Final report

1.1 Project details

Project title	EUDP 15-I Strategi og baggrund for adaptiv termisk komfort i lavenergi bygninger
Project identification (program abbrev. and file)	64015-00009
Name of the programme which has funded the project	EUDP 15-I
Project managing company/institution (name and address)	Technical University of Denmark Anker Engelunds Vej 101A 2800 Lyngby
Project partners	DTU is the only partner that is funded by the grant. Network partners from abroad are funded by national sources.
CVR (central business register)	30 06 09 46
Date for submission	

1.2 Short description of project objective and results

English version
The project was a network activity in the International Energy Agency's Energy in Buildings and Communities Programme. The activity was anchored in IEA Annex 69 "Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings". The aim of the work in Annex 69 was 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 of indoor environment in order to reduce building energy use.

The results of the Annex work are scoped by the three subtasks:

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

Subtask B: Criteria in standards and guidelines for adaptive comfort and personal thermal comfort systems

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

Dansk version
Projektet var en netværksaktivitet under International Energy Agency – Energy in Buildings and Communities. Aktiviteten var forankret i IEA Annex 69 "Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings". Formålet med aktiviteterne i Annex 69 var at skabe en bedre forståelse af de mekanismer, der ligger til grund for adaptiv termisk komfort og at skabe et bedre grundlag for at inkludere konceptet i standarder og retningslinjer for design og drift af bygninger. Anneksets resultater er formet af de tre delopgaver:

Delopgave A: Indsamling af data om komfortforhold i bygninger i praksis og studier af adaptive komfortmodeller

Delopgave B: Kriterier i standarder og retningslinjer for adaptiv termisk komfort og personlige komfortsystemer

Delopgave C: Case studies – Erfaringer fra eksemplariske adaptive bygninger

1.3 Executive summary

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. Current indoor environment standards for mechanically heated and cooled buildings are based on analytical heat balance models for specifying an acceptable comfort temperature range. The same standards also include a data-driven, adaptive approach for office buildings. The basic concept of adaptive thermal comfort is that the comfort zone, or range of acceptable indoor temperatures, drifts upwards in warm weather and downwards in cool weather. The thermal adaptive processes are complex and not yet fully understood. The aim of the project was to connect international thermal comfort researchers to advance our understanding of adaptive thermal comfort.

IEA EBC Annex 69 Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings was approved unanimously in 2013 at the Executive Committee Meeting of the IEA Energy in Buildings and Communities Programme. Focus of the Annex was 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 collaborated to establish a worldwide database of building performance metrics, 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 and refurbishment, and to evaluate new personal thermal comfort systems. The programme had 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 participated in the project. The 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 ended in December 2019. During the course of the Annex, the participants have met bi-annually and in May 2017, the meeting was held at DTU in Lyngby.

Subtask A resulted in a massive online open access database of approximately 82.000 complete sets of objective indoor climate observations with accompanying “right-here-right-now” subjective evaluations by the building occupants who were exposed to them. The database intends to support diverse inquiries about thermal comfort in field settings. Also, a modified procedure for estimating running mean outdoor temperature, which is the main input to the adaptive comfort model, was proposed.

The new database includes analysis and visualization tools that allow the field studies to be compared, and statistics such as percent dissatisfied curves to be calculated for a wide range of comfort parameters. Database 2 is already in active use and can be downloaded at http://comfortdatabase.com. It has been used to test metrics and models such as the PMV/PPD and other. It has been used to revisiting the original adaptive comfort model and suggesting nudges to theory, standards, and practice.

Subtask B carried out a critical review of the criteria to the thermal indoor environment across different comfort models in selected national and international standards and how these influence building energy use. A range of updated algorithms for design, evaluation and control of thermal conditions in buildings was suggested. The applicability of personal comfort models was explored and work was initiated to outline a new standard for adaptive methods for achieving thermal comfort in an International Organization for Standardization Working Group (ISO TC159SC5WG1).

