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Investigating the Impact of Different Thermal Comfort Models for Zero Energy Buildings in Hot Climates

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ABSTRACT

The selection of a thermal comfort model has a major impact on energy consumption of Net Zero Energy Buildings (NZEBs) in hot climates. The objective of this paper is to compare the influence of using different comfort models for zero energy buildings in hot climates. The paper compares the impact of applying Givoni's model, ASHRAE 55 adaptive comfort standard, EN 15251 adaptive comfort standard and EN ISO 7730 on energy consumption and comfort. Using ZEBO and EnergyPlus for energy simulation, an existing prototype of a residential apartment module will be used to evaluate energy performance and thermal comfort in two parametric series. The first one is the result of coupling natural ventilation and mechanical cooling and the second one is guided coupling natural ventilation, mechanical cooling and ceiling fans. Results show a significant difference of cooling loads and total energy generation for the compared comfort models. However, the study remains theoretical and requires post occupancy evaluation for a better reliability of the results.

INTRODUCTION

Net Zero Energy Buildings (NZEBs) aim to reduce at minimum, energy required for space cooling, space heating, ventilation, lighting and appliances. By default NZEBs are grid connected and benefit from renewable energy sources such as direct solar radiation, wind and the earth's thermal storage capacity to balance their energy consumption annually. However, the impact of different thermal comfort models for NZEBs in hot climates has been scarcely studied. Most energy efficiency research is conducted with cold climate in mind. Using the words of the European standard EN 15251: "An energy declaration without a declaration related to the indoor environment makes no sense. There is therefore a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings" (CEN 2007). Thus, the specification about thermal comfort objectives that a building must achieve is a prerequisite for its design. Such objectives shall be explicitly included as an integral part of the definition of a zero energy building in hot climate and needs to be quantitatively defined through reliable and explicit methods for assessing the thermal comfort performance of a building. This paper is a presentation of the initial findings of a research project concerning the impact of different thermal comfort model on the design and energy consumption of NZEB in hot climates. The project aims to examine the potential benefits and feasibility of thermal comfort models and to investigate the NZEB objective in hot climates. The paper will consider wide range of thermal models through a particular case for a residential apartment module

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in Cairo, Egypt. The aim of this paper is to develop a basis for strategic decision making of thermal comfort for NZEB design by comparing different models in hot climates. The methodology used consists of screening the existing comfort models suitable in hot climates. The study includes an inventory of suitable comfort models that can be used as solutions for NZEBs. Then a typical basecase building is selected for simulation analysis to examine the impact on performance. The building energy use analysis will be performed using the ZEBO and EnergyPlus program aiming to conduct global parametric analysis where the parameters are varied (Attia 2012, DOE 2013). Finally, analysis of result provides guidance on the strategic design decision making for thermal comfort of NZEBs.

PRINCIPLES OF THERMAL COMFORT

Hassan Fathy said: "People living in the hot, climates, are faced with a different problem: amplified ultraviolet rays that hit our concrete structures and rebound onto us in hot and humid weather conditions" (Fathy 1986). In hot climates, it is always necessary to avoid sensible and latent heat gains in every possible way and to achieve thermal comfort conditions while minimizing energy consumption. This section reviews thermal comfort model for (residential) NZEBs in hot climates and list multiple model and systems solutions.

Thermal comfort is usually used to indicate whether an individual does not feel too hot or too cold with respect to a given thermal environment. It is a concept that attracted the attention of a number of scientists and doctors and it has been defined according to three approaches: a physiological, a psychological, and a rational (also called heat-balance) approach. According to the physiological approach, thermal perception of an individual is due to the entity of nervous impulses that start from thermal receptors in the skin and reach the hypothalamus. According to the psychological approach, thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" (ISO 7730). This definition is reported in the international standard ISO 7730 and a similar definition is also reported in the American standard ASHRAE 55, although the ASHRAE definition highlights the subjective character of such concept by adding to the previous definition the sentence "[…] and is assessed by subjective evaluation" (ASHRAE 55). According to the last approach, thermal sensation is related to the heat balance of the human body and thermal comfort is that condition when heat flows leaving the human body balance those incoming and the skin temperature and the sweat rate are within specified ranges depending on metabolic activity (Hoppe 2002). Therefore, the term thermal comfort is used to provide information about the thermal state of an individual within a given thermal environment.

