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The Potential for Mixed-Mode Office Buildings in Arid Climates

Sherif Ezzeldin[a] and Simon Rees [b]

[a] Department of Architectural Engineering & Environmental Design, Arab Academy for Science and Technology and Maritime Transport, AASTMT (Cairo Campus), Egypt.

[b] Institute of Energy and Sustainable Development, De Montfort University, UK.

Abstract

The application of Mixed-Mode ventilation in severe arid climates and its integration with other passive cooling strategies is very challenging. This paper presents a systematic evaluation of the performance of various Mixed-Mode cooling strategies for office buildings with different levels of internal heat gain operated in four cities representative of arid climates. The results of the simulations are evaluated in terms of appropriate thermal comfort criteria and subsequently potential reductions in plant energy consumption so that the most effective strategies for each representative arid city can be identified. The results show that mixed-mode ventilation could save about half of the plant energy consumption compared to common active air-conditioning systems. Savings in plant energy due to the application of mixed-mode strategies that include low energy cooling technologies such as radiant, evaporative and ground cooling could exceed 90%. We conclude that mixed-mode cooling strategies should be able to provide satisfactory indoor environments and can result in highly efficient office building designs and so should be considered for application in arid climates.

Keywords: Mixed-Mode Ventilation; Cooling Strategies; Office Buildings; Thermal Comfort; Energy Savings; Arid Climates

1 . Introduction

Contemporary recognition of climate change and global warming has brought building energy consumption into sharp focus. The non-residential building sector consumes approximately one fifth of the energy of the United States [1] and this can be considered an indicator of the importance of non-residential building energy in the developed world. A sample of 4859 U.S. non-residential buildings [1] has shown the office building to be the most common type and associated with the greatest building energy demands. Improving energy performance in office buildings can therefore lead to long-term energy and carbon emission savings on a significant scale.

Arid Climates have received little attention in low energy office building research although this is one of the world's dominant climate types. Hot desert arid regions cover 14.2 % of the entire earth's land area [2] and are characterized by high dry-bulb temperatures, scarcity of rain and severity of insolation. This work is concerned with examining the performance of mixed-mode office building designs and their potential to reduce energy demands in such climates.

Arid regions are often identified and categorized according to four variants using the Köppen classification system [2]. The arid classification is primarily defined according to mean annual air temperature (MAT) and annual precipitation. However, the climates of cities in these zones also show variations in other parameters such as relative humidity and diurnal temperature variation that are important determinants of the effectiveness of some low energy cooling technologies. For the purposes of the analysis reported here, and after a systematic analysis of many arid climate data sets, four cities have been selected that characterize these variations [3]. These cities are Alice Springs in Australia, Manama in Bahrain, El Arish in Egypt and Madinah in Saudi-Arabia. The ranges of temperature and humidity conditions, insolation and diurnal temperature swing are shown in Figure 1.

The effective cooling of office buildings in arid climates requires designers' particular attention. Cooling demands are affected not only by the severity of the ambient weather conditions but also by the high internal heat gains due to occupants, lights and equipment that can be expected in modern offices. As a result, designers are inclined to adopt fully air-conditioned designs for office building developments. This can, in most cases, ensure comfort conditions can be maintained but at the expense of relatively high energy demands and carbon emissions.

Interest in energy efficiency and carbon emissions reduction has caused the revival of interest in integrated passive cooling strategies such as natural ventilation, evaporative cooling, radiant and earth cooling and effective application of thermal mass. Although these passive strategies are environmentally advantageous and potentially provide greater occupant satisfaction and increased productivity [4], designers are reluctant to adopt them in arid climates.

Mixed-mode or Hybrid cooling systems are designed to make maximum use of passive cooling methods but incorporate supplementary mechanical cooling systems for use in the most extreme conditions [5]. Energy can be potentially minimized using this approach while maintaining satisfactory comfort [6]. Considerable research into hybrid ventilation has been carried out within the International Energy Agency IEA-Annex 35 [7] and recently within the University of California, Berkeley [8] but has mostly been concerned with applications in temperate climates such as that of northern Europe. The application of Mixed-Mode ventilation in severe arid climates and its integration with other passive cooling strategies is very challenging and has not been systematically studied.

2 . Methodology

In this study, a set of mixed-mode cooling systems and common active air-conditioning systems has been simulated using EnergyPlus [9] for a prototypical office building design. The results of the simulations are evaluated in terms of appropriate thermal comfort and indoor air quality. Particular attention is paid to making comparisons based on similar levels of thermal comfort satisfaction. This, in turn, has led to careful consideration of the mixed-mode control algorithm – details of the algorithm adopted are presented below. The feasibility of each proposed system is examined and energy savings are predicted so that the most effective strategies for each representative arid city can be identified.

2.1 Prototypical Office Building Design

A single prototypical office building design (Figure 2) has been used in this work for the purposes of establishing base-case energy demands and testing various mixed-mode cooling systems. The prototypical design was optimized for best plant annual energy demand by varying shape, space arrangement, orientation, glazing percentage, shading devices and envelope construction. The following features were found optimal [3]:

- Rectangular single-zone space at intermediate floor level with internal dimensions of 30m x 20m x 3.5m.
- East-West building axis.
- 30% and 90% glazing for South and North facades respectively (North and South in the case of Alice Springs).
- 300mm overhangs for the 30% glazing.
- Daylight sensors located 2.5m from windows controlling the lights at up to 5m from the window.