Subtask B also evaluated the energy consumption when two different control strategies were applied in simulated building models: a prescriptive thermal comfort control based on the Predicted Mean Vote model and an adaptive thermal comfort control. Depending on the building type and the outdoor climate, the energy savings achieved by using the adaptive model varied from 0 to 150 kWh/m². Nevertheless, applying the adaptive approach also caused considerably longer periods with temperatures higher than 27ºC at several of the included locations. In the warmer climates, occupants will be exposed to temperatures above 27°C during almost the entire year.

In subtask C, a framework for adopting adaptive thermal comfort principles in design and operation of buildings was elaborated and a database with case studies providing practical learnings from exemplary adaptive buildings was established.

The input variable to the adaptive model is the prevailing or running mean outdoor air temperature, which is based on a weighted average of the mean daily temperatures over some period of days. With an aim to derive the optimal determination of the running mean temperature, the Subtask C database was utilized. The result of the analysis suggested that the weighting of the mean daily temperature is not critical for the calculation of the running mean outdoor temperature as the indoor neutral temperature and occupant clothing behavior were not particularly sensitive to running mean outdoor temperature calculated with different weights. The values of the weights as currently prescribed in the thermal comfort standards seem to be reasonable (satisfactory) predictor of indoor thermal comfort.

The number of alternative approaches and models to both heat balance based and adaptive thermal comfort is increasing. The final Annex activity is to evaluate the accuracy of these models in the deliverables that will be submitted to IEA in February 2020 and later, and finally all project findings will be summarized in a final report, based mostly on the articles appearing in the special issue of Energy and Buildings.

1.4 Project objectives

The aim of the work in Annex 69 was to provide scientific description and clearer understanding of occupants' adaptive thermal comfort in buildings, which is a fundamental science question related to the appropriate design, evaluation and control of indoor environment in order to reduce building energy use.

1.5 Project results and dissemination of results

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

The ASHRAE Global Thermal Comfort Database II ("Comfort Database") and its accompanying analysis tools were developed to inspire researchers and practitioners who might want to use this open resource. The Comfort Database is made available under the Open Database License, which means that end-users are free to share (i.e., duplicate, disseminate and use the database), to produce new works from the database, and to transform the Comfort Database.

A simple web-based interface to the database enables filtering on multiple criteria, including building typology, occupancy type, subjects' demographic variables, subjective thermal comfort states, indoor thermal environmental criteria, calculated comfort indices, environmental control criteria and outdoor meteorological information. Furthermore, a web-based interactive thermal comfort visualization tool has been developed that allows end-users to quickly and interactively explore the data. Figure 1 shows the location of the field studies contained in the comfort database.

Figure 1. Location of the field studies contained in the comfort database (From Foldvary et al. 2018).

A screenshot of the database analysis web interface is shown in Figure 2.

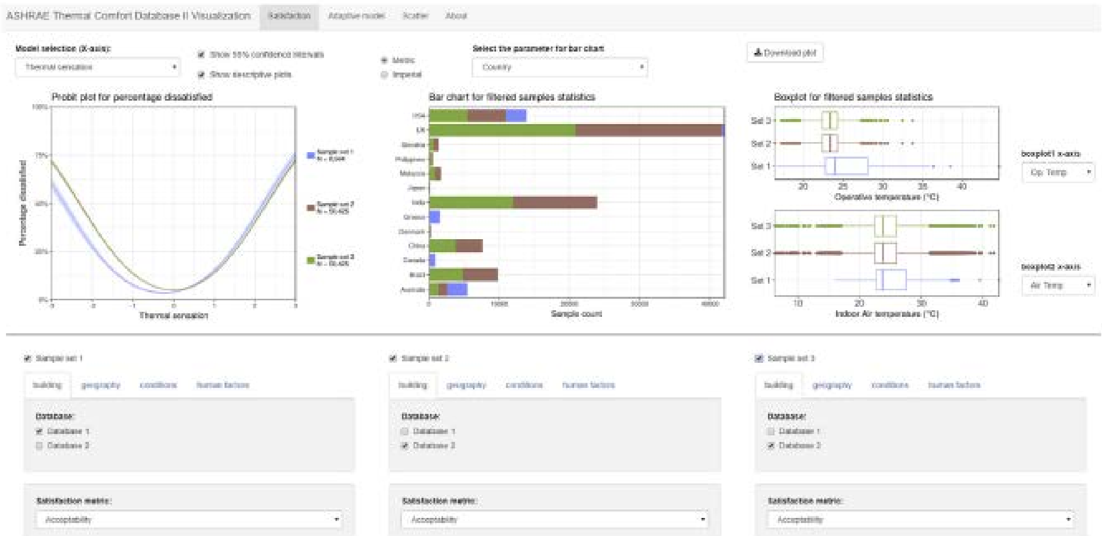

Figure 2. Screenshot of the thermal comfort visualization tool (From Foldvary et al. 2018).