Thermal Comfort Parameters

Thermal comfort is viewed as a state of mind where occupants are satisfied with their surrounding thermal environment and desire neither a warmer nor a cooler condition (Fanger 1970). Six primary factors affecting thermal sensation are either environmental or personal parameters; these factors are air temperature, mean radiant temperature, air velocity, humidity, metabolic rate and clothing (ASHRAE 2007). Research has shown that other contributing parameters include climate change with time, building and its services, and occupants' perception (Nicol and Humphreys 2002, Evans 2003 and Hellwig et al. 2006). Due to biological variance beyond occupants and psychological phenomena, neither perfect conditions nor well defined comfort boundary settings exist, but rather a comfort zone with a band of operative temperatures that satisfy the highest percentage of occupants (Nicol and Humphreys 2007). Humphreys found the best representation to predict occupants' thermal comfort, had to be derived from field studies (Nicol 1995). Using field survey questionnaires with synchronized records of parameters this was done while measuring personal thermal states or changes (Auliciems and Szokolay 1997). According to literature the evaluation of the personal thermal state is suggested through a series of guidelines with three scales (ASHRAE 2007):

1. A scale of perception of the personal thermal state with seven degrees and two poles: from cold to hot with a central point of indifference that corresponds to the absence of hot and cold.
2. An evaluative scale with four degrees and one pole: present affective assessment from comfort to discomfort

3. A future thermal preference scale with seven degrees and two poles; from 'cooler' to 'warmer' with a central point of indecision that corresponds to the absence of change.

The evaluation of thermal surroundings or local climate can be made through two additional scales:

- 4. Scale of personal acceptability of local climate with 2 degrees: from generally acceptable to generally unacceptable.
- 5. Scale of tolerance of local climate with 2 degrees: from tolerable to intolerable.

On the other side, the strict reliance on laboratory-based comfort standards such as ASHRAE ignores important cultural and social differences in the need or desire for air-conditioning. A special issue of Energy and Buildings (Kempton and Lutzenhiser 1992) focused on these non-thermal issues, with a variety of papers examining how individuals and cultures vary in their perceived need for and expectations of air-conditioning.

THERMAL COMFORT MODELS

Thermal comfort standards help designers to establish indoor conditions that suit occupants' expectations. In hot climates there are no current standards or models that define what those "comfortable" ranges or conditions that should be in residential buildings. At the same time, the available models worldwide are mainly focused on office buildings, partly because of the limited number of surveys in the area of residential buildings. Recent standards are based on Fanger's PMV-model for sealed air-conditioned buildings and adaptive models for naturally ventilated buildings (Nicol 2004). The ASHRAE standard 55-2004 and the PrEN 15251 refer both to Bragger and de Dear's studies. Parsons (1995) finds that western world standards aren't appropriate for many countries, especially hot climate countries, and an updated international standard for thermal comfort is required (Nicol et al. 1995, Nicol 2004). Therefore, the largest issue in this discussion remains the applicability of those standards and models of none air-conditioned buildings in hot climate residential buildings.

EN ISO 7730

Following the development of air-conditioning, the business community has been more inclined towards artificial indoor environments and sealed buildings (CIBSE 2007). Based on climate chamber experiments, Fanger's Predicted Mean Vote (PMV) model of thermal comfort, introduced in 1970 and developed by Fanger, first established a relation between six primary factors based on a thermal balance equation under steady-state conditions (Fanger 1970). The model has been incorporated into a number of standards and design codes (e.g. EN ISO7730:2005). The model is intended for application to situations similar to those of sealed air-conditioned buildings. In these types of buildings, the envelope is completely sealed with non-operable windows and occupants interact with an artificial indoor environment totally disconnected from the outside one. Recent field measurements derived in hot regions (Pakistan and Kalgoorlie-Boulder) highlighted some inaccuracies when the model is applied to either air-conditioned or non air-conditioned buildings (Nicol 2004, Nicol et al. 1999, and Cena and de Dear 2001). The model was found to overestimate and underestimate occupant response in warm climates. Givoni suggests one important factor is the absence of sweat evaporation in the heat balance equation (Heidari and Sharples 2002). Researchers have suggested that the PMV-model should only be used for sealed air-conditioned buildings (Nicol 2004, Van der Linden et al. 2006). Nevertheless, the PMV-model is commonly applied in the design of air-conditioned office buildings in hot climate zones. Since there are no other models for net zero energy residential buildings, it has been applied in the analysis of fully air conditioned NZEBs in this study.