The building envelope U-values and glazing SHGC were chosen to comply with ASHRAE standard 90.1 [10]. The requirements of this standard are similar to those of the International Energy Conservation Code [11] and a number of standards adopted by countries in arid climate zones. Since this study included some passive strategies, a thermally heavy-weight fabric has been defined. The prototypical design was simulated with low and high internal heat gains of 25 W/m² and 50

W/m² respectively as described in Table 1. Building operation follows the scheduled working pattern with 8 hours of operation per day and for five working days per week. Lights, equipment and cooling systems are to operate at full load within the occupied hours and at low levels during out-of-hours operation.

2.2 Alternative Cooling Strategies

Thermal Comfort is seen as the ultimate objective in the design of building environmental systems that affect occupant productivity. Satisfactory thermal comfort depends on several variables but for the purpose of evaluating the designs, the evaluation has been made in terms of adequate control of room operative temperature and this is approximated as the average of room dry-bulb and mean radiant temperatures. A number of systems can be devised that seek to maintain satisfactory operative temperatures – by either controlling room air and/or surface temperatures – that can be thought of as either active (using fans and refrigeration) or passive. Mixed-mode (hybrid) systems seek to make optimal application of both active and passive measures. Purely passive strategies (e.g. natural and night ventilation) were found to be incapable of maintaining thermal comfort especially at peak weather conditions. This research has, accordingly, focused on active and mixed-mode cooling strategies that maintain satisfactory thermal comfort.

2.2.1 Active Cooling strategies

In this study, the active cooling systems used as base cases are those thought to be typical of modern office building design practice for arid climates, namely CAV and VAV air conditioning. These are denoted systems (A) and (B). The third base case system is a radiant cooling system with a CAV fresh air supply system (C). The latter CAV system allows control of the fresh air supply temperature and humidity - some additional cooling can also be achieved when required. The simple CAV system (A) has been included in the study mainly to allow comparison with the

Radiant/CAV system (C). In the base case active system simulations, an air-cooled chiller is used as a cooling source for the air handlers and radiant system.

2.2.2 Mixed-Mode Cooling Strategies

Since adaptive occupant behavior – where opportunities for adaptation exist – leads to acceptance of a wider range of room conditions, simply allowing periods of natural ventilation should save energy [4]. Every mixed mode cooling system presented in this study has the control set-point temperatures of the active component adjusted to allow the maximum natural ventilation provided thermal comfort criteria are met. The two basic mixed-mode systems included in the study are variations of the VAV and Radiant Cooling systems (systems (B1) and (C1) respectively) that operate by natural ventilation during the occupied period except when room temperatures exceed a control system set-point temperature.

The subsequent two systems (B2) and (C2) are similar but allow natural ventilation outside occupied hours to achieve convective night cooling. Systems (B3) and (C3) supplement the basic mixed-mode systems with moisture pad in the Air Handler to achieve direct evaporative cooling of the air stream. System (C4) and (C5) are mixed-mode radiant systems with alternative cooling sources. In system (C4), a cooling tower is coupled to the radiant system and in system (C5) an array of 12 borehole heat exchangers are coupled to the radiant cooling system. In these latter cases, the energy demands of the refrigeration system are avoided altogether. The mixed-mode cooling systems are listed below and shown in matrix form together with the active systems in Table 2.

- System (B1) or (C1): Simple mixed-mode ventilation – natural ventilation during working hours alternated with an active system (B or C) in peak conditions.
- System (B2) or (C2): mixed-mode ventilation as above and a night convective cooling strategy.
- System (B3) or (C3): mixed-mode ventilation combined with direct evaporative cooling.

- System (C4): mixed-mode ventilation with the radiant cooling elements coupled to a cooling tower (indirect evaporative cooling).
- System (C5): mixed-mode ventilation with the radiant cooling elements coupled to borehole heat exchangers (earth cooling).

2.3 Performance Evaluation Criteria

Comparisons between the performance of conventional air-conditioning systems and mixed-mode strategies are only meaningful if this is on the basis of both systems achieving satisfactory thermal comfort. In all the cases studied, as these climates are strongly cooling dominated, minimum energy demands occur where the control set-point temperatures are adjusted to the maximum allowable without compromising thermal comfort. Initial parametric calculations were made to adjust set-point temperatures in this way and also to adjust the opening window control parameters to ensure minimum ventilation rates were maintained.

2.3.1 Thermal Comfort

Different models of perceived thermal comfort were applied depending on whether an active or mixed-mode system was being evaluated. The PMV heat balance thermal comfort model [12] incorporated into a number of standards and design codes (e.g. [13]) is intended to be applied to assess fully air-conditioned buildings only. An alternative adaptive approach, incorporated in the ASHRAE standard 55 [14] and EN 15251 [15], is more appropriate where there is a sense of connection between the indoor and the outdoor environment. This approach was initially derived from a field survey project RP-884 commissioned by ASHRAE in 1995. The model equations are derived from a statistical analysis of this data rather than a heat balance approach based on climate chamber data. The model seeks to account for differing perception of thermal comfort where occupants have opportunity to adapt their activities, clothing and ventilation in response to varying external conditions. This is thought to be appropriate to passive and mixed mode buildings [16]. Recent studies indicate the model may give conservative rather than optimistic estimates of comfort levels in hot arid climates [17]. This adaptive model has accordingly been applied in evaluating the performance of the mixed-mode systems in this study.