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

Comparison of operative temperature limits across standards requires definition of reference levels for environmental and personal parameters that may vary depending on the season or the type of building (e.g. residential or commercial). The temperature limits shown in Figure 3 and Figure 4 refer to low air velocity (typically less than 0.2 m/s), clothing insulation of 0.5 clo for summer and 1 clo for winter, sedentary activity and air humidity around 50%. Figure 3 and Figure 4 compare operative temperature ranges for these reference levels during the cooling and heating season, respectively. The figures include only heat balance based models as the acceptable indoor temperature ranges defined the adaptive comfort models by definition depend on dynamic, outdoor temperature variation.

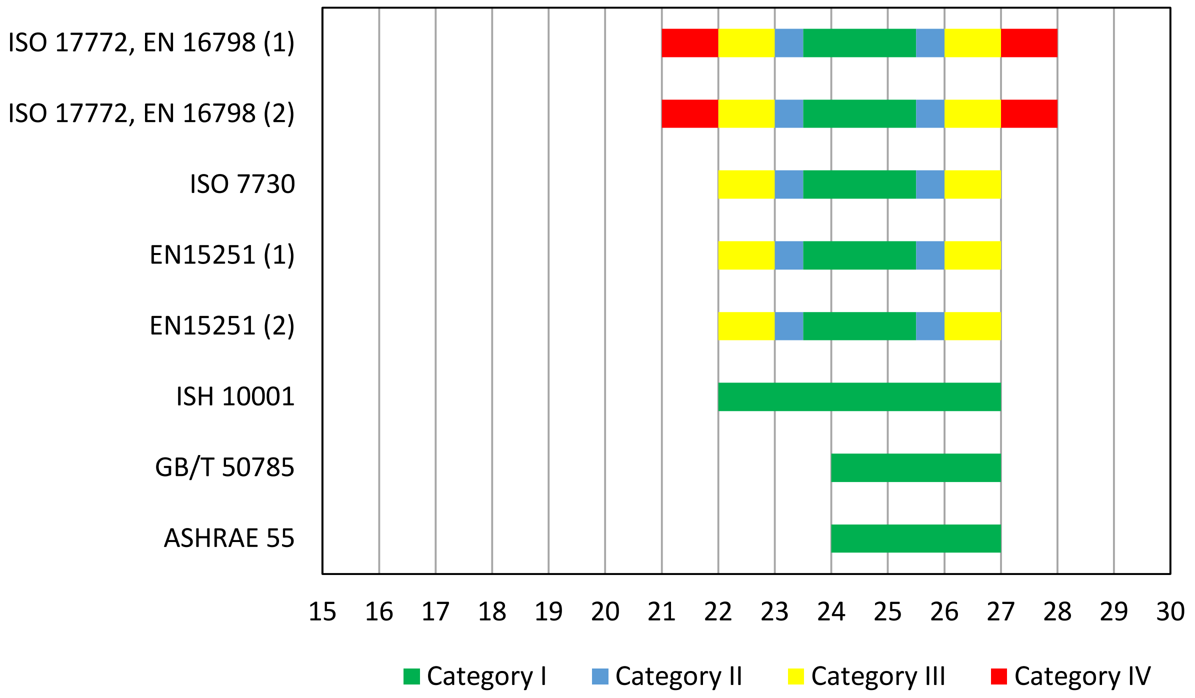

Figure 3: Categories for acceptable operative temperature ranges during the cooling season. (1) residential settings, (2) offices.

