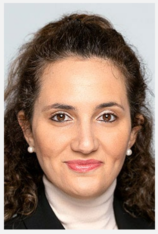
Articles

Requirements for health-promoting and resilient HVAC and IEQ control



MARCEL SCHWEIKER
Head of Healthy Living Spaces Lab, Institute for Occupational, Social and Environmental Medicine, Medical Faculty, RWTH Aachen University
mschweiker@ukaachen.de

HANNAH PALLUBINSKY
PhD in Thermophysiology and Health; Healthy Living Spaces Lab, Institute for Occupational, Social and Environmental Medicine, Medical Faculty, RWTH Aachen University + Dept. of Nutrition and Movement Sciences, NUTRIM School for Nutrition and Translational Metabolism Research, Maastricht University

RANIA CHRISTOFOROU
PhD in Clinical Psychology; Healthy Living Spaces Lab, Institute for Occupational, Social and Environmental Medicine, Medical Faculty, RWTH Aachen University

Concepts for HVAC and IEQ control are challenged by a multitude of traditional and new requirements. This article aligns these frontiers within the human-building resilience framework and discusses resulting performance needs and advancements for HVAC and IEQ control together with existing research gaps from the users' comfort and health perspective.

Keywords: Resilience; health; comfort; adaptation; alliesthesia; IEQ control; energy

Historical requirements

Traditionally, the design of HVAC systems and IEQ controls requires an optimization of user safety and comfort, together with resource efficiency among others. Both requirements are regulated by existing standards and technical guidelines, aiming at high user comfort and safety through low resource usage. First requirements were derived from occupational safety and health perspectives dating back to 1700 and before [1]. Since the two oil crises in the 1970's, energy efficiency not only became a market advantage, but more and more turned into a requirement, and regulations constantly got stricter.

For a long period, both types of requirements were embedded in rather stable, steady state contexts. Recent developments with respect to the COVID-19 pandemic, climate change, and human comfort and health aspects, however, challenge these existing approaches and emphasize simultaneous considerations of the demands for robustness, dynamics, flexibility and individualization. While these needs partly appear contradictory to each other, their consideration offers new trajectories and perspectives for technological advancements as outlined in the following.

Contemporary and future challenges and opportunities

The last two decades can be characterized by an explosion of new requirements for and challenges to traditional views on HVAC and IEQ control (**Figure 1**), of which a few will be highlighted in the following.

Climate change and the COVID-19 pandemic have emphasized the importance of IEQ and *flexibility*. Climate change decreases predictability of future conditions under which HVAC and IEQ controls implemented today will have to operate. As far as predictions tell, heat waves and floods will be more frequent and severe, summer nights warmer and pollen periods longer than today, among others [2]. On the one hand, these extreme weather events pose new challenges to IEQ control concepts characterized by a lower predictability and slower adaptability. On the other hand, consequences of climate change are predicted to increase negative consequences for the populations' mental (e.g., elevated risk for depression, anxiety and post-traumatic stress disorder, which will be maintained even years after exposure) and physical (e.g., increases in total, cardiovascular and respiratory mortality and morbidity) health [3]. The ongoing COVID-19 pandemic gave a glance at the importance of the indoor environment for the future – though such 'discovery' did not come as a surprise for those involved in this area for many years. In addition, the pandemic accelerated the move towards home office and mobile working. Especially the former raises questions on the provision of IEQ in residential places previously meant for relaxation, recharging, and social life, now becoming simultaneously work places and as such building the foundation for the height of ones' earnings, and potentially affecting career opportunities. These challenges of climate change and COVID-19 pandemic highlight the need for providing *safe* indoor conditions with *robust,* but *flexible* concepts.