Thermal comfort indicators have been calculated for every hour of the occupied periods. This data can be conveniently represented graphically and used to evaluate annual performance and diagnose problematic periods. Examples are shown in Figure 3 and 4 for the PMV and adaptive models respectively. Each chart shows the acceptable range of thermal comfort with upper and lower boundaries for the 10% (continuous line) and the 20% (dashed line) predicted percentage dissatisfaction (PPD). Active cooling and mixed-mode control set-points have been adjusted to the maximum possible without any hours falling outside the 20% band in the case of mixed mode systems and, equivalently, the +0.85 and -0.85 PMV comfort limits for active systems. Thermal comfort has been evaluated in this way before any energy demands have been derived.

It is worth noting that, in the case of the active systems, it was not always possible to maintain conditions within the limits noted above by using a single set-point air temperature throughout the whole season. Lower air set-point temperatures were required in midsummer to compensate for the effects of high surface temperatures (e.g. at the glass inside surface). Satisfactory operation was simulated with set-point temperatures that differed on a monthly basis.

The set-point temperatures arrived at for mixed-mode system control, are noticeably higher than those for purely active operation even though thermal comfort is always maintained. For example, the room air set-point temperature can be raised from 21ºC to 24ºC for the VAV system operating in mixed-mode in Manama in July and operation with night cooling allows it to be raised to 26ºC. Higher set-point temperatures are possible in other cities. These temperatures can be higher than those in the active system simulations because of the higher limits incorporated into the adaptive comfort analysis but also as surface temperatures are moderated in strategies such as those employing night cooling.

2.3.2 Indoor Air Quality

Indoor air quality is a measure of indoor pollution and health risk levels. As the flow rate of fresh air across the space increases, assuming non-polluted outdoor environment, the contamination of indoor pollutants (such as CO_2) decreases which makes the indoor environment healthier and more pleasant [18]. For office buildings, the supply of fresh air should not be lower than 10 l/s per person for acceptable indoor air quality according to Jaakkola and Miettinen [19] and this is the benchmark adopted in the simulations reported here.

In the EnergyPlus models of the prototype building that included active cooling systems, the air handler economizer controls were set to provide minimum outside air flow rates of 400 l/s and 750 l/s for low and high internal gain offices respectively. The hourly values of outside air flow rate were varied according to room and climate conditions. In the case of the mixed-mode cooling systems, the parameters of the complementary mechanical system were set in a similar way as the active systems to ensure minimum fresh air rates were maintained at all times.

2.4 Mixed-Mode Cooling Control

Building Energy Management Systems (BEMS) are usually required to control mixed-mode strategies but the combination of sensors and actuators employed and the control strategies adopted, vary considerably. A review of the literature suggested that there is no generic control algorithm for mixed mode strategies [8]. In this study, a mixed-mode/hybrid ventilation control algorithm has been implemented based on an analysis of the most significant parameters and the proposals published by Martin and Banyard [20]. The algorithm is presented in the form of two flow charts that are applied according to the occupancy period – Figures A1 and A2 in the appendix for occupied and non-occupied periods respectively.

The proposed control algorithm has been developed with reference to the ASHRAE Standard 55 [14] adaptive comfort model temperature limits and control decisions are based primarily on the operative temperature. Decisions as to the mode of operation are made primarily by comparing the zone operative temperature with heating and cooling set-point temperatures T_{HSP} and T_{CSP} (HSP and CSP in Figures A1 and A2) which are monthly varying values defined by the upper and lower 80% satisfaction limits in ASHRAE Standard 55:2004. These are defined in degrees Celsius as,

$$T_{HSP} = 0.31T_{mdb} + 14.3\ (°C) \tag{1}$$

and

$$T_{CSP} = 0.31T_{mdb} + 21.3\ (°C) \tag{2}$$

where T_{mdb} is the prevailing monthly outdoor dry-bulb temperature. This temperature is defined as the arithmetic average of the mean daily minimum and mean daily maximum outdoor dry-bulb temperature for the month in question [21].

In the proposed algorithm, when some form of cooling is required during occupied hours (Figure 16), highest priority is given to natural ventilation, then low energy cooling systems and ultimately active cooling. When heating is not required, natural ventilation openings are modulated to increase flow as temperatures rise towards the cooling set-point (T_{CSP}). An additional check against the outdoor temperature is made to see if increasing the natural ventilation flow is thermodynamically advantageous. If the zone operative temperature has risen above the cooling set-point and there is no thermodynamic advantage in further natural ventilation, operation is switched to low energy cooling. If the zone operative temperature rises above the cooling set-point during application of the low energy cooling system, the mode of operation is changed to fully active cooling.

When natural ventilation is permitted, inlet and outlet opening size is modulated according to indoor-outdoor temperature differences. At the same time, a check is made to ensure the flow is not reduced below that required to maintain acceptable indoor air quality. Rules are also defined that result in the closure of openings when there are high wind speeds or rain occurs.

