Architectural Science Review

ISSN: 0003-8628 (Print) 1758-9622 (Online) Journal homepage: https://www.tandfonline.com/loi/tasr20

Applying a comfort model to building performance analysis

Mark Luther, Olubukola Tokede & Chunlu Liu

To cite this article: Mark Luther, Olubukola Tokede & Chunlu Liu (2020): Applying a comfort model to building performance analysis, Architectural Science Review, DOI: 10.1080/00038628.2020.1742645

To link to this article: https://doi.org/10.1080/00038628.2020.1742645

ARCHITECTURAL SCIENCE REVIEW
https://doi.org/10.1080/00038628.2020.1742645

Taylor & Francis
Taylor & Francis Group

Applying a comfort model to building performance analysis

Mark Luther, Olubukola Tokede and Chunlu Liu

School of Architecture and Built Environment, Deakin University, Geelong, Australia

ABSTRACT
This paper considers the application of comfort parameters as a mechanism for building performance analysis and control. It challenges traditional methods of evaluating zonal comfort through thermostatic dry-bulb temperature alone. In contrast, it creatively applies a 'calibrated' Comfort Tool software to measure comfort improvements in buildings. A comfort cart built according to ASHRAE-55 standards together with thermal imaging surface temperatures is combined in a comprehensive thermal performance analysis in buildings. This paper is about demonstration and discussion in the development of a measurement and analytical process which is a systematic approach towards spatial comfort improvement. Two houses were measured and analysed, over an extreme daytime period in Darwin, Australia. Improvement in overall thermal conditions of up to 35% and 59% were realised with the most reliable potential for thermal improvements found in surface temperature (mean radiant temperature), conditioning changes indicating between 32 – 38% overall comfort improvement in the building.

ARTICLE HISTORY
Received 22 July 2019
Accepted 8 March 2020

KEYWORDS
ASHRAE-55; building performance measurement; comfort models; thermal imaging; mean radiant temperature; energy-efficiency

1. Introduction: problems of energy efficiency & control in buildings

The manner in which we control for thermal comfort in buildings is antiquated and not effective. Thermostatic control of air temperature is not only problematic but energy-intensive. According to the research of Hoyt et al. (2009), a significant energy-saving is dependent upon the dry-bulb air temperature set-point of the thermostat. Increasing the cooling set-point by one degree from 24°C to 25°C results in annual energy-savings of 7–15% depending upon the climate location of the building. When the set-point is expanded to 28°C, a difference in the annual savings could be as much as 35–45% in cooling conditioning. Temperature settings alone, between 1°C and 4°C difference from the 'standard' of 21.5°C in heating mode can account for 7–35% savings, depending upon the duration of the heating season (climate). These findings may question the manner in which we control our buildings. Perhaps they may also question the way we design for the conditioning of our buildings and the service system we apply in the first place (Hoyt et al. 2009).

The advancement of sensors and associated equipment is no doubt one of the main factors in providing energy-efficiency as well as comfort to our buildings. Zampetti, Arnesano, and Revel (2018) utilized a thermographic infrared sensor with a 360° rotating mechanism to determine the surface temperatures within a space, thereby obtaining the mean radiant temperature. Together with other collected parameters of dry-bulb and humidity, an ISO7730 (2005) Fanger comfort assessment could be instantaneously obtained. This sensing-control system alone accounted for a 12–17% energy savings from the existing HVAC system. Interestingly, this research dealt with convective (air) mechanical conditioning of the space only and did not provide for other mechanisms that may have provided for further reduction in energy consumption.

A discovery made from measurements of an open office space inspired the newly proposed interest in applying comfort outcomes as a building control parameter (Luther and Ahmed 2019). Figure 1 illustrates the Winter period for an office building in Melbourne, where a thermostatic (air) temperature determines an occupant's comfort. As it would appear, most occupants would be in agreement with this uniform and reasonable interior air temperature at the various locations shown on the floor plan.

It may not be surprising to those knowledgeable of comfort models, to discover, that at the same locations within this open office, that a vast discrepancy among comfort results exists (see Figure 2). This is indeed the very reason for the argument for thermal comfort as a building control parameter. If designers and engineers could consider how to include devices and systems that allow for control ranges in the comfort parameters, we might just have an answer to comfortable buildings at an affordable energy cost.

The use of past research on office buildings in relation to temperature and comfort measurement is an example of a principle only. In other words, while temperature has a relatively minor change throughout a space (i.e. an office in this case), the comfort variability can be dramatically different. We believe that this principle holds true no matter what the function of space might be (i.e. a hospital, a library, or a house) Rafique, Gandhidasan, and Haitham (2016) predicted that the energy required to provide human thermal comfort conditions is about 50% of

CONTACT Olubukola Tokede ✉ olubukola.tokede@deakin.edu.au School of Architecture and Built Environment, Deakin University, Geelong, VIC 3220, Australia

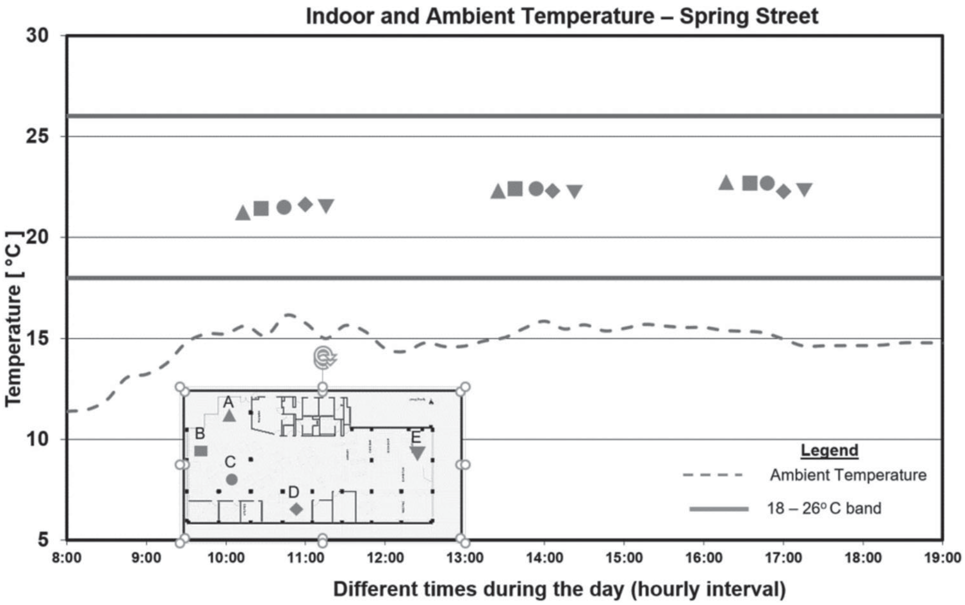


Figure 1. Air temperatures at various locations in an open office.

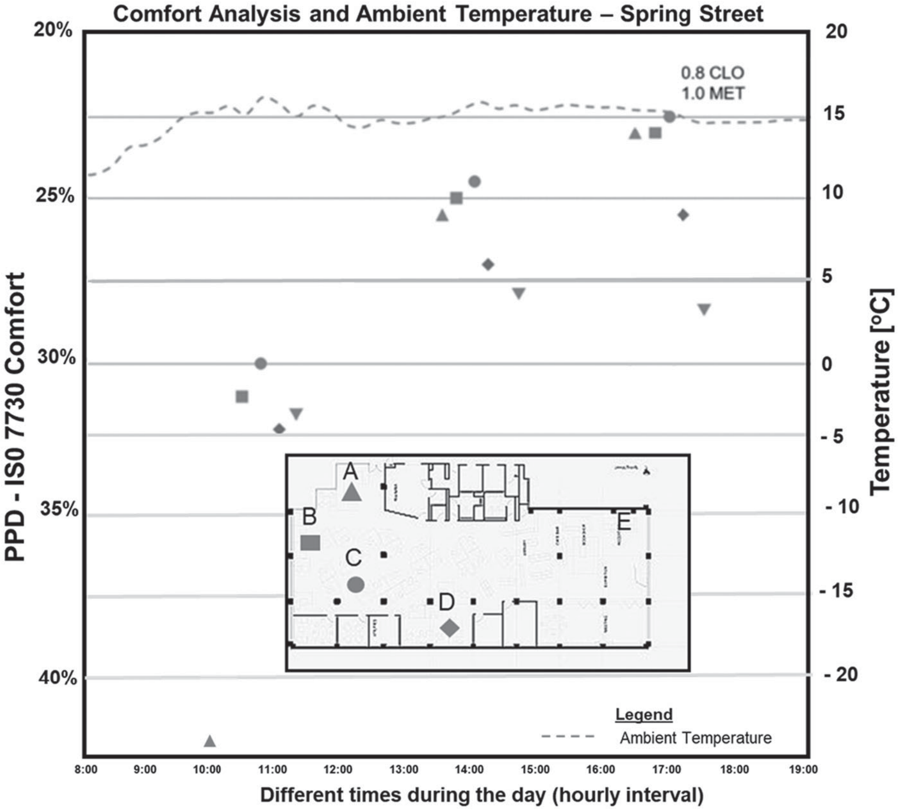


Figure 2. ISO 7730 comfort results for an open office.

the building's total operational energy. Judson and Maller (2014) also argued that interventions to minimize energy consumption in residential buildings would depend on frequently performed daily practices. Based on these findings, integrating occupant behaviour and energy-efficiency in buildings becomes a necessary requirement in improving the sustainability performance of the built environment (Kim, Schiavon, and Brager 2018; Brager, Zhang, and Arens 2015; Godithi et al. 2019). Zampetti, Arnesano, and Revel (2018), therefore, proposed that optimal and energy-efficient comfort management of indoor spaces must include (i) a real-time and multipoint measurement of thermal comfort; (ii) an advanced controller, and (iii) a personalized or sub-zonal heating/cooling system. The authors of this paper believe that if we are to prevent future predicted increases in energy consumption, we must begin to look at different measures and processes that have an influence on comfort.