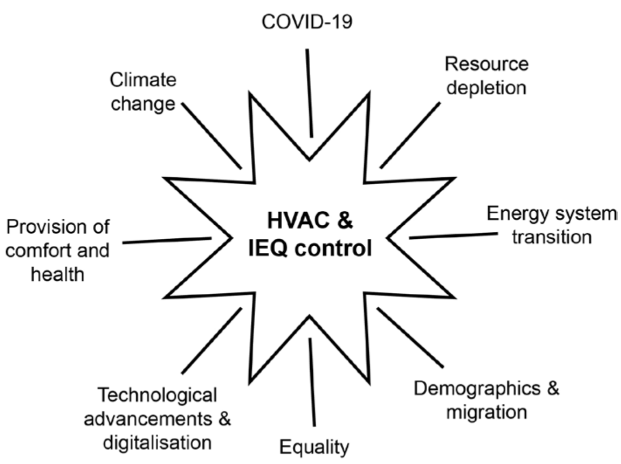


Figure 1. Traditional and new challenges for HVAC and IEQ control.

Energy resource depletion and energy system transition require an intensified search for the most *efficient* solutions together with new, partly *dynamic* concepts to deal with a higher share of fluctuating renewable energies. In addition, increasing costs for energy usage and materials raise questions regarding equality of access and *affordability* (see also next point). Such effect is emphasized – unless countermeasures such as additional payments are implemented – in the context of the move towards increased home office hours, since some energy costs will shift from the employing organizations to the employed individuals.

Demographic factors, migration and equality will add additional variance to required conditions, ideas on comfort requirements, and cultural practices in the interaction between occupant and building – overall requiring a high degree of *flexibility* and *robustness*. HVAC and IEQ control concepts need to consider a partly more vulnerable society and increasing injustice in access to required resources to avoid long-standing challenges due to energy insecurity and inequality [4]. For example, local split-type air-to-air air-conditioning units permit those able to afford them cooling in summer, while increasing urban heat island and noise pollution effects for others in the immediate surroundings and thereby reducing their potential for natural ventilation concepts.

Technological advancements and digitalisation have led to numerous innovations, efficiency improvements and will lead to further opportunities. At the same time, potential risks in relation to ecological, economic, and social dimensions need to be put into perspective [5]. One example is related to adaptive control opportunities, i.e. an individual occupants' control over window state, set points, among others. Some of the first automation systems completely removed the control options for the occupants. Such misconception was reduced only after an increased understanding that **actual adaptive control opportunities** are a pre-requisite for occupants' satisfaction [6]. Therefore, especially more complex HVAC and IEQ controls (if they really need to be that complex) require understandable interfaces and need to provide adaptive control opportunities. At the same time, it is not clear to what extend control is required, because too much control and the need to constantly hassle with IEQ settings has been reported as a source of stress and dissatisfaction itself [7].

At last, a **changing approach towards the provision of comfort and health** is one of the most, if not the most important aspect related to changed requirements. Through efficiency thinking and the neutrality paradigm, comfort has been for long, and largely still is, defined as a provision of conditions, which are leading to a maximum relief from potential thermal, visual, IAQ, and acoustic stressors. Recent discussions promote to change the view from relief (i.e. maintaining neutrality) at all times, towards relief where necessary, in combination with encouragement (i.e. increasing adaptive opportunities) and enjoyment (i.e. potential for perception of alliesthesia) [8, 9]. While, for example, the provision of thermally neutral conditions is still standard in practice, research highlights the benefits of IEQ control applying more varied conditions or naturally occurring dynamics for resource efficiency [10], satisfaction [11], and also health-related parameters [12, 13]. The provision of visual conditions changed from considerations of minimum illuminance levels alone to considerations of circadian effects and the quality of lighting [14]. Such approach is in line with the trend in medicine from a focus on risk assessment, which was dominant in the 1970's, towards risk management including well-being and salutogenesis from 2000 onwards [1]. These upcoming paradigm shifts, towards a more holistic view on comfortable *and* health-promoting conditions, add further requirements to HVAC and IEQ control in terms of *flexibility* and opportunities for *individualization*. At the same time, basic requirements such as the avoidance of toxins in the air or other harmful conditions, should stay in place and be developed further according to the newest level of information and evidence. Furthermore, multi-sensory thoughts are required [15]: for example, having large windows for maximum daylight exposure is not helpful by itself in case the overall building design requires day-long shading (e.g. to avoid overheating), as this may lead to the reverse or rebound effect of reducing the potential for such daylight exposures.