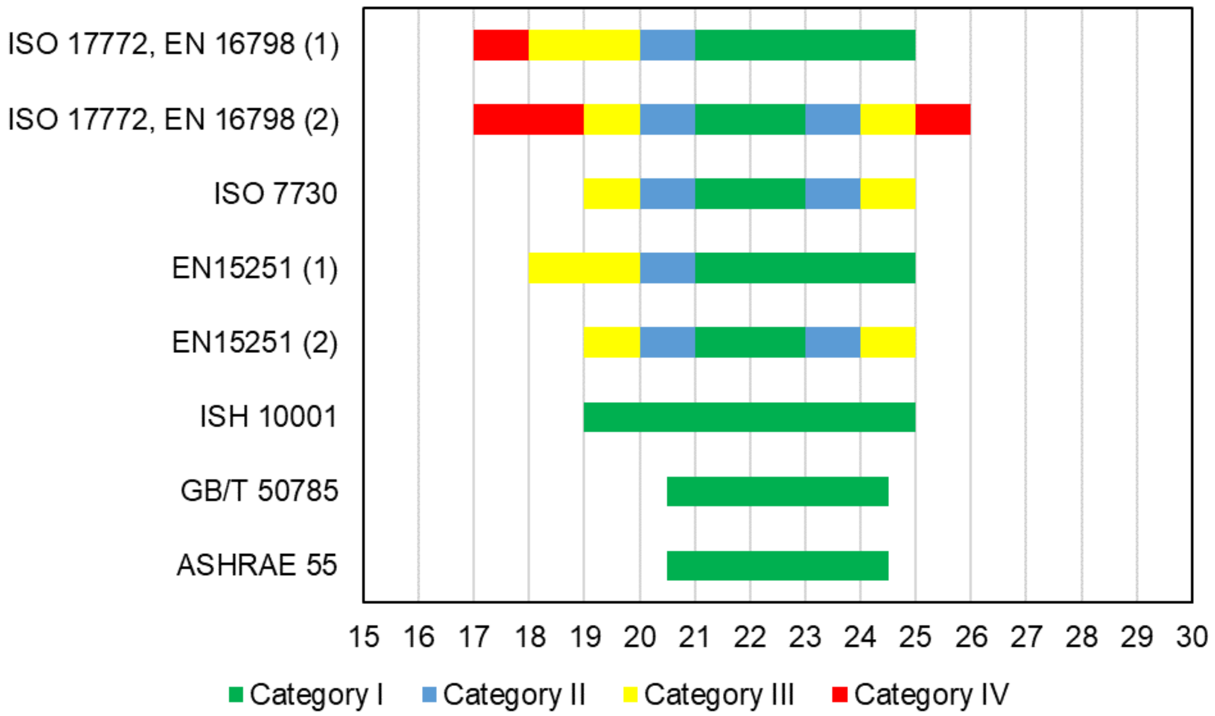

Figure 4. Categories for acceptable operative temperature ranges during the heating season. (1) residential settings, (2) offices.

The application of indoor environment standards informs the design of indoor environments and operation of building systems, increasing energy efficiency and occupant comfort and well-being. The discrepancies across standards in terms of the specifications for optimal thermal conditions will have an impact on occupant comfort, but also on the energy consumed by heating, ventilation and air conditioning systems. These differences were evaluated by energy consumption assessment through dynamic simulations. The main aim was to compare the energy consumption when two different control strategies were applied in simulated building models: a prescriptive thermal comfort control (PTC) based on the Predicted Mean Vote (PMV) model and an adaptive thermal comfort control (ATC) defined by the adaptive model.

The adaptive model defines a linear regression between comfortable indoor temperatures and the prevalent outdoor temperature. The temperature range in which the regression is valid varies depending on the specifications given by different standards. Figure 5 shows the energy savings of using the ATC instead of the PTC in the different building types at the included locations. Overall, applying the ATC instead of the PTC resulted in a significant reduction in the energy use in the simulated buildings. The energy savings gained by using ATC depended considerably on the outdoor temperature and the building type. Cold climates had a lower potential to reduce the energy consumption as compared with climates with higher outdoor temperature. Moreover, the differences between the calculated energy savings for the residential, school and office building models were partially explained by the magnitude of the internal heat gains. Depending on the building type and the outdoor climate, the energy savings using the adaptive model varied from 0 to 150 kWh/m². Nevertheless, applying the ATC approach also caused considerably longer periods with temperatures higher than 27ºC at several of the included locations. In the warmer climates, occupants will be exposed to temperatures above 27°C during almost the entire year.

