and operation of adaptive buildings

For operational planning, commissioning and operation of the building the chosen and documented design portfolio of adaptive opportunities (see previous section) is the driver to bring all measures in place, which make sure that the planned adaptive opportunities are also those available and used during the building use phase.

Operational planning: During operational planning, several actors play a significant role for the effective implementation of adaptive actions (Collins et al. 2017). In case the later occupants' are known, assessing their needs at an early design and operational planning stage is helpful. At a later stage, they could then informed how they can fulfil their needs by using the building in the intended way. The adaptive opportunities identified in the design portfolio are the basis to develop operational procedures to maintain the adaptive opportunities and to inform the organisational management and the occupants about adaptive opportunities the building offers; they form the operational strategy. Such actions may include easing dress-codes if they exist, flexible working hours, maintaining different temperatures in certain zones, and maintaining functionality and accessibility of adaptive controls (e.g. openable windows, moveable blinds etc.). The result of this process may then be added to the design brief for the building. During the operational planning and based on standardised protocols (e.g. Softlandings, 2018), feedback loops between the players should be defined. They ensure that issues are identified and addressed promptly during operation. The guidelines complement with items related to adaptive thermal comfort operation.

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

- Include in the operation and maintenance manual (see for instance BNB 2015, Wagner et al. 2015) 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, the freedom and the responsibilities of the occupants in interacting with the building. The manual should be in the local language and may be enriched with explanatory illustrations.
- Include an occupants' manual (e.g. BNB 2015) 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. In addition, information should be provided in such a way, that it cannot be lost when occupants change. The manual should be in the local language and may be enriched with explanatory illustrations.
- Making provisions for the facilities manager to have a contact with the design team, especially early on during the building occupation, is essential to the full realisation of the building performance potential (e.g., CIBSE 2000). 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 (initial aftercare and extended aftercare). 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.
- Provisions need to be made to fine tune the building environmental systems and adaptive opportunities as required during the early stages of building operation. This is common practice for all types of buildings, but 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 (CIBSE 2000, 2009).
- A recurrent survey protocol for feedback and a protocol for the continuous performance monitoring of the building needs to be established (post occupancy evaluation, monitoring, BNB 2015). 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.
- To maintain occupants engaged with the good use of the building, a protocol needs to be established indicating provisions for timely response to occupants on not only their feedback on shortcomings or malfunctions, but also the performance of the

building and how their adaptive behaviours result in good environmental quality and energy savings.

- Problems arise in smaller buildings with janitors or other non-skilled facility management. For these cases with a clear lack of technical capacities inhouse, strategies will have to focus on the occupants or responsible persons from the organisation owning/renting such place. In principle, occupant-maintained spaces can include most of the measures described above, though time-constraints will make it more difficult for their implementation.
- 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: For building operation, occupants' perception of responsibility, knowledge of adaptive opportunities (occupant's manual), and the reduction of constraints are important aspects enhancing the implementation of an adaptive concept (Karjalainen and Koistinen, 2007). For overall satisfaction, it is supportive if an occupant – to a certain degree - feels responsible for the indoor climate at their workplace. To facilitate satisfaction of the users an appropriate complaint strategy system of the facility management of the building is desirable. This includes that complaints or feedback of users are taken seriously and comprises an appropriate feedback loop. At the same time, occupants may have to be informed about their adaptive 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 and management should try to minimise constraints to adaptive opportunities, as e.g. for windows it is important that they are accessible and operability is enabled. This requires regular checks from the facility management. 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.

Stakeholders: Facility managers and building operators are instrumental to implement the adaptive design principles and strategies successfully, for occupants' satisfaction and low-energy performance during the building service life. They are directly responsible for making sure that the design intent materialises.

Facility managers and building operators need to meet the following requirements to be able to implement the adaptive design intent successfully: i) to understand the adaptive principles and their role in achieving building performance targets (which outlines quite some future tasks in education and professional training); ii) to be well educated on the singularities of the building and its environmental systems; iii) to be motivated and proactive; iv) to be engaged with the occupants; v) to be well trained on the operation and management of the building environmental systems; and vi) to be properly supported by the higher management and by the building owner.