Resilience thinking from human perspective and required approaches

Above described challenges lead to new requirements for future HVAC and IEQ control, including parameters such as *flexibility*, *robustness*, *dynamics*, *individualized solutions*, *adaptive controls opportunities*, *encouraging*, *health-promoting*, and *equality*. At first sight, those parameters could seem to contradict themselves, like robustness and dynamics (**Figure 2**). At the same time, these requirements can complement each together, when extending the definition of resilience beyond the robustness of buildings by two means: the first mean is to extend the definition of a resilient system from the human perspective, towards a combined human *and* building resilience (**Figure 3**). This approach does not start with the focus on certain room temperatures or energy efficiency levels as questioned earlier [14], but with requirements for relief, encouragement and enjoyment. Guiding questions will be, for example, when and how to keep warm or cool, when and how to offer physiological, behavioural, and psychological adaptive opportunities, and when and how to offer enjoyment as stress relief or motivational driver. The second mean is to consider a resilient system that is not only able to flexibly react to a potential shock or stressor, and restore itself afterwards, but that can also

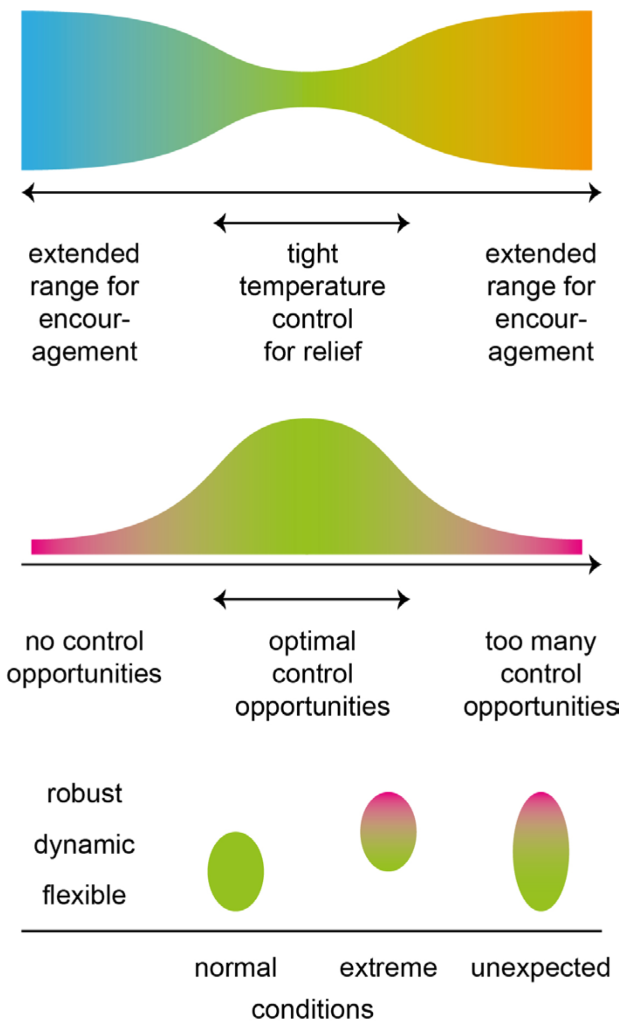


Figure 2. Three areas of tension of future HVAC and IEQ control.