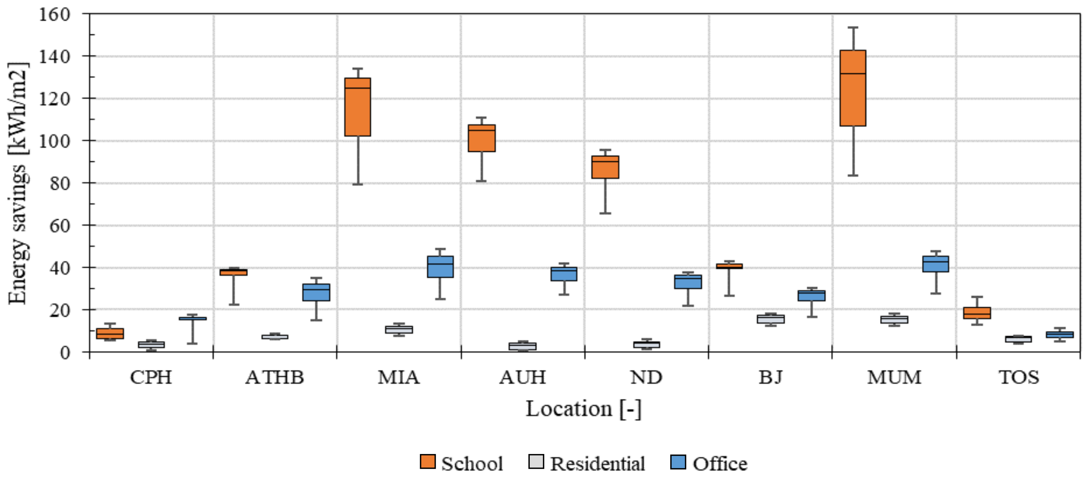

Figure 5: Energy savings (heating, cooling and HVAC auxiliary energy) using the ATC approach instead of the PTC for the three building models analyzed.

Latest developments in standardization efforts

The primary requirement for thermal comfort is that the temperature belongs to a range so occupants do not feel too warm or too cool. This range can be determined based on adaptive thermal comfort models or heat balance models as described in the previous sections. Several standards include additional, secondary requirements to local thermal discomfort factors such as draft, vertical air temperature difference, radiant temperature asymmetry, and floor surface temperature. Some of the latest developments in standardization efforts focus on local thermal discomfort and include:

- Air movement considerations. Revised limits for air movement in spaces including a model for draft risk at the ankles
- Solar control. Development of a method to evaluate the influence on comfort of direct and diffuse solar radiation
- Relaxed criteria for vertical thermal stratification
- Deeper understanding of metabolic rates of activities measured in the field

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

Based on a framework for adopting adaptive thermal comfort principles in design and operation of buildings, a guideline has been developed (Hellwig et al. 2019). With outset in the human thermoregulation and the physical principles of heat exchange between humans and their environment, the adaptive principles complete the set of variables necessary to describe thermal comfort comprehensively. For example, many of the variables describing these principles are not quantifiable and do therefore not find their way into planning and operation practices. The guideline aims to bridge this gap between adaptive thermal comfort theory and real-world building design and operation. It addresses the following objectives: 1) To improve the overall understanding of the adaptive principles; 2) To explain the adaptive principles' relation to building energy use; 3) To help interpreting the adaptive model in building practice; 4) To include advice for heated or cooled buildings into the guideline, facilitating free-running modes in building operation as often as possible but also how to use the adaptive principles in permanently or long-season conditioned spaces. In this context, fourteen office buildings from eight countries were studied employing consistent measurement protocols across all case studies. During the longitudinal monitoring period of at least six months, indoor and outdoor environmental conditions were monitored, and then paired with right-here-right-now thermal comfort questionnaires.