During the non-occupied hours (Figure A2) night ventilation is encouraged as long as the outdoor dry-bulb temperature is less than the zone air temperature. Using this rule alone brings some risk that the zone may be overcooled so that heating may become necessary on the following day – more so during the shoulder seasons. It was found that comparing the daily minimum operative temperature with the heating set-point temperature (T_{HSP}) was a useful indicator of this risk. Night ventilation was inhibited if this temperature had dropped below the heating set-point temperature. High wind speed limits, the occurrence of rain and low outdoor dry-bulb temperatures are considered as barriers to night ventilation, as at other times. When night ventilation is permitted, opening size was modulated according to indoor-outdoor temperature differences in order to reduce the zone radiant temperature to an acceptable limit.

It was not possible to implement this algorithm explicitly in the EnergyPlus models (at least not in the version available at the time) but the same effect was ensured by careful adjustment of the mixed-mode control model parameters according to monthly schedules. The algorithm would not be difficult to implement in a real BMS system. In practice, air quality might be checked by reference to zone CO_2 sensors and operative temperature calculated from surface temperature and air sensor data where operative temperature sensing is not available.

3 . Energy Performance

The three active systems together with the eight mixed-mode cooling strategies were simulated over annual periods using EnergyPlus [9] with the weather data files of the four representative arid cities. The simulation results were evaluated for thermal comfort, indoor air quality and plant energy consumption. Predicted plant energy savings are presented in absolute terms and relative to the base case systems and preferred systems for each city are identified. From the analysis of these results, other combinations of passive measures and low energy cooling sources have been identified that provide further opportunities for improved energy performance. Results of the simulation of these system designs are also presented.

3.1 System Energy Consumption

The plant energy demands for each location and system type are compared in terms of annual plant energy demand per unit floor area in Figures 5 and 6 for low and high internal gains respectively. Generally, as the cooling demands are (for a given level of internal gains) mainly driven by climate conditions, it could be expected that energy consumption be broadly proportional to cooling degree days and mean annual temperature. Accordingly, the results of the base case simulations show the highest energy is consumed at the hottest city (Madinah) and is lowest in the mildest city (El Arish).

The base case results (systems A, B and C) show – as one would expect – that the VAV system (B) is more efficient than the CAV system (A). This is simply due to savings in fan energy as the CAV fan is sized for peak load conditions and runs during the whole occupied period irrespective of cooling demand. During the cooling season, these two systems supply air at relatively low cooling set-point temperatures in order to achieve room air temperatures that balance high zone mean

Although the simulation results for evaporative cooling systems show distinctive energy savings, this saving is associated with significant water consumption. By their very nature, adequate water supply can be an important issue in arid climates. The locations with the greatest and least annual water consumption associated with the evaporative cooling system are Madinah (1250m³ per year) and El Arish (384m³ per year) respectively. Water supply is provided in some arid locations by desalination and this may be used for evaporative cooling but has an energy penalty associated with it. Available data [22] shows – taking mean values for the most common process – that 4.25 kWh of electricity are required to produce one cubic meter of water. When this is considered, the total energy consumed by evaporative cooling systems increases but only modestly. For example, the desalination energy raises the total energy consumption of system (C4) by 5% at the humid cities (Manama and El Arish) and by 15% at the least humid city (Madinah).

Lastly, it was found that the mixed-mode systems that use borehole heat exchanges to reject heat from the radiant system (C5) were feasible at milder locations (Alice Springs and El Arish) and more efficient than the similar system using a chiller (C1). At these locations, the mean temperature of the deep ground reaches nearly 21°C and 20°C for Alice Springs and El Arish respectively and, although relatively high, is still able to provide useful radiant cooling that can contribute to moderating operative temperatures (Figures A1 and A2). In Manama and Madinah, the ground temperature is significantly higher so that cooling by ground heat exchangers coupled to the radiant cooling system is infeasible and offers no potential energy savings.

3.2 Relative Energy Savings

The plant energy savings due to the application of the eight mixed-mode cooling systems have been expressed in terms of predicted percentage reduction relative to system (B, VAV) in Figure 7 and Figure 8. The main observations can be summarised as follows.

- Savings by simply operating conventional active systems in mixed mode, such as in system (B1), can be significant and ranges between 51%-63% and 35%-51% for low and high heat gain office buildings respectively.

- The radiant cooling implemented in system (C1) could provide additional savings over those of system (B1) of up to 12% with the greatest benefits in warm cities (Alice Springs and El Arish).
- Adoption of night ventilation as part of the mixed mode strategy was predicted to achieve significant reductions in energy demand: between 62% and 78% for system (B2) and between 70% and 79% for system (C2) for low heat gain cases, and furthermore between 56% and 66% for system (B2) and between 63% and 71% for system (C2) for high heat gain cases.
- Application of direct evaporative cooling, as applied in systems (B3) and (C3), may provide further savings over those of simple mixed-mode ventilation systems (B1) and (C1). At the least humid cities (Alice Springs and Madinah) additional savings of up to 20% were predicted.
- Using a cooling tower to reject heat from the slab radiant cooling system (C4) was shown to be worthwhile – resulting in up to 17% further savings compared to system (C1) and up to 25% further saving compared to system (B1) with the greatest savings at the less humid locations (Alice Springs and Madinah). The total plant energy savings are potentially 55%-73% compared to system (B, VAV).
- Using borehole heat exchangers to reject heat from the slab radiant cooling system may be worthwhile in arid sub-climates with lower mean average air temperature (Alice Springs and El Arish) – up to 12% further savings over those of the simple mixed-mode system (C1) and up to 25% over those of system (B1) were predicted. The total plant energy savings were calculated to be 51%-72% compared to system (B, VAV).