1.1. Comfort models

Comfort models have been in existence and active for almost over 50 years now. These have demonstrated that air temperature alone does not guarantee our comfort in a space and that there are many other parameters that can determine comfort. In 1970, Dr O. Fanger was attributed to producing the method applied in the ISO 7730 standard. This approach, known as the 'static model of comfort' considers a thermal vote (a Predicted Mean Vote – PMV) or a Predicted Percentage Dissatisfied (PPD) as the outcome of six different variables; dry-bulb, mean radiant temperature, air velocity, humidity, clothing level, and metabolic rate. Perhaps the comfort models in opposition to the 'static' model are those labelled as the 'adaptive' model as explained by De Dear and Brager (1998); and Humphreys and Fergus Nicol (2002) as well as others. In fairness, there is a distinctive difference claimed by developers of the 'adaptive' model that it is best applied to buildings that allow occupants to dress relaxed and according to climatic conditions as well as to have control over their environments, such as the opening of windows, use of ceiling fans, shading devices, and so on. These models all hover around obtaining a 'neutral temperature' often based upon a relationship with outdoor mean operative temperature conditions alone. Equation 1 provides a mathematical expression of the relationship between the neutral temperature and the monthly mean exterior temperature.

$$T_c = 13.5 + 0.54\,T_o \qquad (1)$$

where Tc = the indoor comfort temperature or 'neutral temperature and, To = the monthly mean of the exterior temperature.

This equation, in particular, is for free-running buildings, yet similar equations exist for hybrid buildings. An alternative to Fanger's comfort model are adaptive models. Adaptive models assume a linear relationship between a comfortable indoor temperature and prevailing outdoor temperature. Kim, Schiavon, and Brager (2018) criticize the existing (static) comfort model for their failure to recognize that both human perception and physical conditions of thermal comfort can change over time. In view of this, another approach – personal comfort models – is emerging, which predicts an individual's thermal comfort response by leveraging on IoT (i.e. the Internet of Things) and machine learning. Evidence abounds that personalized comfort system (PCS) provides occupants with the opportunity to meet their own preferences (Kim, Schiavon, and Brager 2018; Godithi et al. 2019) while simultaneously achieving energy and comfort performance improvement in buildings (Brager, Zhang, and Arens 2015). The focus of this paper is however on the static model of comfort, and its efficacy in enhancing building performance.

While the authors do not dispute the value of the adaptive model principles, at this point in their development, unlike the ISO 7730 (static model), they do not offer the variables within building designs themselves that influence the calculation of comfort. In other words, an architect can design for an adaptive building to allow for user-control but does not know to which extent various parameter influences have over comfort, as they cannot be calculated (Griego, Krarti, and Hernández-Guerrero 2012). The designer would have no influence over the external temperature or its mean; however, they could provide shading, openable windows, and other control devices, yet, there is no numerical or objective manner by which a decision for one can be made over the other (Kim, Schiavon, and Brager 2018). Further development and an extension to interior air temperature might involve, mean radiant temperature of the surrounding surfaces, interior air velocity, and humidity and would undoubtedly assist the 'adaptive' equation of comfort. These parameters are in fact part of the 'static model' and can be useful to those wanting to consider controlling their ranges. Perhaps the crucial point of what our buildings require are parts of the 'static' comfort model making their way into the 'adaptive' model.

1.2. Comfort models and building energy – an overview

Comfort management in buildings has witnessed a growing interest in recent times. A seminal paper by Yang, Yan, and Lam (2014) discusses the two prominent thermal models and their relationship between comfort and energy-efficiency. It is concluded that adaptive comfort models tend to have a broader range of comfort temperature, offering significant energy-savings in both air-conditioned and naturally-ventilated buildings. Interestingly, aside from comfort models, this paper turns to discuss the application of co- and tri-generation systems advocating a solution to the rising electricity use, costs and a reduction in CO_2 emissions stating that the operational mode of combined cooling, heating and power (CCHP) systems depend on the building thermal and electrical loads, which tend to vary according to the outdoor ambient conditions. Again, a system aligned with the adaptive model relationship to external conditions

Others also continue to discuss a relationship of comfort with energy. Barbadilla-Martín et al. (2018); in particular, demonstrated that the adaptive model is effective for the optimization of HVAC systems and that it is possible to achieve energy-savings without impairing the comfort of its occupants. Implementing the adaptive model algorithm in the HVAC control system during the cooling and heating period resulted in savings of 27.5% and 11.4% respectively (Barbadilla-Martín et al. 2018).

Also, Zampetti, Arnesano, and Revel (2018) indicated a distinctive difference between thermostatic (air temperature) and calculated thermal comfort (ISO 7730 – Fanger) based control. Meaning, that there were no changes to a particular space other than changing the control parameter, from thermostat temperature, to that of a PMV – thermal comfort calculated control which yielded a savings of 17% or more. Contrary to the cases of many other researchers, Attia and Carlucci (2015); Nicol and Michael (2002); and Strengers (2008), primarily depict the 'adaptive model' as an energy-saving control strategy. Zampetti, Arnesano, and Revel (2018) discuss the advantages of using PMV-based controllers that have also through simulations achieved cooling energy reduction of about 20% in comparison with standard thermostatic control.

Griego, Krarti, and Hernández-Guerrero (2012) claimed that a strong correlation exists between the use of thermal insulation and improved thermal comfort, however, that the relationship between PMV ratings with energy-savings still remains unclear. While several researchers may disagree with Griego et al.'s claim pertaining to lack of progress, the interesting aspect is that a relationship of comfort is made here with reference to building materials. This acknowledges an interesting cataloguing on the subject of energy and comfort and our approach to achieving both. In summary, it is realized that there are perhaps three distinctive categories;

- One that looks at control algorithms through the application of comfort models in relation to the operation of equipment.
- Another that suggests that building services themselves could provide for reduced energy and improved comfort.
- and finally, one that states that the materials, insulation, design, and construction quality of the building itself could provide for better energy-saving and comfort.

Regardless of the category, there is an on-going dialogue on the topic, indicating that energy-savings together with comfort are in fact possible (Barbadilla-Martín et al. 2018; Strengers 2008; Yun, Lee, and Steemers 2016). On the other hand, it is continually noticed that designers and consultants forget the models of comfort altogether and resort back to the thermostat in the room as the sole determinant of our comfort.

2. Research method

The realization and inspirational backbone of this paper emanated from the experimental measurement of several real case studies. The Mobile Architecture and Built Environment Laboratory (MABEL) investigated several building types at various locations throughout Australia providing the data and analysis used in this paper (Luther 2013)

Measurements of comfort typically utilized two comfort carts constructed according to the ASHRAE Standard 55 (ASHRAE 2017) see Figure 3. Each measurement consist of five-second readings averaged into 15-minute intervals. This has been explained in more significant details in Luther (2013).

The next important information in the understanding of building performance is that of surface temperatures, provided through thermal imaging. A NEC AVIO high-level thermal imaging camera, as shown in Figure 4, was applied to the imaging of several different houses during a performance measurement investigation in Darwin, Australia. This camera had the capability of producing photo imaging measurements every 15 min. The results produced a logging of the surface temperatures of the space while at the same moment measurements of comfort parameters were recorded with the comfort cart.

A time-series example of combining both the Comfort Carts with thermal imaging measurements is provided in Figure 5. The data output of the two instruments is what we require for the analysis of spatial comfort performance within the entire space.

