Institution: University of Reading		
Unit of Assessment: 13, Architecture, Built Environment and Planning		
Title of case study: Energy Savings Through Adoption of Adaptive Thermal Comfort Models in Chinese Building Design Standards		
Period when the underpinning research was undertaken: 2007-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Runming Yao	Lecturer; Reader Professor	2007 – present
Period when the claimed impact occurred: 2015–20		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Covering a floor area of over 65,000,000,000m^2, China's building stock has a high energy demand. In 2017, it consumed approximately 30% of primary energy and accounted for approximately 21% of the country's electricity consumption. Indoor environmental design, which allows a range of temperatures, therefore has an impact on building energy consumption. Research led by Yao at the University of Reading has developed an Adaptive Predicted Mean Vote (aPMV) model which can quantify the dynamic thermal comfort demand from season to season and across China's varied climatic zones. The model has been adopted within three Chinese National Building Standards (CNS GB) and three further Professional/Industrial Standards since 2015. This has led to energy savings and increased human comfort through improved design and operation of buildings in China. For example, on the basis of the Green Building Standard accreditations issued across China in 2019, it can be calculated that the carbon reduction is estimated at about 10,250,000,000 kg of CO_2 for the hot summer, cold winter zone in China.

2. Underpinning research

Designing and operating indoor thermal environmental conditions is one of the key elements in the energy-efficient-building design process. International standards such as ISO 7730 (ISO7730 1994) apply Fanger's Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices, which are based on steady-state, human body heat balance theory and conducted in a climate chamber. However, this approach overestimates the thermal comfort demand and therefore causes an adverse impact on energy consumption in real free running buildings. Although international standards such as ASHRAE 55 have tried to improve outcomes by becoming "adaptive" comfort standards, there are limitations to this revised method as it depends only on the outdoor temperature and neglects indoor factors.

Yao's research [Section 3, ref 1] developed an adaptive model (aPMV), which, building on the PMV/PPD indices, embraced and quantified an array of human adaptation factors, such as physiological, behavioural and psychological adaptation [ref 2]. This innovative method has extended thermal comfort calculations in broader ranges, which in turn lead to significant energy savings.

The theoretical studies of adaptive comfort have been supported by the EPSRC through the networking project nCUBUS: Network for China–UK Building and Urban Sustainability (GBP135,911), and later the EPSRC/NCSF-funded UK–China Low-Carbon cities project ('LoHCool'; total GBP798,987). The first publication [ref 1] presented the newly developed "black-box"-based aPMV model using cybernetic concept. The aPMV model can be described as $aPMV = PMV/(1 + \lambda \times PMV)$, and has revealed the generic relationship of the aPMV and the PMV in non-air-conditioned buildings. This involves the adaptive coefficient λ, which reflects a human's adaptive functions as well indoor climate parameters, such as air humidity, velocity, and radiation for system designs. The adaptive coefficient (λ) represents the adaptive factors that affect the sense of thermal comfort; importantly, it bridges the gap between laboratory and field studies. The method of calculating λ has been illustrated by a detailed process of data collection during a year-long field study and including an on-site questionnaire and simultaneous measurement of indoor/outdoor climates in Chongqing. The method has attracted international attention since its publication, with more than 355 citations (Google Scholar). These parameters are essential for environmental system design of buildings, in particular a mixed-mode (mechanical and passive) system aimed at achieving thermal comfort while minimising energy consumption.

Through the nCUBUS EPSRC project (2007–09), the research focused on the understanding of the locality of the adaptive coefficient, which aimed to provide guidance on the design and control of climate-responsive adaptive thermal comfort space using limited energy. In this project, Yao co-led a large-scale nationwide field study, conducted in 14 major cities, covering different climatic zones in China. Over 28,000 test respondents participated in the field study from different climate zones in China [ref 3]. As a result, climate-based λ coefficients were obtained for the “very cold and cold”, “hot summer, cold winter”, “warm winter, hot summer” and “mild” zones with different types of buildings.

Promoting climate-responsive low-carbon building design based on the aPMV model has been further embraced through the UK–China collaborative project LoHCool (2015–19). The aim of this study is to demonstrate how the use of climate-sensitive passive design solutions can help improve indoor thermal conditions while reducing energy needs and ultimately carbon emissions. The model has been used to determine perceived thermal comfort and behavioural adaptation in two climatically contrasting cities in China (Chongqing and Hangzhou). These findings have enabled the development of the concept of “extending the non-heating/cooling period”; they have shown that passive building design can be tailored to include the needs of the dense, and rapidly expanding, population situated in the hot summer, cold winter climate zone in China [ref 5]. These design solutions will therefore offer considerable energy savings.