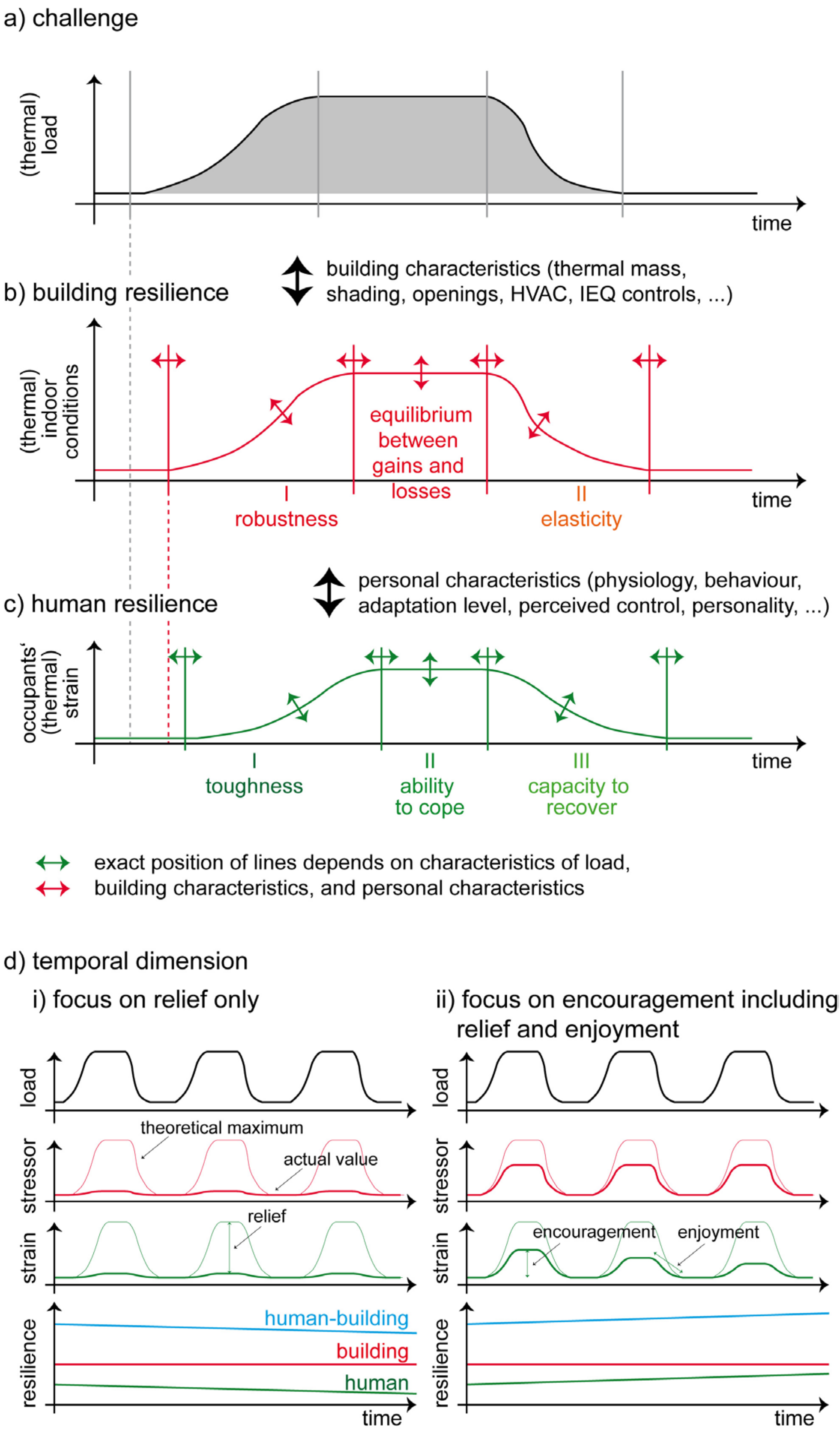


Figure 3. Simplified version of the human-building resilience framework (a-c) including hypothetical temporal evolution of human building resilience (d). Robustness and toughness describes the buildings' and human ability to withstand a load or stressor. Elasticity and capacity to recover describe the ability to return to initial state after removal of load and stressor (adapted from [8,9]).

evolve further in order to increase its capacity before the next shock or stressor occurs [8, 9].