Considering monthly variations in predicted energy savings from the office building simulated with mixed-mode systems (Figures 9 and 10) gives some insight into the relationships between climatic conditions and energy performance. The results show that for mixed-mode systems using VAV and where natural ventilation is permitted for day and night-time (system B2), most of the plant energy savings occur in months with moderate outdoor temperatures. In hot arid climates, outdoor temperatures are moderate during winter and equinox periods. The results show (Figure 9 and 10) relative savings reach almost 100% in some months (although the absolute size of the active system loads is low) as internal heat gains are sufficient to offset heat losses.

Generally, monthly energy savings vary inversely with monthly cooling degree-days and the mean monthly dry-bulb temperature; energy savings are least during the hottest summer periods. During summer months, the savings are mainly due to night ventilation lowering fabric temperatures, reducing room loads and improving conditions during the following days.

3.3 Optimal Mixed-mode Systems.

The results from the study presented above demonstrated the benefits of individual mixed-mode design elements and variations in operating strategy. From this study it has been possible to identify combinations of zone cooling system and cooling energy source that are synergistic and may be more optimal in terms of annual energy savings – depending on arid sub-climate type. Five system configurations (denoted MM1 – MM5) have been identified and the combinations of features embodied in each proposal are indicated in Table 3. All these designs employ passive night cooling. The corresponding predicted energy savings are shown in the rightmost columns in Figures 5 and 6. Energy demand data for these systems is also presented in the following section.

The first two system designs (MM1 and MM2) may be considered where slab radiant cooling is not feasible or architecturally acceptable. The other three system designs (MM3, MM4 and MM5) are proposed for applications where slab radiant cooling can be accommodated and in most cases offer the greatest energy efficiency potential. The cities or arid sub-climate types where each configuration is feasible or most appropriate are indicated in the bottom row of Table 3.

System (MM1) is similar to the simple VAV mixed-mode ventilation system (B2) presented earlier with night ventilation as part of the operating strategy. System (MM2) combines systems (B2) and

(B3). This system is similar to (MM1) in that a VAV system is operated in a complementary manner to natural and night ventilation but differs in that the air supply is conditioned by direct evaporative cooling. System (MM2) is potentially more efficient than system (MM1) but is not predicted to be the best option in more humid arid climates such as Manama.

System (MM3) combines the features of systems (C2) and (C3). In this case, when natural ventilation is insufficient, cooling is provided by a slab radiant system and CAV air supply cooled by evaporative cooling. The primary cooling source is mechanical refrigeration. System (MM4) combines the features of systems (C2), (C3) and (C4). The configuration is similar to that of (MM3) except that a cooling tower is the primary cooling source for the slab radiant system (indirect evaporative cooling) and mechanical refrigeration is avoided altogether. The air handler incorporates direct evaporative cooling but not a chilled water coil. System (MM5) combines the features of systems (C2), (C3) and (C5) and is similar to the design of (MM4) except that the slab radiant cooling system is coupled to borehole heat exchanger array instead of a cooling tower.

Of these five mixed-mode systems, those with slab radiant cooling strategies (MM3, MM4 and MM5) are predicted to save more cooling energy since the radiant temperatures can be moderated, higher air set-point temperature can be tolerated and natural ventilation is possible over longer periods. System (MM4) can be expected to consume the largest amount of water since it uses cooling towers as the primary cooling source.

The most efficient mixed-mode system was found to be partly dependent on location. In the case of Manama, which has higher humidity levels compared to the other cities studied, evaporative cooling was not effective all through the year. Consequently, of the radiant cooling systems considered, only system (MM3) which uses a chiller as the primary cooling source, is feasible. The simulation results (rightmost columns in Figures 5 and 6) show that system (MM3) provides 69%

and 67% plant energy savings when compared with the reference active system (B, VAV) for low and high internal heat gain offices respectively.

In the case of Madinah, a mixed-mode system that combines natural and night ventilation, direct and indirect evaporative cooling (MM4) is predicted to consume the least plant energy. The simulation results indicate that application of system (MM4) may result in 93% plant energy savings when compared with a conventional VAV system (B).

In the cases of warm arid sub-climates such as those of Alice Springs and El Arish, night ventilation, ground cooling, direct and indirect evaporative cooling were found to maximize natural ventilation opportunities. As ground temperatures are lower in these locations coupling of the slab radiant cooling system is feasible and so systems (MM4) and (MM5) have been simulated for both cities. The simulation results showed that the energy savings associated with the ground coupled system (MM5) may be up to 5% greater than (MM4) due to lower water consumption and lower fan energy demands.

In the case of Alice Springs, 95% and 91% of plant energy savings were predicted for system (MM5) when compared with the conventional VAV system (B) for low and high internal heat gain offices respectively – Figures 5 and 6. In the case of El Arish, 95% and 94% of plant energy savings were predicted for system (MM5) when compared with the active system (B,VAV) for low and high internal heat gain offices respectively.

To summarize, the simulation results indicate that the preferred design in Manama is system (MM3) but this does not result in as significant energy savings as systems (MM4) and (MM5) in other locations. This is because the ground temperature and the moisture content of the ambient air are relatively high and so evaporative and ground-coupled cooling strategies are not effective. On the other hand, each of the other cities has appropriate natural heat sinks that encourage passive and low energy cooling strategies. Energy savings due to the adoption of one of the systems that have been identified may exceed 90% in the majority of arid climates.