The research has also laid the foundations for determining the “heating/cooling energy flexibility concept” [ref 6]; this arose from research which explored the year-round thermal adaptation of occupants in residential buildings in the hot summer, cold winter zone in China. The results showed that the measured indoor temperatures were linearly related to the outdoor temperature in transient seasons but were discrete in the summer/winter seasons as a result of the mixed-mode operations of heating/cooling devices. This work contributes to the quantitative understanding of the role of human thermal adaptation in the smart control of residential energy management. It provides evidence for policymaking on flexible thermal design codes in building, to discourage excessive cooling/heating demands and thus reduce energy consumption.

Research at the University of Reading has led the way on modelling thermal comfort on the basis of human adaptive responses. This has not only underpinned building design standards accommodating China’s diverse climatic range, but in so doing it has also brought about design changes in the manufacturing industries associated with the building industry.

3. References to the research

1. Yao, R., Li, B. and Liu, J. (2009) ‘A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV’). *Building and Environment*, 44 (10). pp. 2089–2096. doi: https://doi.org/10.1016/j.buildenv.2009.02.014

2. Liu, J., Yao, R. and McCloy, R. (2012) ‘A method to weight three categories of adaptive thermal comfort’. *Energy and Buildings*, 47 . pp. 312-320. ISSN 0378-7788 doi: https://doi.org/10.1016/j.enbuild.2011.12.007

3. Li, B., Yao, R., Wang, Q. and Pan, Y. (2014) ‘An introduction to the Chinese Evaluation Standard for the indoor thermal environment’. *Energy and Buildings*, 82. pp. 27-36.

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4. Li, B., Du, C., Yao, R., Yu, W. and Costanzo, V. (2018) 'Indoor thermal environments in Chinese residential buildings responding to the diversity of climates'. *Applied Thermal Engineering*, 129. pp. 693-708. doi: https://doi.org/10.1016/j.applthermaleng.2017.10.072
5. Yao, R., Costanzo, V., Li, X., Zhang, Q. and Li, B. (2018) 'The effect of passive measures on thermal comfort and energy conservation. A case study of the Hot Summer and Cold Winter climate in the Yangtze River region'. *Journal of Building Engineering*, 15. pp. 298-310. doi: https://doi.org/10.1016/j.jobe.2017.11.012
6. Du, C., Li, B., Yu, W., Liu, H. and Yao, R. (2019) 'Energy flexibility for heating and cooling based on seasonal occupant thermal adaptation in mixed-mode residential buildings'. *Energy*, 189. 116339. doi: https://doi.org/10.1016/j.energy.2019.116339

The underlying research has been financed by peer-reviewed research council funding and published in high-quality academic journals such as *Energy and Buildings*, *Journal of Energy, Applied Thermal Engineering, Journal of Building Engineering* and *Building and Environment*. The research has developed some sophisticated modelling. The "Black Box" in system theory, representing the control mechanism of the system, has been applied for the first time in the human thermal sensation system to solve the adaptive thermal comfort problem. The peer-review process for both funding and outputs ensures that it meets the 2* criteria of providing important knowledge and the application of such knowledge (through adoption in building and design standards), contributing to an incremental and cumulative advance in knowledge and has been undertaken in a thorough and professional manner. This is the first research to develop the theoretical adaptive model of thermal comfort, which bridges the gap between laboratory-based and field survey studies.

4. Details of the impact

In China, building designs for internal comfort have previously neglected to address human adaption responses, resulting in a high demand for and over-consumption of energy. The novel adaptive thermal comfort model (aPMV) developed at Reading now underpins three Chinese national government green building standards and three standards for national professional bodies (including the Architecture Society for China and the China Engineering Construction Standardisation Association) [Section 5, source 1]. This means that the research has influenced the design of low-energy, green and healthy buildings by quantifying the adaptive thermal comfort zone, which is essential to building system design. It has also influenced the design of products for related industries, such as air conditioning. The sophistication of the model (using adaptive coefficient λ) has produced climate-based λ for China's distinct and varied climatic zones, resulting in significant energy savings.

Context

China has undergone extensive economic development over the last four decades, but is increasingly facing serious issues regarding energy and the environment. China promised to reduce its carbon intensity by 40–45% by 2020 and 60–65% by 2030 (based on 2005 levels), and to decrease peak carbon emissions by 2030 (United Nations Framework Convention on Climate Change 2009, 2015). The building sector consumed approximately 30% of primary energy and accounted for approximately 21% of the electricity consumed in 2017. Energy consumption in heating and cooling for thermal comfort is increasing significantly, owing to economic growth and increased living standards. For example, total urban residential cooling energy consumption was around 85,000,000,000kWh in 2015. It is estimated there will be a continued growth in demand for improved indoor thermal environments, to counteract climate change.