2.1. Application of the ASHRAE 55 comfort tool

The thermal comfort conditions are calculated based on continuous measurement of environmental parameters for a specific zone on each house. The predicted mean vote is the calculated average vote, which would be conceived in a survey among a representative number of occupants under measured conditions, it is the result of a calculation according to ISO 773. The next step is the unification of measurements with that of simulation. This calibration process between measured and simulated data is an important step when considering forthcoming simulation results that evaluate a variable separately for improvements to comfort. Multiple simultaneous surface temperature measurements taken without interrogating the surfaces allows a comparison with air temperature measurements and heat transfer. It was questioned whether the result of the mean radiant temperature (MRT) calculated by the measurements taken at the comfort cart would match (or compare to) those derived by the surface temperatures of the space, obtained by thermal imaging. It was realized that the ASHRAE-55 (2004, 2017) Comfort Tool (software) provided a dual analysis; first, that of comfort evaluation, through PPD and PMV calculation (Figure 6), and second, the calculation of MRT (through a sub-routine of the software) at a specific location (Figure 7), provided that surface temperatures, their location, and their

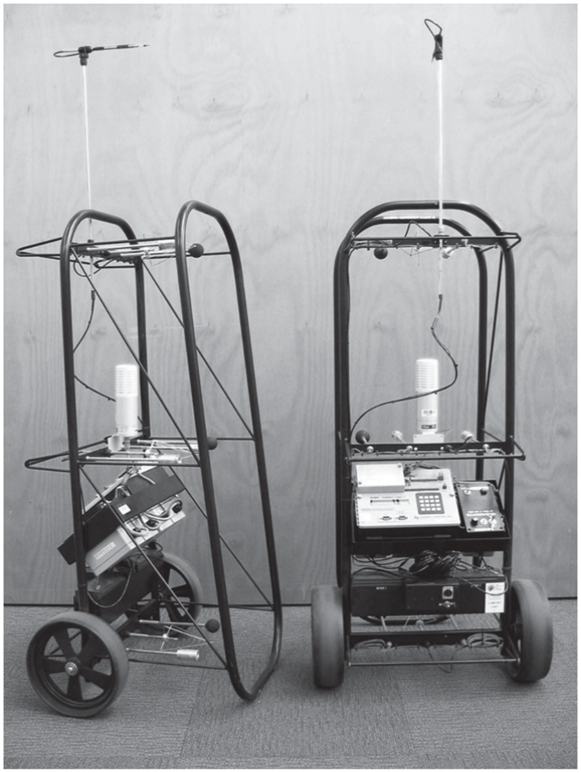
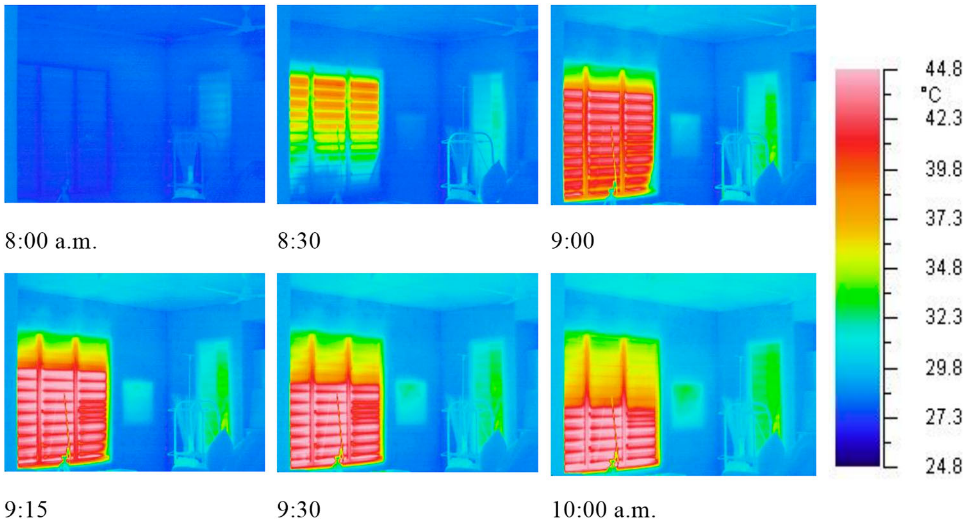


Figure 3. Comfort carts as used in the measurements on a project.

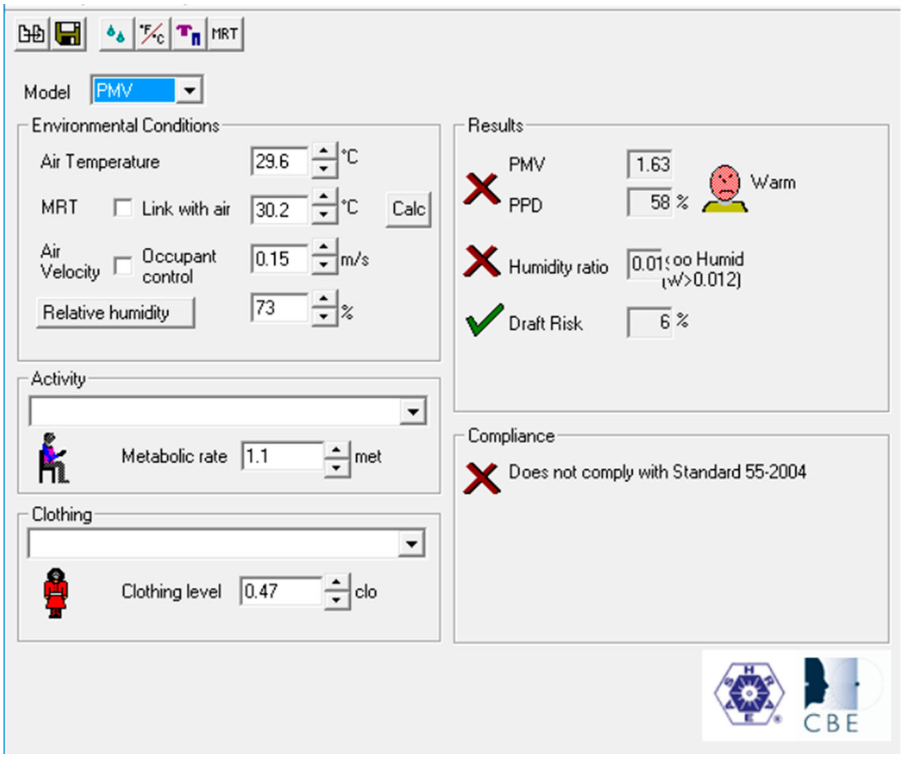
Figure 4. NEC – Avio thermal imaging camera.



8:00 a.m. 8:30 9:00

9:15 9:30 10:00 a.m.

Figure 5. Time step thermal images of the blockhouse (Southeast) living room.



Model PMV

Environmental Conditions

Air Temperature 29.6 °C

MRT ☐ Link with air 30.2 °C Calc

Air Velocity ☐ Occupant control 0.15 m/s

Relative humidity 73 %

Activity

Metabolic rate 1.1 met

Clothing

Clothing level 0.47 clo

Results

PMV 1.63

PPD 58 % Warm

Humidity ratio 0.01: oo Humid (W>0.012)

Draft Risk 6 %

Compliance

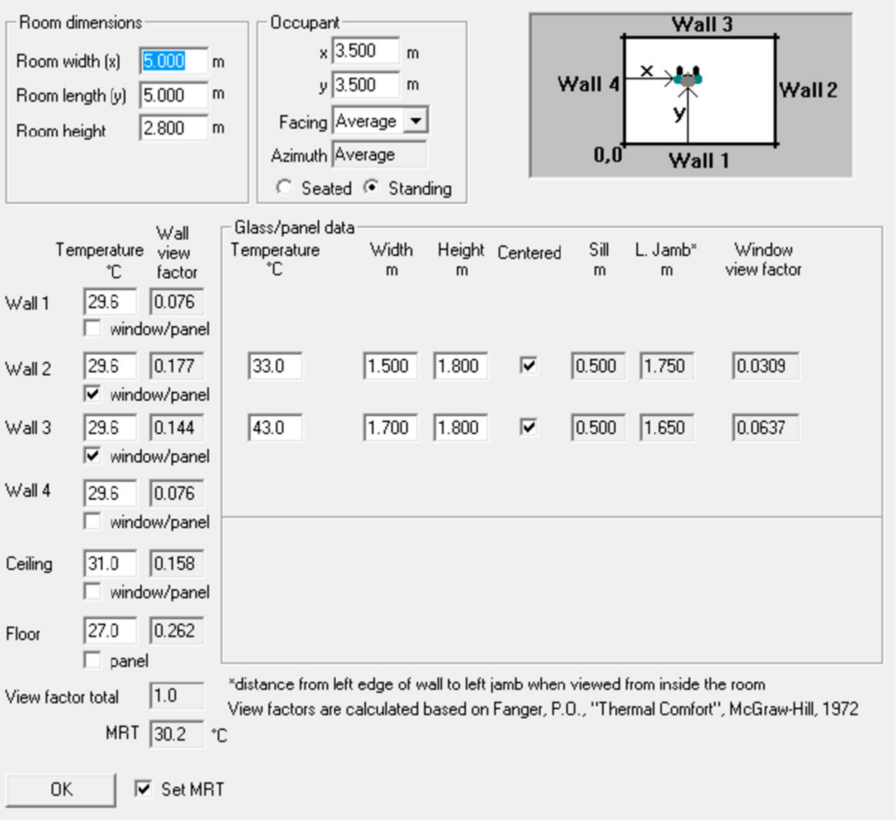
Does not comply with Standard 55-2004

Figure 6. ASHRAE 55 comfort tool – main screen.

area were entered as variables. The output of thermal imaging provides this latter part of information.