4 . Energy Use Indices

Energy Use Indices (EUI) are a common metric used to quantify building energy demands and a useful indicator of relative energy efficiency [23]. EUI are defined in terms of annual demand per unit floor area (kWh/m²). The annual energy demands predicted in this study have been quantified in this way for the low and high internal gain cases respectively. Predicted plant energy is also broken down into cooling (chillers), heating, cooling tower, pump and fan energy categories. Simulated lighting and equipment energy has also been given separately. The data is fully tabulated in [24].

The Energy Use Indices of the highest and the least energy consuming of mechanical air conditioning, mixed-mode ventilation systems and mixed-mode cooling systems for both high and low internal heat gain office buildings are presented in bar-chart form in Figure 11. In these charts, systems in the mixed-mode ventilation category include different combinations of active cooling systems (VAV and CAV with slab radiant cooling) and natural and night ventilation; such as systems (B1, B2, C1 and C2). The particular system is noted at the left of each bar. The systems in the mixed-mode cooling category in Figure 11 are selected from the designs that integrate passive, low-energy and active cooling systems; such as systems MM1, MM2, MM3, MM4 and MM5 as presented in Figures 5and 6.

The EUI data presented in Figure 11 shows that the calculated energy consumption of each cooling system ranges widely according to variation is arid climate conditions. Active cooling systems are predicted to consume from 118 to 359 kWh/m² of total building energy with 44% to72% associated with plant energy consumption.

Systems (A) and (C) demonstrate the highest and lowest plant energy consumption respectively amongst the active cooling systems studied. Chillers are shown to be the greatest energy consumers with 38% – 58% of the total building energy in cases employing active systems. The energy consumption due to lights and equipment for cases employing active systems is 59 kWh/m² and 119 kWh/m² for low and high internal heat gain cases respectively.

It can also be seen (Figure 11) that mixed-mode ventilation systems are predicted to consume from 78 to 231 kWh/m² of total building energy for different internal gain and different arid climate conditions. Mixed-mode ventilation saves about half of the plant energy consumption, which is equivalent to nearly one third of the total. Systems (B1) and (C2) consume the highest and the lowest plant energy respectively of the mixed-mode ventilation systems. The energy consumption due to lights and equipment for mixed-mode cases is about 48 kWh/m² and 105 kWh/m² for low and high internal heat gain cases respectively.

Mixed-mode cooling systems are predicted to consume from 52 to 204 kWh/m² of total building energy for different internal gain and different arid climate conditions. System (MM1) consumes the highest plant energy of the mixed-mode cooling systems. The least plant energy consumption of the different cooling systems is provided by mixed-mode cooling system (MM3) in Manama, system (MM4) in Madinah and system (MM5) in both Alice Springs and El Arish.

These Energy Use Indices (EUIs) data could provide some guidance for designing mixed-mode office buildings in arid climates. The indices could also act as preliminary benchmarks to evaluate the performance of new mixed-mode strategies.

5 . Mixed-mode Operating Conditions

In order to better understand the performance of the proposed mixed-mode designs, five consecutive working days have been analyzed for the reference active system (B, VAV) and the mixed-mode system (MM5) simulated in El Arish during winter and summer. Thermal performance and thermal comfort evaluation criterion have been applied for each system, as shown in Figures 11 and 12. These figures present a sample of the simulation results for El Arish where the performances of cooling systems (B) and (MM5) for a high internal heat gain office were compared during five January winter days and five July summer days respectively. Thermal performance is presented in terms of ambient dry-bulb temperature, indoor air, radiant and operative temperatures. Thermal comfort conditions during the working hours within these five days were evaluated against Fanger's PMV-model and ASHRAE's adaptive approach for system (B) and system (MM5) respectively. The variations in window opening area are also illustrated in Figures 11 and 12 in order to highlight naturally ventilated periods.

uring the five winter days (Figure 12) the ambient dry-bulb temperature varied between 8.5°C and 22.7°C. For both systems, the operative temperatures were always maintained within the comfort boundaries.
This is achieved using only an all-air cooling approach in the active system (B) or a balance between air and radiant-cooling approaches in the mixed-mode system (MM5). The differences between indoor and outdoor air temperatures are smaller with the later system. The indoor radiant temperatures of the mixed-mode system are always lower than those of the active system due to some night ventilation.

In a typical cold period such as that illustrated in Figure 12, almost no cooling is required; energy consumed is mainly associated with ventilation. In the case of system (MM5), natural ventilation enables fan energy savings and is seen to be enabled as long as the indoor temperature was equal to or above 18°C to prevent overcooling (opening below this temperature being inhibited by the control algorithm). Natural ventilation can be seen to operate during the peak daily weather conditions while it was prevented during both the nighttime and the early periods of the day. Overcooling was avoided.