Following the above, resilient and health-promoting built environments are envisioned to provide sufficient relief (prevention), the right dose of encouragement (salutogenesis), and potential for enjoyment for all. Hence, future HVAC and IEQ control trajectories need to provide energy efficient solutions for this balance, while considering the dynamics of multiple environmental stressors and their interactions, the psychological load and potential interactions with the built context, the physical load, and the individuals' characteristics and needs. Such vision may appear utopic and unreachable and will definitely require further research, as several aspects are lacking full evidence. However, we argue that similar to the WHO definition of health from 1946, which defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity", and has been denoted as utopic by some, it is crucial to make a first step by establishing such vision.

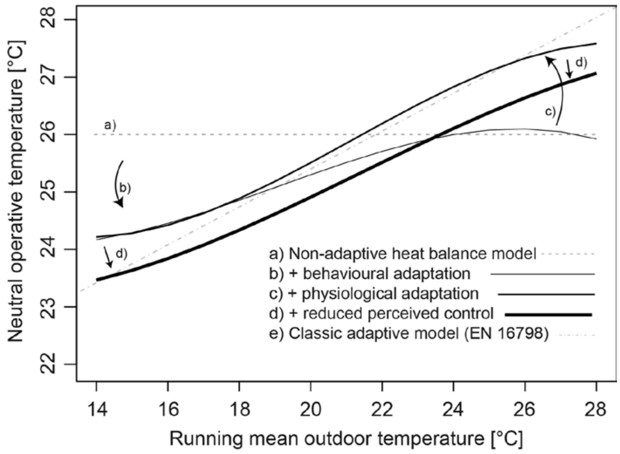


Figure 4. The adaptive heat balance framework enables the prediction of the effect of individual adaptive mechanisms on thermal perception in combination with the six classical influences on human heat balance (adapted from [16]).

Accordingly, concrete steps can be:

(1) Considering resilience by emphasising the need to increase human resilience in the long term. This requires HVAC and IEQ control approaches to support opportunities for adaptation and alliesthesia, and to not only strive for an elimination of even mild stressors. In contrast, evaluating solutions on existing (thermal) adaptation levels, but with future climatic conditions, may prescribe specific cooling solutions. This, however may ignore the adaptation potential when designing for encouragement and lead to rebound effects. Still, further advancements in the prediction of individual aspects of human adaptation are necessary (**Figure 4**) [16].

(2) Approaching resilience of the human-building system including the human, by passive measures (e.g. within the building envelope), and active measures (e.g. through elements of the HVAC system), and not through individual components. This point emphasizes the need for multi-disciplinary, multi-dimensional, and multi-sensory approaches. From the human perspective, flexibility in adaptive controls and measures to fulfil individual needs are relevant. In contrast, focusing on single aspects rather than a holistic approach may lead to unintended energetic and non-energetic side-effects or rebound.

(3) Supporting capacity building of the human-building system, including HVAC and IEQ control under normal operation modes, while being designed for certain robustness to extreme conditions. The robustness then allows occupants sufficient time and opportunity for behavioural and physiological adaptation – something achieved with a high thermal, visual, and ventilation autonomy. For example, rising temperatures in an acute heat wave need to be buffered first, and even with power shortages, the indoor environment needs to keep acceptable conditions.

(4) Considering resilience beyond the individual building towards the neighbourhood or urban scale. Take, for example, above example of decentralized air-to-air air-conditioning units, which reduce (as long as power is available) the thermal strain for the occupants, while increasing the load for adjacent buildings [17].

(5) Creating easily understandable building, HVAC and IEQ concepts in normal and in crisis mode. Best solutions do not require special information such as guidebooks, which will likely be lost soon after operation starts, but are self-explanatory like a window handle or fan switch.

Overall, we are living in an exciting period with dynamic changes at several levels, asking for innovative and creative solutions to improve life indoors. ■

References

[1] D. Gagliardi, A. Marinaccio, A. Valenti, and S. Iavicoli, "Occupational Safety and Health in Europe: Lessons from the Past, Challenges and Opportunities for the Future," *Industrial Health,* vol. 50, no. 1, pp. 7-11, 2012, doi: https://doi.org/10.2486/indhealth.MS1342.

[2] V. Masson-Delmotte *et al.*, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," *IPCC: Geneva, Switzerland,* 2021.