It is the objective of this paper to demonstrate that the product of room surface temperatures, comfort measurements at a specific location, and the ASHRAE-55 Comfort Tool simulation provide for a simplified, yet accurate method in diagnosing the thermal performance of a space. For Figure 5, the Comfort Cart and its measurements, the mean radiant temperatures (MRT) could be determined at the three specific heights of 0.1, 0.6, and 1.1 m. These were averaged into a single result, representing the MRT of this location. This MRT result is, of course, in reference to its surroundings, which are caused by surface temperatures, hence, being measured by the thermal imaging camera. Once an agreement between the calculated MRT of the comfort cart and that of the MRT calculated by the ASHRAE-55 Comfort Tool (MRT sub-routine) are reached, the Comfort Tool can be confidently applied to retrofitting alterations of the space.

In this research, selected houses are measured considering their internal building conditions similar to these offices. A report by Edge Environment (2008) corroborates that there is limited understanding of passive building conditions in Darwin Northern Territory region of Australia, due to reliance on air-conditioning systems. As the research team had extensive data of simultaneous comfort cart with thermal imaging measurements, house in Darwin were applied. The energy authority in Darwin (i.e. Client of the project) arranged for the measurements



Room dimensions

Room width (x) 5.000 m
Room length (y) 5.000 m
Room height 2.800 m

Occupant

x 3.500 m
y 3.500 m
Facing Average
Azimuth Average
○ Seated ● Standing

	Temperature °C	Wall view factor		Glass/panel data Temperature °C	Width m	Height m	Centered	Sill m	L. Jamb* m	Window view factor
Wall 1	29.6	0.076	☐ window/panel							
Wall 2	29.6	0.177	☑ window/panel	33.0	1.500	1.800	☑	0.500	1.750	0.0309
Wall 3	29.6	0.144	☑ window/panel	43.0	1.700	1.800	☑	0.500	1.650	0.0637
Wall 4	29.6	0.076	☐ window/panel							
Ceiling	31.0	0.158	☐ window/panel							
Floor	27.0	0.262	☐ panel							

View factor total 1.0

MRT 30.2 °C

*distance from left edge of wall to left jamb when viewed from inside the room

View factors are calculated based on Fanger, P.O., "Thermal Comfort", McGraw-Hill, 1972

☑ Set MRT

Figure 7. MRT Sub-routine of the ASHRAE-55 comfort tool.

to be taken during the most severe or extreme weather conditions (i.e. having the hottest and greatest humidity levels over the year, the month of February). They arranged for an alternative suitable accommodation for the normal occupants of the house in order to allow for the extreme intrusion of instrumentation to take place. Furthermore, it was decided that any air-conditioning systems of which all houses had, were not to be used, in order to understand the extreme thermal performance of the buildings.

Also, noteworthy is that during the month of February, occupants typically rely on mechanical conditioning systems due to the severe climate conditions. Hence, we wanted to explore the passive conditioning of these buildings, which will expose the potential flaws of the building composition. In particular, the Blockhouse is constructed of block (filled concrete in hollow core concrete block for most of its supporting wall structure). The external walls are insulated minimally, while the ceiling exposed to the roof merely consists of 12 mm gypsum board with halogen downlights and no insulation.

We measure the thermal conditions of the Blockhouse Living room based on the ISO7730 comfort model and present the results in Figure 9. The thermal comfort conditions are calculated based on continuous measurement of environmental parameters for a specific zone on each house.

It should be noted that the calculation for PPD applied a CLO value of 0.4 which may be slightly higher than what occupants would be wearing for this summer period. These houses all underwent measurement periods, over 2–3 days, when unoccupied. Each instrument measured over a 15-minute interval. The Blockhouse floor plan and section are illustrated in Figure 8, alongside instrument locations of measurement.

We select a worst-case scenario, a single time-period, of the Blockhouse at 9:15 am (Figure 10) for an investigation as to how this problematic thermal condition could be improved. The analysis took place in a systematic and staged format, starting with the validated ASHRAE-55 Comfort Tool result, previously explained. This was a revelation in itself, to see how changes made to the building fabric through surface conditioning, window shading, and design mechanisms could influence thermal comfort. Table 1 presents this staged approach and demonstrates the effectiveness of comfort improvement at each interval.

The first change to the original condition was to reduce the ceiling, floor, and wall temperatures through hydronic conditioning (see A-1). While it would be desired to cool the surface temperatures even further, this is not possible due to the dewpoint temperature and high humidity encountered in Darwin, Australia. The next step, B-1, provides exterior shading to the windows within this space, allowing them not to exceed the external temperature of 32°C ambient at the selected time. This alteration has indicated a substantial improvement to comfort conditions within the space (Figure 9).

Finally, a ceiling fan set at a reasonable and tolerant air-velocity of 0.25 m/sec is added to Space (C-1), since the recorded air-velocity was at 0.15 m/sec at the comfort cart. The result is a PPD of 23% which is a very conservative figure according to the adaptive model of comfort, implying that most people in this climate would be very satisfied with this result. Considering also, that this is the comfort improved at a worst-case period for this

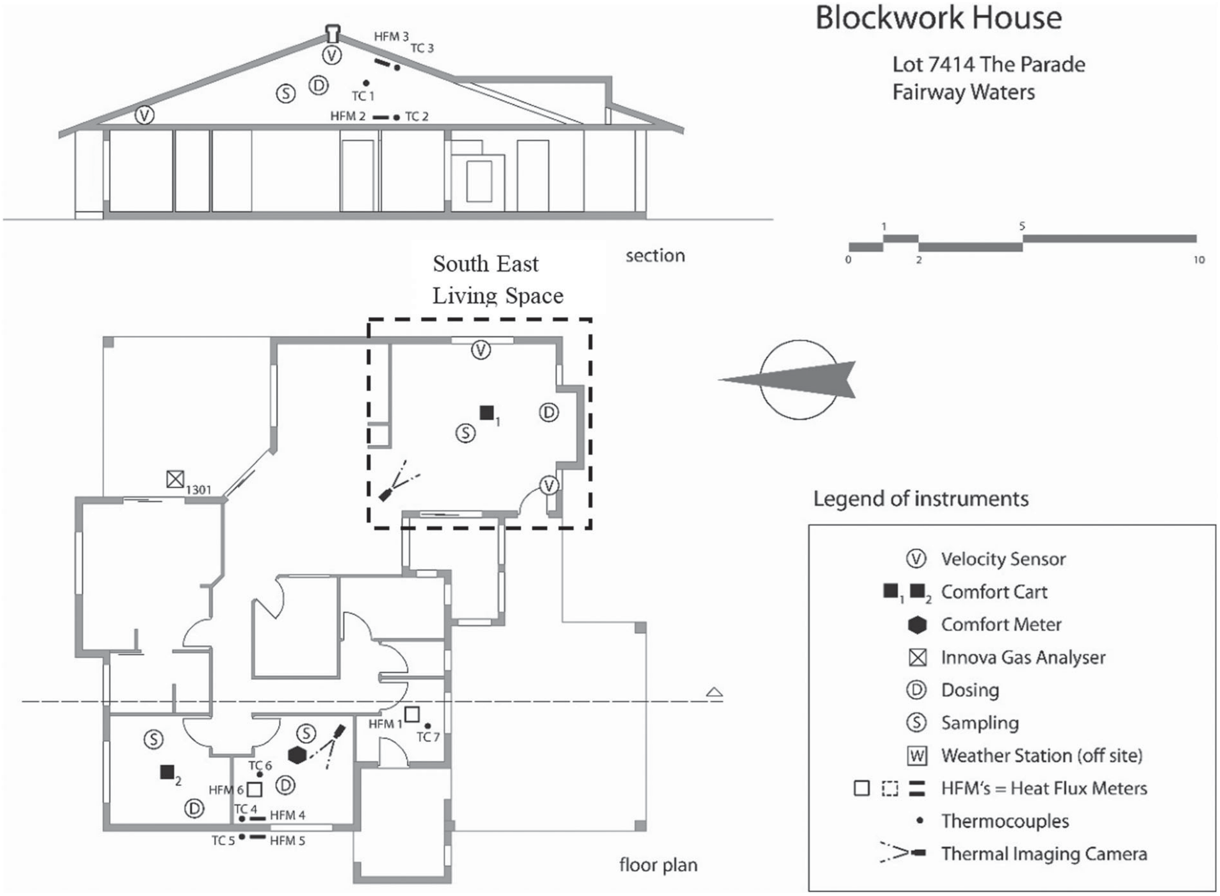


Figure 8. Floor plan and section of the Blockwork house with instrumentation.