During the five summer days shown in Figure 133, the ambient dry-bulb temperature varied between 20.5°C and 35.9°C. The differences between indoor and outdoor temperatures and between indoor air and radiant temperatures are predicted to be smaller in the building conditioned by the mixed-mode system (MM5). The indoor radiant temperatures using system (MM5) are always lower than those of the active system due to the effect of night ventilation and ground cooling. For both systems, the operative temperatures are maintained within the thermal comfort boundaries

In a typical hot period such as that shown in Figure 13, cooling is always required for some portion of the day; energy consumed by the systems are due to both ventilation and cooling. In the case of the building employing system (MM5), use of natural ventilation is shown to enable savings in chiller and fan energy. Natural ventilation was allowed during the whole day as long as the outdoor air temperature was lower than or equal to the indoor air temperature and during the daytime as long as the indoor air temperature was lower than or equal to the cooling set-point temperature (24°C). In the results for these five days, natural ventilation was found to operate only at non-occupied hours and was inhibited during the occupied periods to prevent overheating. This pattern is indicated by the opening area data in Figure 13.

Annual trends in window opening area have been plotted in normalized form in order to show periods where natural ventilation was enabled during either the occupied or the non-occupied hours in Figures 14 and15 respectively (noting winter in Alice Springs occurs during the middle of the calendar year). Smoothed trend curves are shown ot highlight the annual pattern of operation. It can be seen that natural ventilation was enabled most during the equinoxes, and decreased during the winter seasons. There are extended periods in the summer season where windows are not opened during occupied hours. These summer periods are longer at the hotter arid locations in the study (Manama and Madinah). The proportion of total occupied hours of natural ventilation (Figure 14) ranges from 37% in Madinah to 57% in El Arish. In contrast, night ventilation was enabled most often during the equinoxes and decreased during both the mid-summer and mid- winter seasons. The proportion of non-occupied hours of night ventilation (Figure 15) ranged from 64% in Alice Springs to 86% in El Arish.

According to these seasonal comparisons, during winter natural ventilation is more frequently utilized during the occupied hours and during the summer, night ventilation is more commonly enabled. The longest periods where natural and night ventilation are utilized is during the equinox seasons where the outdoor air temperatures are not as extreme during the daytime as in summer and, at the same time, not as low during the night-time as in winter. These findings correspond to the monthly energy saving trends described in section 3.2.

6 . Conclusions

A systematic simulation study has been conducted to evaluate the potential of a range of mixed-mode cooling systems and ventilation strategies in arid climatic conditions. The simulations have examined the potential plant energy savings using weather data from four cities that are representative of the whole range of arid sub-climate types. A large set of simulations has been carried out based on a prototypical office building and energy predictions have been compared with those of conventional VAV system designs. Three fully air-conditioned active systems designs were modeled along with eight mixed-mode cooling systems that integrated passive, low energy and active elements. In each case satisfactory comfort conditions and minimum ventilation rates were verified.

The office building design adopted in this study incorporated features such as high exposed thermal mass, good shading and opening windows. It was demonstrated that adopting a mixed mode strategy by allowing user control of windows and facilitating adaptive behavior, should enable significant plant energy savings (more than 40%) by simply alternating between natural ventilation and VAV cooling. Greater savings were demonstrated where night ventilation formed part of the operating strategy. Night ventilation was shown to be effective during the equinox seasons even in the hottest sub-climates.

It was found that noticeably low air set-point temperatures were required to offset radiant gains in designs with conventional air conditioning in order that PMV comfort criteria were satisfied. In contrast, given the exposed thermal mass in the prototypical building and allowing for comfort to be judged according to an adaptive model, much higher air temperatures could be accepted and so cooling demands reduced by operating at higher set-point temperatures in the case of buildings with mixed-mode systems. It was furthermore demonstrated that a range of systems incorporating slab radiant cooling were more energy efficient when operated in a mixed-mode strategy by virtue of moderating radiant temperatures and allowing higher air set-point temperatures. In all cases direct evaporative cooling of the fresh air supply was shown to make a useful contribution to energy reduction – even after possible desalination energy penalties were considered.

Five system configurations that sought to combine low energy cooling features in a more optimal manner have been proposed and tested through simulation. The most effective systems incorporated slab radiant cooling and direct evaporative cooling. In less humid arid sub-climates refrigeration could be avoided altogether by making use of a cooling tower as a heat rejecter for the radiant cooling system. In less extreme arid sub-climates ground temperatures allowed borehole heat exchangers to work well as the radiant cooling heat rejecters. Plant energy savings due to the application of these optimal designs were predicted to exceed 90% in the majority of arid climate conditions.

Energy Use Indices (EUIs) have been compiled for mechanical air conditioning, mixed-mode ventilation systems and mixed-mode cooling systems for office buildings in different arid sub-climates. Mixed-mode ventilation saves about half of the plant energy consumption of mechanical air-conditioning systems while mixed-mode cooling may save nearly all the plant energy consumption.

Although further research regarding the applicability of adaptive comfort models in mixed-mode buildings is probably required, and further work on optimal control strategies would be valuable, we conclude that application of mixed mode cooling and ventilation strategies to office buildings in arid climates offers very promising levels of energy efficiency.