ASHRAE 55

In order to find an alternative to the PMV-model, in 1995, ASHRAE sponsored a field survey project (RP-884) which focused on statistical analysis of high quality data from existing buildings rather than the heat balance approach derived from climate chamber data. The data was collected from 160 passive, active and mixed-mode office buildings in a number of climate zones, including those considered hot humid and hot dry (de Dear 1998). Occupants in naturally ventilated buildings were found to accept wider temperature variation and higher indoor temperatures than those in air-conditioned buildings (de Dear and Brager 2002, ASHRAE 2005). De Dear and Brager observed that occupants of office buildings showed a low sensitivity to indoor temperature changes. The gradient of their thermal sensation votes with respect to indoor operative temperature turned out to be 1 vote for every 3°C to 5 °C change in temperature. Values in the same range are encountered in work of Oseland and of Van der Linden et al. The apparent acceptance of warmer temperatures is thought to be due to different psychological perceptions and adaptations (Haldi and Robinson 2008). This finding changed the idea that occupants can be considered as passive users (de Dear and Brager 2001), in contrast, occupants either adapt the surrounding environment to suit their expectations –using windows, blinds, fans (ceiling), and doors– or shift their comfort temperature by a number of physiological thermoregulatory mechanisms; changing metabolic rate (activity level and cold drinks), rate of heat loss (clothing) and thermal environment (controls) (Nicol and Raja 1996, de Dear 1999, Nicol and Humphreys 2002, and Pfafferott et al. 2007).

Across a number of adaptive comfort studies, outdoor temperature was proven to have the dominant effect on defining comfort conditions (Saberi et al. 2006, Nicol and Raja 1996). A number of adaptive models seek to correlate perceived comfort with some measure of recent external temperatures and the current internal temperature (Pfafferott et al. 2007) through a two-step procedure. The first step has been to develop a linear correlation between the mean outdoor temperature (To) and the operative temperature (Tc) as Tc =a To + b, the second step has been to specify 90% and 80% ranges of acceptance (De Dear and Brager 2002). In this work, the operative temperature (Tc) is defined as the average of the indoor air and radiant temperatures. Different values of coefficients a and b were determined by Humpheys, Auliciems, Nicol, Brager and others. This indicates the lack of universal parameter values (a and b) (Bouden and Ghrab 2005).

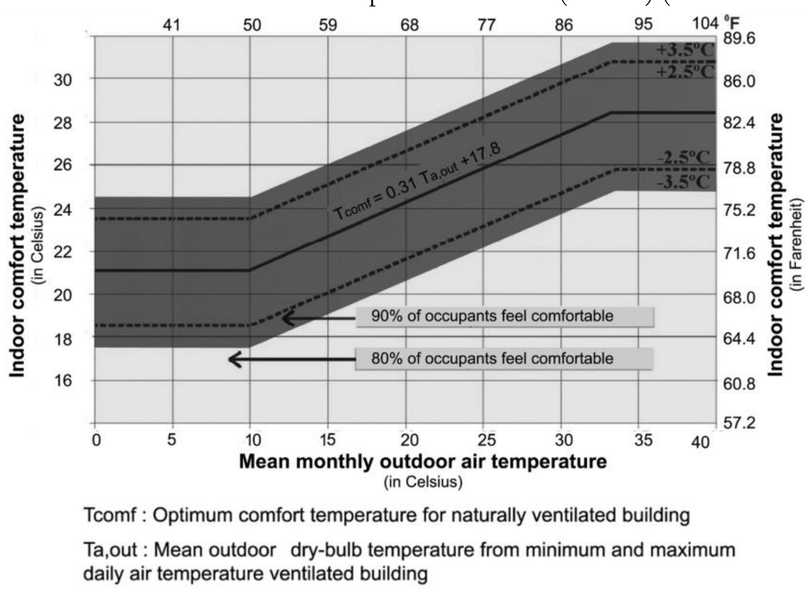

Figure 1 Acceptable operative temperature ranges for naturally ventilated office spaces based on the ASHRAE Adaptive comfort model (De Dear and Brager 2002)