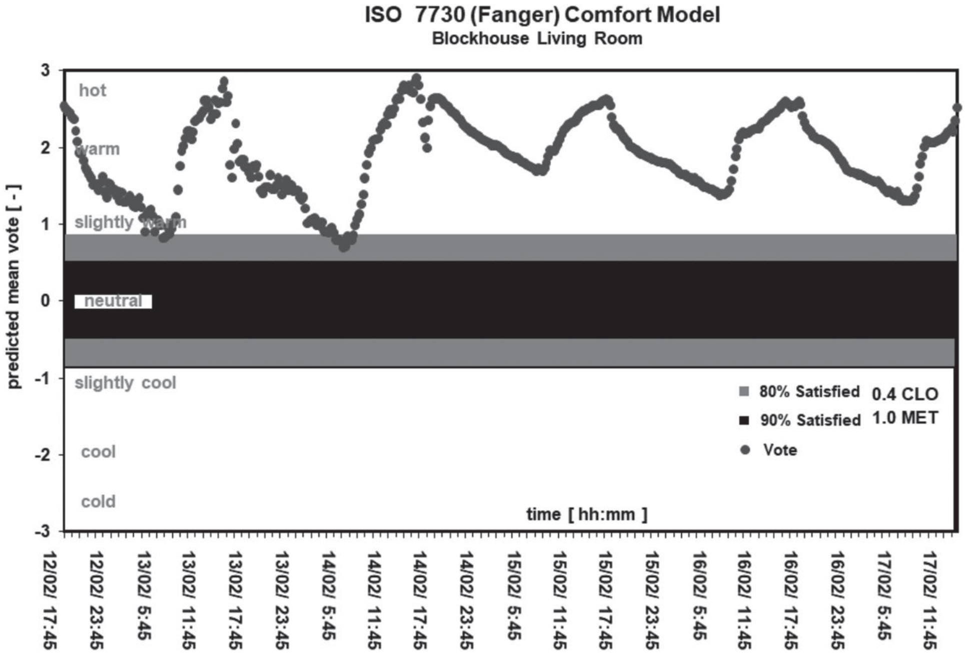


Figure 9. Comfort conditions in the BlockHouse living room.

Table 1. The blockhouse living room – original comfort case & improvements.

Case	PPD	$DB_{(air)}$	MRT	Relative Humidity	Glass Temperatures		Air Velocity	Ceiling Temp	Floor Temp	Wall Temp
I	58%	29.6°C	30.2°C	73.0%	43°C	33°C	0.15 m/s	31.0°C	27.0°C	29.6°C
A-1	47%	29.6°C	28.9°C	73.0%	43°C	33°C	0.15 m/s	26.0°C	26.0°C	26.0°C
B-1	29%	28.6°C	28.0°C	73.0%	32.0°C	32.0°C	0.15 m/s	26.0°C	26.0°C	26.0°C
C-1	23%	28.6°C	28.0°C	73.0%	32.0°C	32.0°C	0.25 m/s	26.0°C	26.0°C	26.0°C

☐ = original measured case: ASHRAE 55 Comfort Tool Simulation calibrated to Comfort Cart measurements.

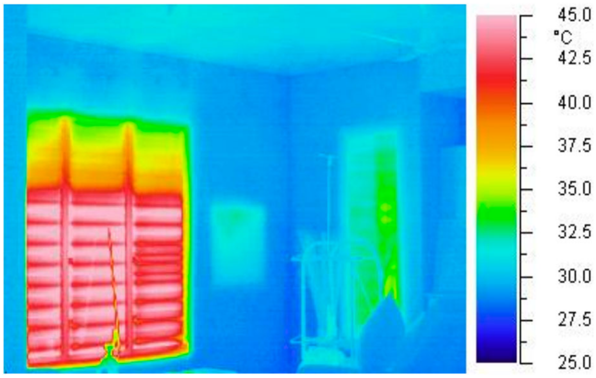


Figure 10. Thermal imaging and comfort cart location of the analysed Case – 9:15 am.

space, these solutions would be more than acceptable. The next example is for another house in Darwin, labelled as the Elevated House (see Figure 11 for section and floor plan).

Our next case for analysis is taken from the elevated house living room where again the solar penetration into the space accounts for a significant part of spatial heating resulting in discomfort. This house is constructed of a concrete block on its lower level with no insulation in the walls. The upper level is a corrugated metal cladding on a minimally insulated stud wall. The ceiling consists of gypsum board and is minimally insulated in this case. Sarking foil is applied under the metal roofing. We measure the thermal conditions of the Elevated House Living room based on the ISO7730 comfort model and present the results in Figure 12. These figures chart the Predicted Percentage Dissatisfied (PPD) which will never be less than 5% (PPD) due to human nature. Therefore, it is generally considered that conditions within a 20% PPD are acceptable. It should be noted that the Fanger comfort model is very conservative and that levels of 25–30% PPD would be welcomed in this climate.

Figure 13 illustrates several of the recorded thermal images over the pre-heating and post-cooling down of the space. Again, it is of importance to note that the selected period of analysis is the extreme period where the space exhibits the most considerable period of discomfort (see 10:00 am slide). Meaning

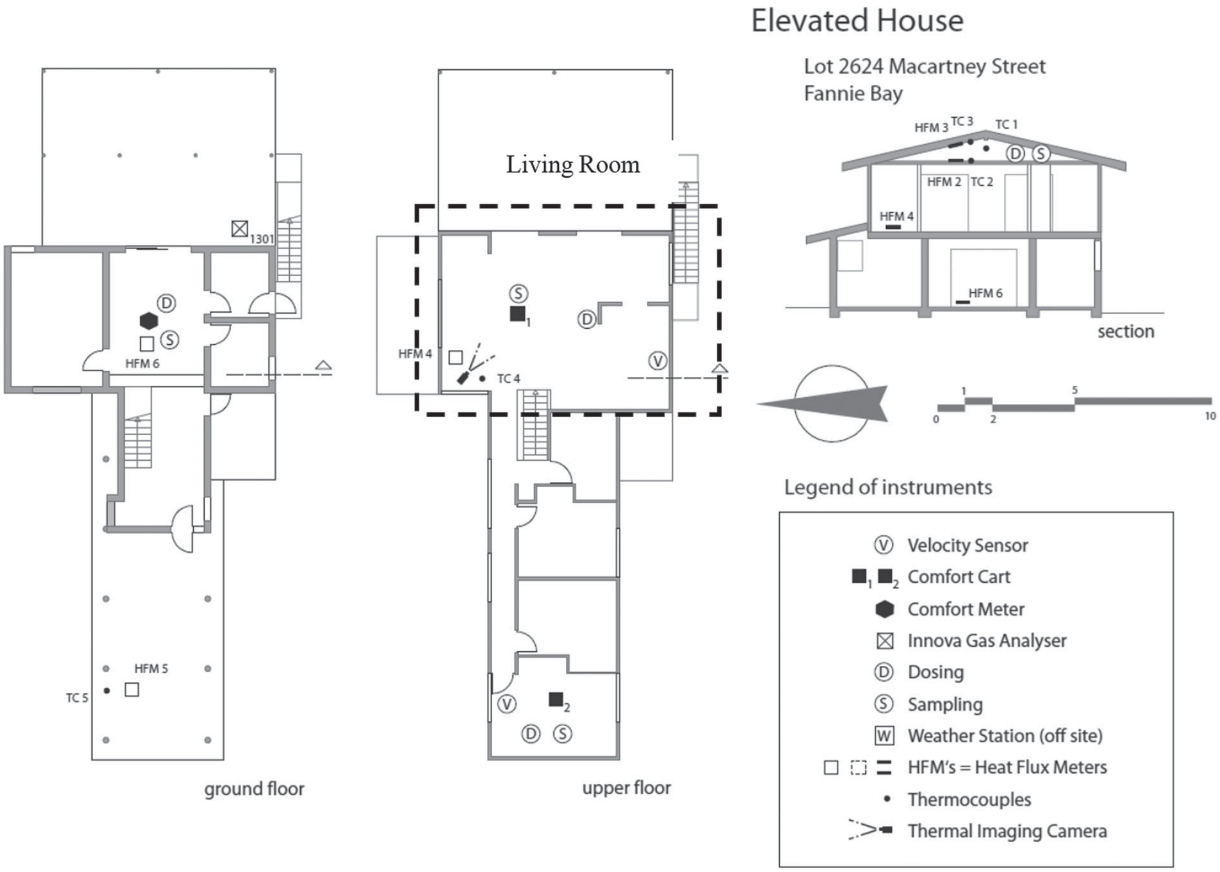


Figure 11. Floor plan and section of the elevated house with instrumentation.