Exemplary solutions from practice and diverse climates make the guideline more illustrative. The guideline will address multiple building practitioners, including building planners and building operators. It will also be a useful source and guidance for educating future building professionals because a successful adaptive thermal comfort design, in which design for human thermal adaptation is foreseen, planned, and embedded in the design and operation intent, is based on broad knowledge and understanding of the multiple factors influencing human perception and human building interaction.

Additional information about the Annex may be found at www.annex69.org.

1.6 Utilization of project results

The project results target the building sector, which will be presented for the alternative paradigm for building operation and its potential. Knowledge about activities in the building sector in the partnering countries will be imported and disseminated through the Annex publications. The project results will also be synthesized in guidelines for energy efficient design of indoor environments. Currently, (February 2020) a deliverable is being prepared for submission to IEA, which will later be followed up by the Annex final report. Meanwhile, much of the work carried out in the Annex is reported in the project deliverables that form the basis of the results reported in this final report. In addition, the outcomes of the Annex activities are described in a special issue of the scientific journal Energy and Buildings. Currently around 30-35 papers for the special issue have been accepted and a few of these are still in review. A long list of other, related publications authored by annex participants can be found at: http://annex69.org/allpub

1.7 Project conclusion and perspective

A large database of comfort responses and matching indoor environment descriptors was established. The database will support studies of thermal comfort in field settings. The paper that presents the database was published in 2018 and has already received 23 citations in Web of Science (February 2020), which documents the demand of such a research tool.

The procedure for estimating running mean outdoor temperature, which is the main input to the adaptive comfort model, was evaluated. The determination of the comfortable temperature ranges was fairly independent of the weighing used to determine the running mean outdoor temperature indicating that the procedure already included in standards is robust.

Energy implications of designing thermal indoor environments according to traditional heat balance models or by using the adaptive approach were evaluated by simulations. Depending on the building type and the outdoor climate, the energy savings using the adaptive model varied from 0 to 150 kWh/m². Nevertheless, applying the adaptive approach also caused considerably longer periods with temperatures higher than 27ºC at several of the included locations.

A guideline was developed promote the adoption of adaptive thermal comfort principles in design and operation of buildings. The guideline addresses multiple building practitioners, including building planners and building operators. To support the guideline, exemplary solutions from practice and diverse climates were included in a database.

Overall, the project has developed recommendations for "adaptive" building design, operation and refurbishment to increase the performance of future buildings.

Annex

General Annex information:

http://annex69.org/index
https://www.iea-ebc.org/projects/project?AnnexID=69

List of Annex publications (excluding publications in the special issue of Energy and Buildings):

http://annex69.org/allpub

List of publications co-authored by project participants affiliated with DTU:

Khovalyg, D., Olesen, B.W., Halvorsen, H., Gundlach, I., Toftum, J., Kazanci, O.B., Bahnfleth, W. (2019) Critical review of national and international standards on indoor environment. Energy and Buildings (In press – available online). doi.org/10.1016/j.enbuild.2020.109819

Rawal, R., Schweiker, M., Kazanci, O., Vardhan, V., Jin, Q., Duanmu, L. Personal Comfort Systems: A review on comfort, energy, and economics. Submitted to Energy and Buildings.

Kazanci, O. B., Coakley, D., & Olesen, B. W. (2019). A review of adaptive thermal comfort implementation in international thermal comfort standards. In 2019 ASHRAE Annual Conference.

Aguilera, J.J., Kazanci, O.B., Toftum, J. (2019) Thermal adaptation in occupant-driven HVAC operation. Journal of Building Engineering, 25, September. DOI: 10.1016/j.jobe.2019.100846.

Aguilera, J.J., Toftum, J. (2019) Predicting personal thermal preferences based on data-driven methods. Proc. of CLIMA 2019, May 26-29 2019, Bucharest, Romania. This article was also selected for publication in the European REHVA HVAC Journal 2019-03, 49-56.

Khovalyg, D., Olesen, B.W., Halvorsen, H., Gundlach, I., Toftum, J., Kazanci, O.B., Bahnfleth, W. (2020) Impact of indoor environmental quality standards on the simulated energy use of buildings. Submitted to Windsor Conference 2020 on Resilient Comfort.