The ASHRAE adaptive comfort model, defined in ASHRAE standard 55-2004, is applicable for outdoor temperature ranges 10ºC - 33ºC (50-91.4°F) (De Dear and Brager 2001) with constant comfort boundaries above and below these ranges as shown in Figure 2.6 The external temperature is expressed as the mean monthly outdoor temperature and can be easily determined from meteorological data (De Dear and Brager 2002) while Auliciems and Szokolay (1997) chose mean daily outdoor effective temperature to represent both temperature and humidity. Acceptable ranges of 10% and 20% predicted percentage dissatisfaction (PPD) with ±2.5ºC and ±3.5ºC as ranges of acceptance respectively, used in this model, and are equivalent to ±0.5 and ±0.8 predicted mean vote (PMV), Figure 1 (de Dear and Brager 2001).

Many researchers, however, challenge this assumption of universal applicability, arguing that it ignores important contextual differences that can attenuate responses to a given set of thermal conditions. Fanger disagree with the adaptive approach in concept since it only deals with outdoor temperature and neglect the other five primary factors they identified. The 6 parameters should be taken into consideration. We have to find an experiential law with indexes for all those six parameters. In hot climates we need at least air temperature, surface temperature and air velocity. This was also acknowledged by Givoni (1992), who revised his already notable work on the building bioclimatic chart. He expanded the boundaries of the comfort zone based on the expected indoor temperatures achievable with different passive design strategies, applying a "common sense" notion that people living in unconditioned buildings become accustomed to, and grow to accept higher temperature or humidity.However, a proposed addendum in September 2008 suggested the use of the PMV model to air speeds below 0.20 m/s. Air speeds greater than this may be used to increase the upper operative temperature limits of the comfort zone in certain circumstances. This could be achieved by using ceiling fans to elevate air speed to offset increased air and radiant temperatures. As shown in Figure 2a, elevated air speed is effective at increasing heat loss when the mean radiant temperature is high and the air temperature is low.

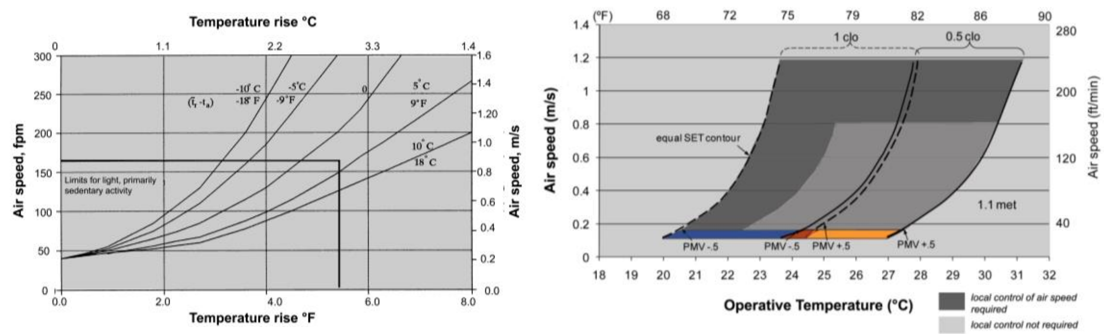

Figure 2a Air speed required offsetting increased temperature [ASHRAE] 2b Acceptable ranges of operative temperature and air speeds [ASHRAE]

However, if the mean radiant temperature is low or humidity is high, elevated air speed is less effective. The required air speed for light, primarily sedentary activities may not be higher than 0.8 m/s. But the ceiling fans effect cannot control humidity and depends on clothing and activity. Figure 2b shows the acceptable range of operative temperature and air speed for a given clothing level.