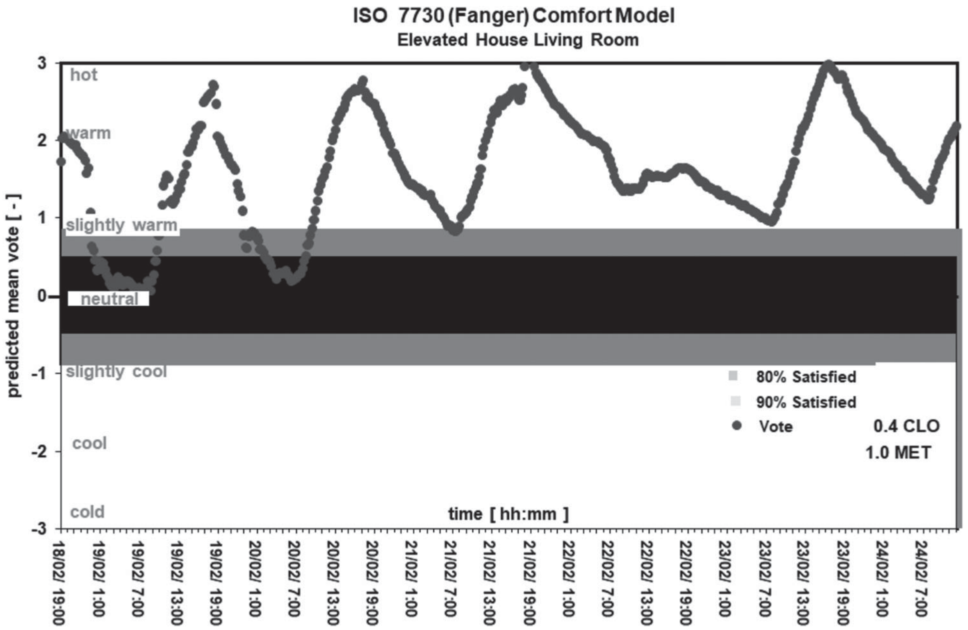
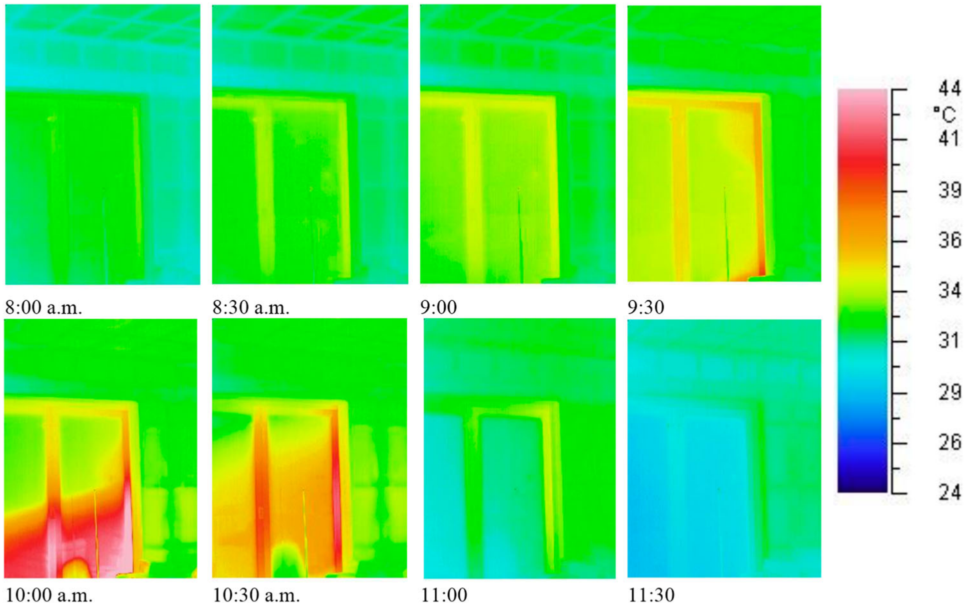


Figure 12. Elevated House Living Room ISO 7730 thermal comfort conditions.



8:00 a.m. 8:30 a.m. 9:00 9:30

10:00 a.m. 10:30 a.m. 11:00 11:30

Figure 13. Time step thermal images of the elevated house – living room.

that all other time-periods would benefit significantly from the suggested improvements to conditioning.

As before in the Blockhouse example, the process of calibrating both the mean radiant temperature results with those of the comfort cart through the ASHRAE 55 Comfort Tool is accomplished. We present the PPD (predicted percentage dissatisfied) results from a step-by-step process of interior conditioning alterations towards comfort improvements in Table 2.

The first step (A-2) is to assume that the floor and ceiling are cooled through hydronic conditioning to 24.0°C, which is above the dewpoint in this case (Note: the construction methods for hydronic cooling systems are presented later in this paper). The result is a significant drop in Predicted Percentage Dissatisfied by over 20%.

Next, we deal with the rogue intrusion of direct solar radiation and its heating of the glass. While the ASHRAE 55 Comfort Tool does not yet account for direct solar radiation in its simulated calculation, at the moment, it is important to realize that the new ASHRAE -55 Standard (2017) does. This is important to acknowledge because the penetration of direct solar is the cause of surface temperature increase. Therefore, the blockage of this gain would reduce surface temperatures and, consequently, lessen the MRT of the surface. As it stands, we are calculating PPD with this increased surface temperature, while at the same

Table 2. The elevated house – original case & improvements.

Case	PPD	DB$_{(air)}$	MRT	Relative Humidity	Glass Temperature	Air Velocity	Ceiling Temp	Floor Temp	Wall Temp
II	94%	32.5°C	32.7°C	61%	40.0°C	0.2 m/s	33.5°C	31.0°C	32.5°C
A-2	71%	32.5°C	28.4°C	61%	40.0°C	0.2 m/s	24.0°C	24.0°C	32.5°C
B-2	68%	32.5°C	28.0°C	61%	32.0°C	0.2 m/s	24.0°C	24.0°C	32.5°C
C-2	43%	30.5°C	28.0°C	61%	32.0°C	0.2 m/s	24.0°C	24.0°C	32.5°C
D-2	35%	30.5°C	28.0°C	61%	32.0°C	0.3 m/s	24.0°C	24.0°C	31.0°C

▨ = original measured case: ASHRAE 55 Comfort Tool Simulation calibrated to Comfort Cart measurement. Note: all other cases are simulations – ONLY – calculated through the ASHRAE 55 Comfort Tool.

time we are shading the glass surface, reducing only glass surface temperature. This, of course, yields a conservative (higher) result in discomfort, more likely than it would be. In order to account for some of the effects of direct solar-gain blockage and the reduced surface-temperatures, it is reasonable to predict that there would be a reduction in air-temperature to the space primarily through convective heat-transfer to the cooler surfaces in the room. We account for this in C-2 by dropping the air-temperature by 2.0°C.

Finally, in D-2, we introduce some air-velocity to increase ventilation to the space by up to 0.3 m/sec. This can easily be provided through a ceiling fan. This has made about an 8% improvement in comfort. Overall, the result is an improvement of PPD by 2.7 times achieved through reasonably low-energy inputs. While the PPD remains relatively high at 35% we believe that this is still a very conservative figure, meaning that the adaptive model would be substantially lower in its PPD result. Furthermore, this room experiences this extreme temperature for approximately 30–45 min, on a typical day. Other periods of the day are far less severe than the one dealt with here.

Results indicate that the application of radiant systems in a hot, humid climate is effective in improving comfort. In particular, the idea of cooling interior ceiling, floor and possibly wall surfaces through hydronic systems is explored by others (Tye-Gingras and Louis 2012). The introduction of lightweight capillary hydronic mats (German and Japanese manufacturers) integrated with gypsum drywall construction or tiled and even wooden floors as a possible cooling solution is proposed. Surface temperature levels that are between 24°C and 26°C and well above dew point (2–3°C) indicate promising results for improved comfort in these environments. Furthermore, radiative conditioning, for leaky and poorly insulated houses, offers an improved energy cost–benefit when compared to convective air-conditioning systems.

3. Discussion – principles of comfort: evaluating the parameters

The following takes into consideration the specific parameters of the ISO 7730 (Fanger – 'static') comfort model. It examines the potential of each and considers how designers might use these to improve the specification of materials, systems, and services to control their buildings better. In other words, the 'static' model offers parameters that can be addressed in the mechanical system fit-out, architectural design, or the control of the air through its temperature, humidity, and velocity. In fact, the static model together with the Comfort Tool by ASHRAE-55 or the CBE could imply a deep understanding of a multitude of decisions influencing the comfort in a building

3.1. Radiative vs convective conditioning: understanding MRT

One of the curious realizations presently, in our buildings, is that we may be conditioning them incorrectly altogether. The principles by which air-convection conditions a space is secondary to that of radiation where surfaces in a space may be separately conditioned and offer a significant temperature difference (5–15°C) from that of the air-temperatures in a room (Moe 2010). The fact is that radiative surfaces offer the conditioning principles inclusive of convection. Unfortunately, this principle is not reciprocal or as effective for convection, where air temperature would condition a surface to obtain a significant change in its radiative effect.

Ultimately, a conditioned building through room surface radiation can provide a substantial opportunity for energy reduction. A lower ΔT between interior and exterior air-temperature can be maintained when surfaces are radiative conditioned, through the provision of a higher MRT, thus, yielding a lower energy loss across the building envelope. An outcome of this was explained earlier (in this paper) with the set-point of thermostatic control changes (Hoyt et al. 2009).