[3] V. Weilnhammer *et al.*, "Extreme weather events in europe and their health consequences – A systematic review," *International Journal of Hygiene and Environmental Health,* vol. 233, p. 113688, 2021/04/01/ 2021, doi: https://doi.org/10.1016/j.ijheh.2021.113688.

[4] C.-f. Chen *et al.*, "Extreme events, energy security and equality through micro- and macro-levels: Concepts, challenges and methods," *Energy Research & Social Science,* vol. 85, p. 102401, 2022/03/01/ 2022, doi: https://doi.org/10.1016/j.erss.2021.102401.

[5] O. Renn, G. Beier, and P.-J. Schweizer, "The opportunities and risks of digitalisation for sustainable development: a systemic perspective," *GAIA-Ecological Perspectives for Science and Society,* vol. 30, no. 1, pp. 23-28, 2021.

[6] R. T. Hellwig, M. Schweiker, and A. Boerstra, "The ambivalence of personal control over indoor climate – how much personal control is adequate?," *E3S Web Conf.,* vol. 172, p. 06010, 2020. Available: https://doi.org/10.1051/e3sconf/202017206010.

[7] B. Bordass, A. Leaman, R. Bunn, B. C. I. Association, and others, *Controls for End Users: a guide for good design and implementation*. BCIA, 2007.

[8] M. Schweiker, "Rethinking resilient comfort – definitions of resilience and comfort and their consequences for design, operation, and energy use," in *11th Windsor conference - Resilient comfort*, Windsor, UK, S. Roaf, F. Nicol, and W. Finlayson, Eds., 2020: NCEUB, pp. 34-46.

[9] M. Schweiker, "Rethinking resilient thermal comfort within the context of human-building resilience " in *Routledge Handbook of Resilient Thermal Comfort*, J. F. Nicol, S. Roaf, and H. B. Rijal Eds.: Routledge, 2022.

[10] R. Ming *et al.*, "Assessing energy saving potentials of office buildings based on adaptive thermal comfort using a tracking-based method," *Energy and Buildings,* vol. 208, p. 109611, 2020/02/01/ 2020, doi: https://doi.org/10.1016/j.enbuild.2019.109611.

[11] Y. M. Ivanova, H. Pallubinsky, R. Kramer, and W. van Marken Lichtenbelt, "The influence of a moderate temperature drift on thermal physiology and perception," *Physiology & Behavior,* vol. 229, p. 113257, 2021/02/01/ 2021, doi: https://doi.org/10.1016/j.physbeh.2020.113257.

[12] H. Pallubinsky *et al.*, "Passive exposure to heat improves glucose metabolism in overweight humans," *Acta Physiologica,* https://doi.org/10.1111/apha.13488 vol. 229, no. 4, p. e13488, 2020/08/01 2020, doi: https://doi.org/10.1111/apha.13488.

[13] W. van Marken Lichtenbelt, M. Hanssen, H. Pallubinsky, B. R. M. Kingma, and L. Schellen, "Healthy excursions outside the thermal comfort zone," *Building Research & Information,* vol. 45, no. 7, pp. 819-827, 2017, doi: https://doi.org/10.1080/09613218.2017.1307647.

[14] E. Shove, "What is wrong with energy efficiency?," *Building Research & Information,* vol. 46, no. 7, pp. 779-789, 2018/10/03 2018, doi: https://doi.org/10.1080/09613218.2017.1361746.

[15] M. Schweiker *et al.*, "Review of multi-domain approaches to indoor environmental perception and behaviour," *Building and Environment,* pp. 106804-106804, 2020, doi: https://doi.org/10.1016/j.buildenv.2020.106804.

[16] M. Schweiker and A. Wagner, "A framework for an adaptive thermal heat balance model (ATHB)," *Building and Environment,* vol. 94, pp. 252-262, 2015, doi: https://doi.org/10.1016/j.buildenv.2015.08.018.

[17] IEA, "The Future of Cooling," IEA, Paris, 2018. Available: https://www.iea.org/reports/the-future-of-cooling.