From the start of planning to beyond the commissioning, users should be involved in the decision-making processes as part of an intensive communication strategy, whenever possible. This avoids misunderstandings, minimises misconceptions and enables participation. The advantages of involving occupants are two-fold: 1) learning their thermal needs and experiences, motivating them and managing their expectations, and 2) informing them about the building. This information increases their awareness on the building environmental systems and intended environmental variability with benefits to the occupants and the environment. Most importantly, it outlines their role in controlling their own thermal environment and its impacts on building performance. Thus, a greater knowledge and understanding of building environmental features and controls can lead to a relaxation of comfort expectations, with significant implications for energy use (Brown and Cole 2008). Furthermore, research is focussing on how to engage users in the design and operation process of buildings (e.g. Martek et al. 2019, Bull and Janda 2018).

Appendix, **Error! Reference source not found.** includes sample checklist for organisational management, the operators/facility managers and the occupants, which refers to the criteria that allow the building to run in adaptive mode during the operation phase.

5. Conclusion

A guideline has been developed to bridge the gap between adaptive thermal comfort theory and building design and operation practice. The guideline aims to promote the adaptive thermal comfort thinking and the multiple benefits that it entails for people's health and wellbeing, as well as for energy conservation and the environment. The paper focused on three main areas addressed in the guideline. First, an update of prevalent knowledge about human thermophysiology and adaptation was summarised in an integrated chart on factors, mechanisms and main interrelations forming human thermal comfort perception. The statement of hierarchy of thermoeffectors demonstrates that designing for personal control means to design for a basic human need. It does not mean that designers have the right to remove stimuli and design for the perfect control (as it does not exist). Instead, being in a respectful dialogue with the building users about what a building design can provide (a normal predictable indoor environment including e.g. seasonal effects, Humphreys and Nicol, 1998) and being clear about their opportunities to make themselves comfortable in this environment might contribute to some clarification of expectations and contributions.

The second area addressed in the paper is the development of a procedure for the design of adaptive opportunities, which relies on to the context of the area the building is built in (climate, building type, human context/social norms, constraints) and on new technologies (personal comfort systems) or developments (e.g. climate change) which should lead to new kinds of adaptive opportunities.

Finally, the paper focuses on the role of actors, the communication of building use, function and maintenance with regard to adaptive opportunities in the operational planning and operation of adaptive buildings. Occupants' participation is encouraged already in an early design stage with the aim to learn their needs and later inform them on how to use the building in the intended way. Further aspects will be addressed, as initially stated, in the full report on guidelines by the authors of this paper (in preparation).

While these guidelines show important aspects for design and operation of buildings according to adaptive principles, it got clear that knowledge of the effect of specific design decisions on particular adaptive mechanisms is still scarce. Research on adaptive comfort continues creating so-called adaptive comfort models, which are simple regression lines between prevailing outdoor conditions and suggested indoor conditions. While being important on its own, this type of research often fails to include theoretical reasoning why regression coefficients differ between climatic or building contexts. Continuing creating solely adaptive regression models holds the potential of documenting people's adaptation to misinterpreted comfort demands (Hellwig 2018) without being able to respond to real necessities of the future, e.g. climate change mitigation or heat waves. In order to overcome such shortfall of current research activities, research needs reveal further insights into particular adaptive principles and their relationship to design and operation, as for example in advanced adaptive comfort models (e.g. the ATHB approach of Schweiker and Wagner, 2015). Research needs to systematically address and analyse particular aspects such as climatic context or building typologies and in such a way permitting causal conclusions.

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Appendix

Table 5. Enabling adaptive opportunities for occupants: Exemplary design and operation actions by stakeholder

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	-	Relax dress-code	-	dress for clothing adjustment

Use of ceiling fan and other active systems	Integrate active systems which can be adjusted by occupants	-		
Use of personalised comfort systems (desk fans, warmers, etc)	-	Allow/provide PCS		
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/deactiva te 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
…	…	…	…	…