Figure 14 charts two of the most competing parameters of thermal comfort: air-temperature and mean radiant temperature. When observing the circle or the triangle location points of a given temperature condition on the chart, it is clear that an acceptable comfort level is not achieved, according to PPD (percent predicted dissatisfied) boundaries. Take the location of the circle, at point A, for instance, if we move only in the vertical direction, that of air temperature (only) we find that we require a 3.5°C. As previously identified in the research of Hoyt et al. (2009), this could imply a 30–45% increase in energy costs. On the other hand, it is advised that we might move in the horizontal direction – only (point B) – which would imply an MRT of 23.5°C or an increase in MRT of about 4.5°C. The investigation of operational cost to increase surface temperatures to provide this MRT requires further investigation. Preliminary work indicates that 30°C–35°C surface temperatures in the floor and/or ceiling could easily provide for this MRT result. This implies that heated water of 34°C–38°C would be required which is believed to be approximately 8–10°C less than that typically supplied to convective heating coils for ducted air-conditioning. Therefore, the preliminary indication is that radiative systems could operate at conditioning requirements far below the energy requirements for ducted systems.

Another alternative is to acknowledge the positioning of changes to both air temperature and mean radiant temperature – point C, in Figure 14. This is perhaps the most logical and the shortest path towards accomplishing the desired result. Most

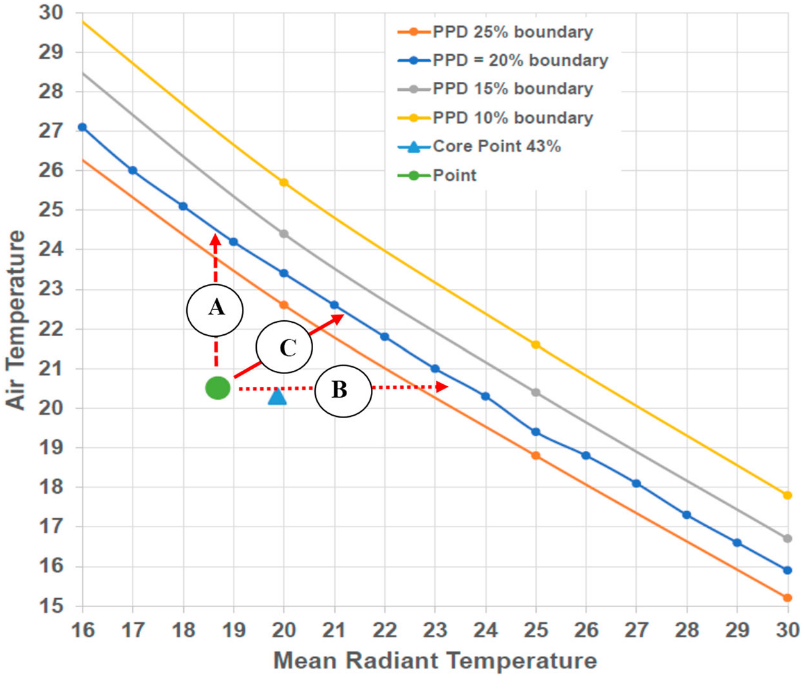


Figure 14. Air temperature vs mean radiant temperature in relation to PPD.

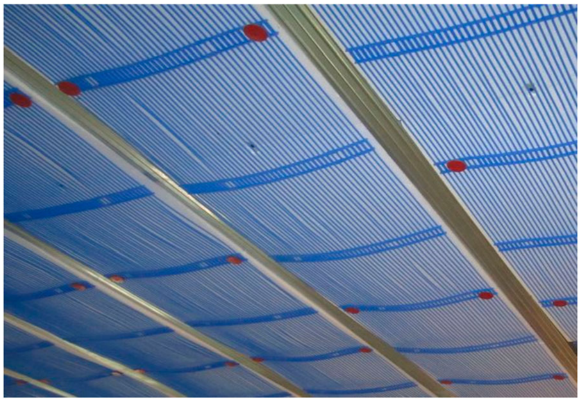


Figure 15. Exposed capillary hydronic matts for radiative conditioning.

likely, there will be some increase in energy consumption due to a rise in dry-bulb temperature, but it might be considered justifiable.

With the advent of new, cost-effective capillary radiant systems, it is now highly possible to implement radiant conditioning into building surfaces (see Figure 15). These can be applied for heating as well as cooling in allowing for an effective mean radiant temperature change within an entire surface to take place.

Each of the thermal improvements were assessed based on respective building performance measures. Percentage analysis was conducted based on the impacts of the improvement in thermal comfort changes based on the base rate thermal situation. For the Blockhouse Living room investigated, the PPD reduced by 31.5% when hydronic conditioning (a change to MRT) was incorporated, while there was a 39% reduction in PPD of the Elevated House. Table 3 provides overall an summary of each thermal improvements and its percentage impact on the total improvement in thermal comfort achieved.

Table 3. Summary of thermal improvements in houses measured.

	Thermal Comfort Changes	Blockhouse Living Room	Elevated House
1	PPD overall improvement	35.0%	59.0%
2	Mean radiant temperature	31.5%	39.0%
3	Glass shading	51.4%	5.0%
4	Increase in air velocity	17.1%	13.6%
5	Air temperature drop	Not Applied	42.4%

3.2. Glazing and shading

Another significant contribution to changing and controlling the mean radiant temperature is through glazing selection and shading devices. No doubt one of our biggest problems in commercial office buildings is the expansive area of glazing on the façade and the temperature of the glass as well as its solar transmittance. The manner in which this is dealt with can have a tremendous effect on thermal comfort (Anderson and Luther 2012). For the two case studies examined, the glass shading systems proved effective as it accounted for 51.4% reduction in PPD for the Block House, and 5% reduction in PPD for the Elevated House. Cho, Yoo, and Kim (2014) also corroborated that appropriate use of shading can enhance thermal comfort and minimize energy consumption. Although, dynamic shading systems in facades has been suggested for substantiating indoor thermal comfort, they tend to be relatively costly and still remain a subject of research (Moloney et al. 2019).

3.3. Air velocity

While it has been stated that air movement suppresses the effects of radiation (Malcolm and Moir 1966), it is highly important to consider a control range of this parameter at the appropriate time in spatial conditioning. Slight air movement increases and or decreases can have a significant effect on thermal comfort. It may also be appropriate to consider that the convective energy transfer across surfaces may be enhanced through air-velocity (Moe 2010).

The more recent personal comfort model at workplaces is inclusive of desktop air velocity control. They take an individual person as the unit of analysis rather than populations or groups of people. Also, they use direct feedback from individuals (i.e. thermal sensation, preference, acceptability, pleasure) and additional relevant data to train a model. The benefits of personal comfort models include improved predictive power with 20–40% accuracy gains compared to conventional comfort models by employing machine learning algorithms; and diversities in types of data and occupant feedback obtained from various sensors and connected devices (Kim, Schiavon, and Brager 2018).

For the two case studies examined, the ceiling fan provided additional ventilation towards enhancing air-velocity by 0.1 m/s. This translated into an improvement in thermal conditions of the Blockhouse Living room by 17.1%, and an improvement in thermal comfort conditions in the Elevated House by 13.6%.

3.4. Clothing values

One of the most enormous 'adaptive' changes to the 'static' model of comfort – ISO 7730 is that of occupant clothing. Studies conducted in several office buildings throughout Australia indicated that on no particular day and/or external conditions, clothing among occupants could vary ±0.2 CLO (Luther and Horan 2011). Clothing alone is a very significant influence upon comfort, and this parameter alone could account for 50% or more of an occupants comfort under periods where an interior environment is in the 20–40% Predicted Percentage Dissatisfied (PPD) range (Luther and Horan 2015). It has, however, been admitted that more accurate clothing properties could provide more data for thermal sensations (Park and Nagy 2018). Tracking occupant's clothing via an infrared camera to obtain such thermal sensation data could be expensive but more pertinently could be perceived as invading one's privacy (Kim, Schiavon, and Brager 2018). More recent research has also advocated electrically heated clothing as an alternative to improve thermal comfort (Li et al. 2018). It is, however, essential for measurements on thermal comfort indices to drive a systematic approach towards spatial comfort improvement.

In summary, we noted that the greatest potential for thermal improvements was found in the glass shadings. Although there were discrepancies in the thermal improvements achieved from glass shadings (i.e. 51.5% in the Blockhouse; and 5% in the Elevated house), this was attributable to the large glass area in the Blockhouse relative to that of the Elevated house. An increase in air-velocity was also in the order of 10–20% for both houses. An air temperature drop in the Elevated house of 2°C produced a 42% PPD improvement, based upon surface convection from the low MRT. The MRT changes through hydronic conditioning were presented as the most consistent parameter for improvement ranging between 30 and 40% PPD change. Table 3 provides an overview of the thermal improvements in both houses examined. The overall improvement based on PPD was 35% in the Blockhouse and 59% in the Elevated House. The individual 'thermal comfort changes' represent a percentage of the total change that occurred in each house. For example, glass shading in the Blockhouse attributed 51% of the overall PPD improvement of 35%.

4. Conclusion

This paper explored the on-going research of others on thermal comfort and energy consumption. In our review, it is discovered that there is evidence of both 'static' and 'adaptive' models improving the interior environments as well as improving energy performance. Specifically, Improvement in overall thermal conditions of up to 35% and 59% were realized with the most reliable potential for thermal improvements found in surface temperature (mean radiant temperature), conditioning changes indicating between 32 and 38% overall comfort improvement in the building. Furthermore, our own measurements identify a real case where air temperature at various locations appears to indicate thermal satisfaction; however, when analysed according to a comfort model calculation this is clearly not the case.