Engagement and adoption

Yao's deep engagement with the Ministry of Housing and Urban-Rural Development (MOHURD) resulted in the creation of a new national (Chinese) standard "GB.T 50785-2012 – Evaluation standard for indoor thermal environment for civic buildings". This was launched in 2012 and underpinned by the detailed adaptive coefficient λ for different climate zones, based on the aPMV model. This was a step-change in determining thermal comfort, using algorithms based on indoor and human adaptation or response data as opposed to outdoor temperatures or climate-chamber-based theory. During the REF period, Yao sat on the China Green Building Council International Advisory Board (since 2014) and became an Expert Committee Member for Green and Eco-urban Assessment (since 2018). Her research and expertise have underpinned guidance on the development of green building assessment standards, “and influenced policy and strategy development in China’s low carbon green building movement” [source 2]. As a result, three national standards and three professional standards were adopted between 2015 and 2019. They are all underpinned by both the previously launched GB.T 50785-2012 and the adapted aPMV model from Yao’s research after 2015, which has informed building design. They are as follows: 1) Green Retrofitting CNS GB/T 51141-2015; 2) Green Building CNS GB/50378-2019; 3) Green Store Building GB/T 51100-2015; 4) Healthy Building T/ASC02-2016; 5) Healthy Residential Building T/CECS 462-2017; and 6) Green Interior Decoration T/CBDA2-2016 [Section 5, sources 1, 2].

Through the implementation of the national standards, Yao’s research has inspired the design and operation of mixed-mode buildings; these use a combination of a mechanical and a passive hybrid approach to space conditioning, that is, both natural ventilation from operable windows, and mechanical systems that include air distribution equipment and refrigeration equipment for cooling. This is being demonstrated through a project where Yao is Chief Scientist. She spends half of her working hours seconded to Chongqing University (2016–20) leading a “flagship” project, “Solutions to heating and cooling of buildings in the Yangtze river region” [source 3]. This region is significant, accommodating 550,000,000 people, with a building stock of some 9,000,000,000m^2. “Under her leadership, 32 demonstration buildings were constructed to achieve a 20 KWh/m^2 target and maintaining an indoor temperature falling within the range defined by the adaptive thermal comfort aPMV model” [source 3]. This is the largest research project in China’s Green Building Programme, forming part of the 13th Five-Year Plan’s Research and Development programme, with RMB125,000,000 contributed by the Ministry of Science and Technology as well as the construction industry. Through this role, Yao has engaged intensively across the building-related industries, providing expert advice to building design consultancies, who have incorporated the concept of extending the non-heating and cooling period by improving passive building design. Her collaboration with the Shanghai Research Institute of Building Science, whose previous iconic projects have included Shanghai Disneyland and Pudong Airport, delivered the Demonstration Office Building [refs 2,3,5; source 4]. Through its thermal properties and temperature settings based on the adaptive thermal comfort range, this demonstration building has a “reduced heating/cooling demand of 40%”. In the region, “the impact on energy saving will be significant”, with 3,000,000m^2 of new office space under construction in Shanghai alone each year [source 4].

As a result of this research project, Yao is co-leading the development of a further professional standard (China Association of Engineering Construction Standardisation). Again underpinned by Yao’s research [refs 1-6; source 3], this specification “will be used as a guideline by design companies for buildings located in the hot summer and cold winter zone in China with 550 million population contributing over 45% [of] China’s GDP, and will achieve significant energy efficiency” [source 3]

The Reading research does not impact only on China’s low-energy building standards but also on the broader related industries developing and manufacturing energy-efficient appliances for heating and cooling. For example, the country’s biggest air conditioner manufacturers (Haier and Midea) have developed a high-efficiency air supply device based on the dynamic thermal comfort needs, and flexible control (temperature, humidity and airflow speed) technology based on the adaptive thermal comfort model. The appliances have now gone to the market. The use of seasonal control modes for cooling will significantly reduce energy consumption, compared with using traditional air conditioners. [Text removed for publication].

Heating and air conditioning account for 41% of building energy consumption. Until now energy consumption has been inefficient as it has not accounted for human adaptive response (behavioural and physiological) to thermal comfort and climate. The research described above has pioneered the understanding of the human adaptive response to indoor temperature. It has been adopted by numerous national and professional building and design standards, demonstrated in exemplar buildings, and it has underpinned significant increases in revenue from innovative designs for more efficient air conditioners. The adaptive model can be used across all of China's distinct and varied climatic zones. In 2019 alone, the hot summer, cold winter zone experienced new construction of 2,500,000,000m^2 accredited with Green Building Standards. It can be calculated that increased flexibility in temperature settings for that year and region would result in a reduction in 10,250,000,000 kg of CO_2 [source 7]. With evidenced increases in energy-efficiency savings in demonstration buildings, the uptake of the national building and design standards in a country experiencing rapid urbanisation means that energy savings and reductions in carbon emissions are significant.

5. Sources to corroborate the impact

- **[S1]** List of websites for three Chinese national and three professional institution (building and design) standards.
- **[S2]** Testimonial from the Chairman of the China Green Building Council.
- **[S3]** Testimonial from Director of Institute of Building Environment, Chongqing University.
- **[S4]** Testimonial from Shanghai Research Institute of Building Science.
- **[S5]** Testimonial from Midea.
- **[S6]** Testimonial from Haier.
- **[S7]** Estimation of carbon reduction for one year (2019)