EN 15251

According to EN 15251 (2007) standard, acceptable comfort temperatures actually depend on the type of system used to provide summer comfort. If cooling is provided by an active system then indoor temperatures must respect those defined by the Fanger Model plus certain assumption of acceptability for different categories of buildings. Instead if summer comfort is provided by passive cooling strategies then the upper temperature limit is set by the Adaptive Model plus certain assumption of acceptability for different categories of buildings. Generally the implementation of the Adaptive model indicates that indoor thermal comfort is achieved with a wider range of temperatures than does the implementation of the ISO 7730 model (see Figure 3). Both models use statistical analysis of survey data to back up their claims in their respective areas of applicability. In some situations it proves possible to maintain a building's interior conditions within the 15251 Adaptive Comfort limits entirely by natural means. In these cases there is no energy use associated with achieving indoor summer comfort.

Givoni's Building Bioclimatic Chart (BBCC)

In 1963, Baruch Givoni introduced the Building Bioclimatic Chart (BBCC) –developed by Milne and Givoni 1979 – based on expected indoor temperature rather than the outdoor conditions. The BBCC presents boundaries of comfort zone and passive strategies –derived from experiments of residential buildings. The psychrometric chart is considered as the best representation of climatic variables (Szokolay 1986). In 1992, Givoni proposed two sets of boundaries for developed and hot developing countries with a suggested elevation of 2K (Givoni 1992). Recent researches based on dynamic thermal simulation have indicated the inaccuracy of the boundaries (Lomas et al. 2004) and highlighted the lack of diurnal and seasonal variations that may impact the pattern use of the passive strategies (Visitsak and Haberl 2004). At early stages of the design, indoor temperatures can hardly be identified since the design is still immature.

CASE STUDY

A reference building for dwellings was selected to assess the impact of the different thermal models. Cairo weather file was selected for this case study. Cairo is part of the mid-latitude global desert zone and its climate is considered extremely hot and dry according to Köppen Classification (Group B). According to ASHRAE climate classification Cairo is hot humid (2b). The selected benchmark represents Egyptian (non-sealed) flat apartments in narrow front housing blocks. For this study we selected a benchmark based on a recent research (Attia el al. 2012), to develop a benchmark models for the Egyptian residential buildings sector. It was assumed to represent apartments (typology 1) in high urban densities of Egyptian cities, incorporating surrounding buildings and streets. The benchmark developed to describe the energy use profiles for air-conditioners, lighting, domestic hot water and appliances in respect to buildings layout and construction.

RESULTS

To put the available comfort models in perspective, Figure 3 compares the impact of the application of four comfort models, namely Fanger EN ISO 7730, ASHRAE 55, EN 15251 and Givoni Model, using the climate data of Cairo. The difference in consumption varied from 2526 kWh/year to 2114 kWh/year (16%) to 1995 kWh/year (21%) to 1900 kWh/year (25%). The variation in the comfort model is so huge and summarizes the previous discussion. For example, the Fanger model indicates that indoor thermal comfort (operative temperature) is achieved with a very narrow (red line) temperature range. On the other range of the spectrum, the Givoni Model (black line) has a very wide temperature range of temperature reaching 30 ^{o}C. Generally the, application of the adaptive model (ASHRAE 55 and EN 15251) can be achieved with a wider range of temperatures than the Fanger model. In consequence, in some situations it is possible to maintain building interior conditions within the adaptive comfort limits entirely by natural means (Pagliano 2010). In these cases there is no energy use associated with achieving indoor summer comfort. Therefore, as the adaptive model of thermal comfort is thought to be more appropriate for mixed-mode buildings in hot climates (Rijal et al. 2008, Pfafferott et al. 2007, De Dear 1999). Therefore, we recommend to adopt the EN 15251 model for the residential NZEBs.

Mixed mode buildings are considered more similar in their operation to naturally ventilated buildings than to fully air-conditioned ones. Rijal et al. (2008, 2009) observed that operation of windows and fans in naturally ventilated and mixed mode buildings was almost identical. Furthermore, across a database of 370 mixed-mode and air-conditioned buildings, mixed-mode buildings were found to provide higher occupant satisfaction (Brager and Baker 2008). The EN 15251 adaptive comfort model, with its wider range of acceptable conditions, could promote longer operation of natural ventilation; reduce the dependence on mechanical cooling and consequently save ventilation and cooling energy (Nicol et al. 1999). The thresholds that regulate the alteration between active and passive modes have to respect the adaptive comfort criteria especially when sizing equipment (De Dear and Brager 2001). Energy savings using this comfort model was estimated as 10% - 18% of the cooling load for temperate climate such as that of Europe (Nicol and Humphreys 2002). More energy savings can be expected for buildings in hot climates with greater cooling demands.