The authors argue that static models allow for variables that can be enacted through tools such as the ASHRAE-55 Comfort Tool and the CBE Comfort Tool. In addition to the review, there appear to be three distinctive categories for future investigation of improving comfort with a reduction in energy. These are:

- 'Comfort-Stats': a control of mechanical system operation through that of comfort models – either an 'adaptive model' or a 'static' (PMV/PPD – ISO 7730) model.
- An adaptation in conditioning and energy generating service systems, i.e. radiant conditioning, Co- and Tri-generation services, etc.
- Improved building design, materials and construction practices that allow and provide for adaptation and change to conditioning.

In closing, the main point of this paper is to acknowledge that spaces can be measured for their comfort performance, analysed, and that notable changes or problems can be enacted upon and improved. Identifying that thermal comfort sensors and thermal imaging instrumentation can be combined in the manner of spatial comfort evaluation and improvement as presented in this paper is not only unique but also valuable in the advancement of future building performance measurements and analysis. The results of these two instruments have been successfully brought together in conjunction with the ASHRAE-55 Comfort Tool in this paper. The comfort tool together with measurement provides for a numerical objective result and allows further evaluation (i.e. changing conditioning systems and comfort variables) that can produce an improvement in comfort.

This paper dealt with improvement in comfort conditions based on the assessment of the extreme daytime periods in both houses. It is, however, expected that the improvements in thermal conditions will translate into substantial energy-savings, although this will be a subject of future research. We believe that an understanding of the variables and the degree to which they produce comfort changes is important in the design of buildings. The more we can realize what makes buildings perform the way they do, the more prepared we will be to make the necessary adjustments for climate-change adaptation in our building construction of the future.

Disclosure statement

ORCID

Olubukola Tokede http://orcid.org/0000-0002-5116-3390

References

Anderson, Timothy, and Mark Luther. 2012. "Designing for Thermal Comfort Near a Glazed Exterior Wall." *Architectural Science Review* 55 (3): 186–195.

ASHRAE. 2004. "Standard 55-2004, Thermal Comfort Conditions for Human Occupancy." In: *American Society of Heating, Air-Conditioning, and Refrigeration Engineers*, Inc.

ASHRAE. 2017. "Standard 55-2017, Thermal environmental conditions for human occupancy. 2017." In.: *American Society of Heating, Air-Conditioning, and Refrigeration Engineers*, Inc.

Attia, Shady, and Salvatore Carlucci. 2015. "Impact of Different Thermal Comfort Models on Zero Energy Residential Buildings in hot Climate." *Energy and Buildings* 102: 117–128.

Barbadilla-Martín, Elena, José Guadix Martín, José Manuel Salmerón Lissén, José Sánchez Ramos, and Servando Álvarez Domínguez. 2018. "Assessment of Thermal Comfort and Energy Savings in a Field Study on Adaptive Comfort with Application for Mixed-Mode Offices." *Energy and Buildings* 167: 281–289.

Brager, Gail, Hui Zhang, and Edward Arens. 2015. "Evolving Opportunities for Providing Thermal Comfort." *Building Research & Information* 43 (3): 274–287.

Cho, Jinkyun, Changwoo Yoo, and Yundeok Kim. 2014. "Viability of Exterior Shading Devices for High-Rise Residential Buildings: Case Study for Cooling Energy Saving and Economic Feasibility Analysis." *Energy and Buildings* 82: 771–785.

De Dear, Richard, and Gail Schiller Brager. 1998. "Developing an Adaptive Model of Thermal Comfort and Preference." *ASHRAE Transactions* 104 (1b): 145–167.

Edge Environment. 2008. "The Northern Territory Government Consultation Feedback: Questions and Answers from Consultation in Darwin on 9th December and 11th December 2008." *Alice Springs*.

Godithi, Sam Babu, Enna Sachdeva, Vishal Garg, Richard Brown, Christian Kohler, and Rajan Rawal. 2019. "A Review of Advances for Thermal and Visual Comfort Controls in Personal Environmental Control (PEC) Systems." *Intelligent Buildings International* 11 (2): 75–104.

Griego, Danielle, Moncef Krarti, and Abel Hernández-Guerrero. 2012. "Optimization of Energy Efficiency and Thermal Comfort Measures for Residential Buildings in Salamanca, Mexico." *Energy and Buildings* 54: 540–549.

Hoyt, Tyler, Kwang Ho Lee, Hui Zhang, Edward Arens, and Tom Webster. 2009. "Energy Savings from Extended Air Temperature Setpoints and Reductions in Room Air Mixing." Paper presented at the International Conference on Environmental Ergonomics. Boston. August 2009.

Humphreys, Michael A, and J. Fergus Nicol. 2002. "The Validity of ISO-PMV for Predicting Comfort Votes in Every-day Thermal Environments." *Energy and Buildings* 34 (6): 667–684.

ISO7730. 2005. "ISO 7730." International Standard Organisation ISO 7730: Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria Genève.

Judson, Ellis P, and Cecily Maller. 2014. "Housing Renovations and Energy Efficiency: Insights From Homeowners' Practices." *Building Research & Information* 42 (4): 501–511.

Kim, Joyce, Stefano Schiavon, and Gail Brager. 2018. "Personal Comfort Models–A new Paradigm in Thermal Comfort for Occupant-Centric Environmental Control." *Building and Environment* 132: 114–124. doi:10.1016/j.buildenv.2018.01.023.

Li, Ziqi, Ying Ke, Faming Wang, and Bin Yang. 2018. "A Study of Thermal Comfort Enhancement Using Three Energy-Efficient Personalized Heating Strategies at two low Indoor Temperatures." *Building and Environment* 143: 1–14.

Luther, M. 2013. "Chapter 3.8: A Diagnostic Toolkit for Multi-Dimensional Testing of Built Internal Environments." In *Sustainable Retrofitting of Commercial Buildings: Warm Climates*, edited by R. Hyde, N. Groenhaut, F. Barram, and K. Yeang, 243–255. London: Routledge Taylor and Frances Group Publishers.

Luther, M., and T. Ahmed. 2019, January. "Revisiting the Comfort Parameters of ISO 7730: Measurement and Simulation." In IBPSA 2019: *Proceedings of the 16th Conference of Building Simulation Association*, 1–7. International Building Performance Simulation Association.

Luther, M. B., and P. Horan. 2011. "Preliminary Tools Assisting Collected Building Performance Measurements." Paper presented at the ANZAScA 2011: From Principles to Practice in Architectural Science: *Proceedings of the 45th Annual Conference of the Australian and New Zealand Architectural Science Association*.

Luther, Mark, and Peter Horan. 2015. "Comfort Models as Applied to Buildings." Paper presented at the ASA2015: Living and learning: research for a better built environment: *Proceedings of the 49th International Conference of the Architectural Science Association*.

Malcolm, John R, and Roland K Moir. 1966. "Optimization of Crew Comfort System." The Space Congres Proceedings 4.

Moe, Kiel. 2010. *Thermally Active Surfaces in Architecture*. New York, NY: Princeton Architectural Press.

Moloney, J., A. Globa, R. Wang, C. Khoo, and O. Tokede. 2019. "Hybrid Environmental-Media Facades: Rationale and Feasibility." *Architectural Engineering and Design Management* 15 (5): 313–333.

Nicol, J Fergus, and A Humphreys Michael. 2002. "Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings." *Energy and Buildings* 34 (6): 563–572.

Park, June Young, and Zoltan Nagy. 2018. "Comprehensive Analysis of the Relationship Between Thermal Comfort and Building Control Research-A Data-Driven Literature Review." *Renewable and Sustainable Energy Reviews* 82: 2664–2679.

Rafique, M Mujahid, P. Gandhidasan, and MS Bahaidarah Haitham. 2016. "Liquid Desiccant Materials and Dehumidifiers–A Review." *Renewable and Sustainable Energy Reviews* 56: 179–195.

Strengers, Yolande. 2008. "Comfort Expectations: The Impact of Demand-Management Strategies in Australia." *Building Research & Information* 36 (4): 381–391.

Tye-Gingras, Maxime, and Gosselin Louis. 2012. "Comfort and Energy Consumption of Hydronic Heating Radiant Ceilings and Walls Based on CFD Analysis." *Building and Environment* 54: 1–13.

Yang, Liu, Haiyan Yan, and Joseph C Lam. 2014. "Thermal Comfort and Building Energy Consumption Implications – a Review." *Applied Energy* 115: 164–173.

Yun, Geun Young, Je Hyeon Lee, and Koen Steemers. 2016. "Extending the Applicability of the Adaptive Comfort Model to the Control of Air-Conditioning Systems." *Building and Environment* 105: 13–23.

Zampetti, L., M. Arnesano, and G. M. Revel. 2018. "Experimental Testing of a System for the Energy-Efficient sub-Zonal Heating Management in Indoor Environments Based on PMV." *Energy and Buildings* 166: 229–238.