CONCLUSION

The review presented in this papers covers different thermal comfort models and standards for sealed and non-sealed residential buildings. This review is fundamental because it has direct impact on defining NZEB in hot climates and the implications and requirements that influence the design. This study shows, that the percentage of energy consumption difference meeting the comfort criteria according to ISO 7730 in comparison to EN 15251, ASHRAE 55 or Givoni's model varied up to 16%, 21% and 24.7% respectively. This contradicts with the strict comfort limits as defined in ISO 7730 Standard, which suggest a very high level of precision in terms of thermal comfort predictability. The introduction of a certain level of comfort negotiability in adaptive thermal comfort standards might be helpful, to take advantage of the individual range of adaptive possibilities in a specific building. This could support the application of natural ventilation in buildings as well as the satisfaction of occupants. When predicting adaptive thermal comfort by using building simulation, the results should refer to the weather data set and occupant behavior the study has been based on, and provide information concerning their likelihood for variability due to different influences.

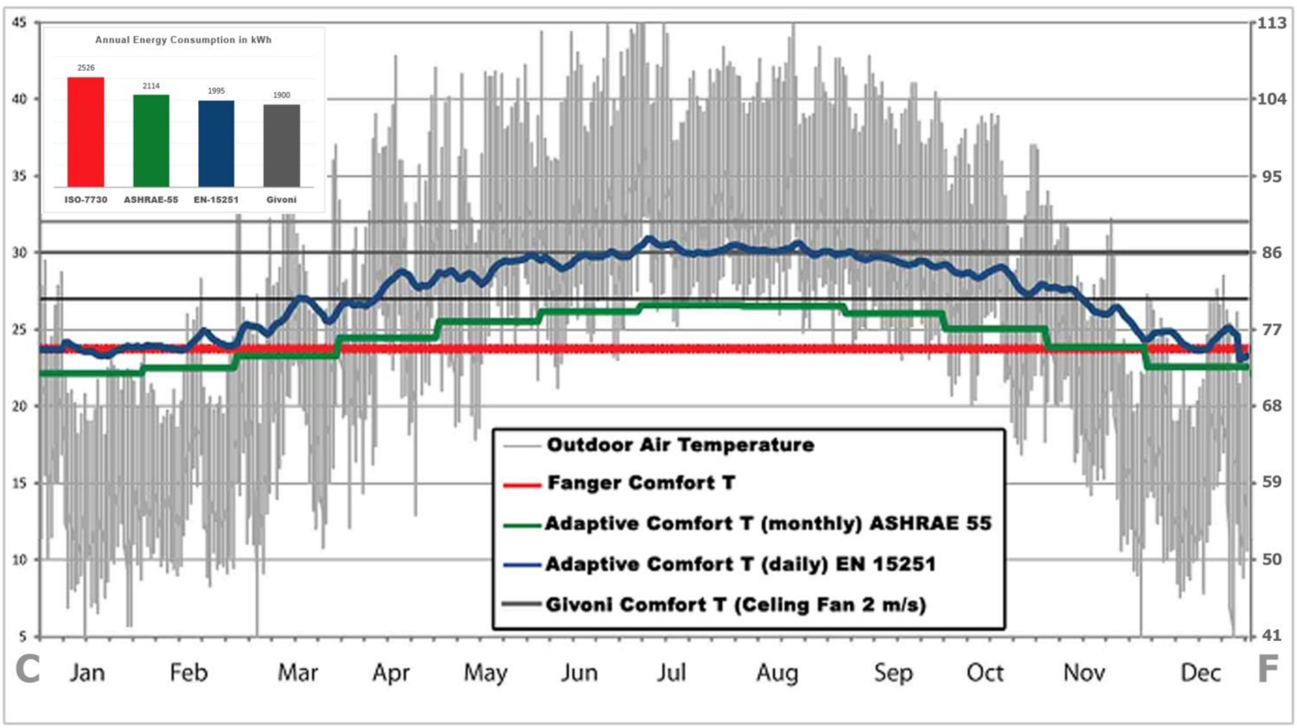

Figure 3 The application of four models for Cairo in relation to the operative temperature and energy consumption

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