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Table 1 Internal heat gain per unit area of the prototypical office building

Building Model		Occupants W/m²	Lights W/m²	Equipment W/m²	Total W/m²
Office	Low	7.2	10	7.8	25
	High	13.5	15	21.5	50

Table 2 Simulated Cooling Strategies

Components of the Cooling System		Active Sys. A	Active Sys. B	Active Sys. C	Mixed-Mode Systems B1	B2	B3	C1	C2	C3	C4	C5
Compact HVAC Sys.	CAV	Active		Active				Active	Active	Active	Active	Active
	VAV		Active		Active	Active	Active					
Natural Ventilation	Day				Passive/Low	Passive/Low	Passive/Low	Passive/Low	Passive/Low	Passive/Low	Passive/Low	Passive/Low
	Night					Passive/Low			Passive/Low			
Evap. Cool.	Moist. Pad						Passive/Low			Passive/Low		
Radiant System	Rad. Ceiling			Active				Active	Active	Active	Passive/Low	Passive/Low
	Chiller			Active				Active	Active	Active		
	Cool Tower										Passive/Low	
	BHE											Passive/Low

Active Components; Passive/Low energy Active Components

Table 3 Optimal Designs of Mixed Mode Cooling Systems for Office Buildings in Arid Climates

Cooling System Components		Mixed-Mode Cooling Systems (Optimal Designs) MM 1 B2	MM 2 B2+B3	MM 3 C2+C3	MM 4 C2+C3+C4	MM 5 C2+C3+C5
Compact HVAC System	Compact Air Volume (CAV)			A		
	Vairable Air Volume (VAV)	A	A			
Passive Ventilation	Natural Ventilation (NV)	P	P	P	P	P
	Night Ventilation (nv)	P	P	P	P	P
Direct Evaporative Cooling	Moisture Pad in the AHU		L	L	L	L
Radiant Cooling System	Slab Radiant Cooling (SRC)	Non-Feasible	Non-Feasible	L	L	L
	Chiller	Non-Feasible	Non-Feasible	A		
	Cooling Tower	Non-Feasible	Non-Feasible		L	
	Borehole Heat Exchanger	Non-Feasible	Non-Feasible			L
Representative Arid City		Manama	All except Manama	Manama	All except Manama	Alice Springs El Arish

A Active Components; P Passive Components; L Low Energy Components; ☒ Non-Feasible

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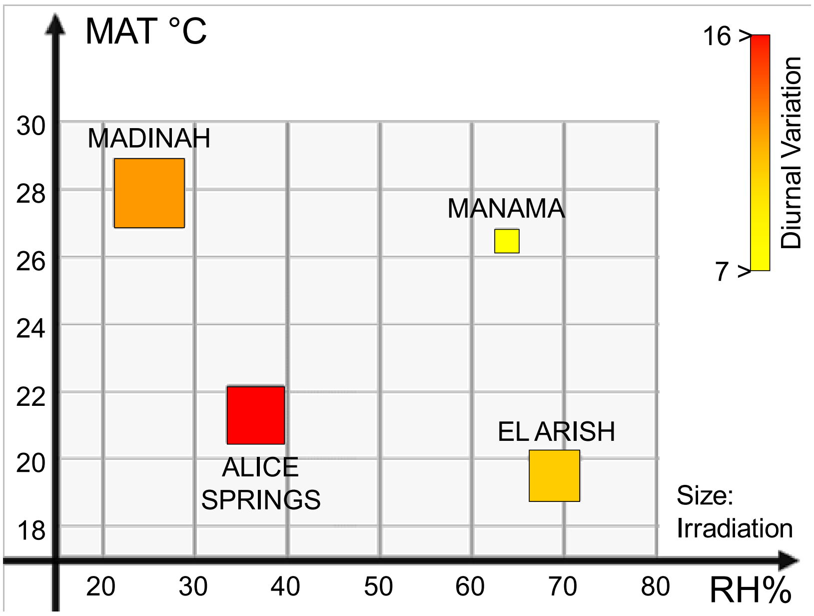

Figure 1 Mean Annual Temperature and Relative Humidity of the four representative arid cities. Symbol size and colour define the annual solar irradiation and average diurnal temperature variation respectively.

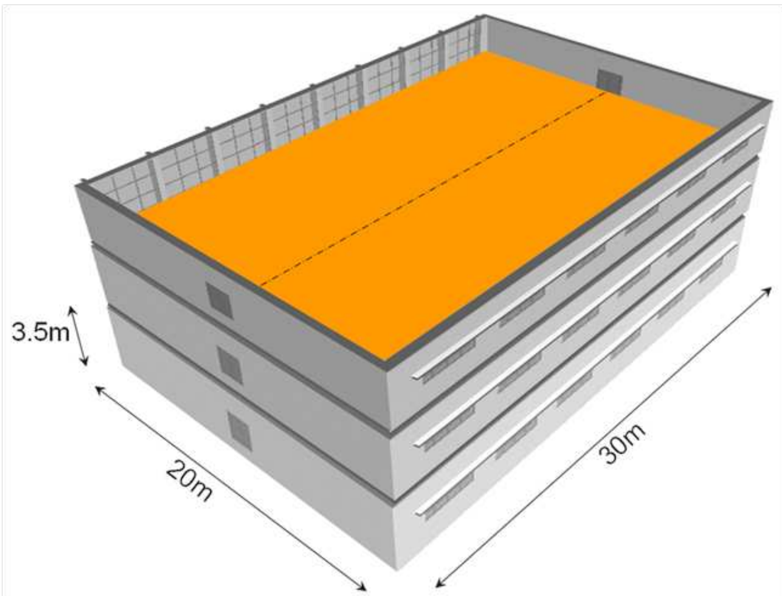

Figure 2 The prototypical office building design derived from parametric analysis. An intermediate single-storey was used in the final model.

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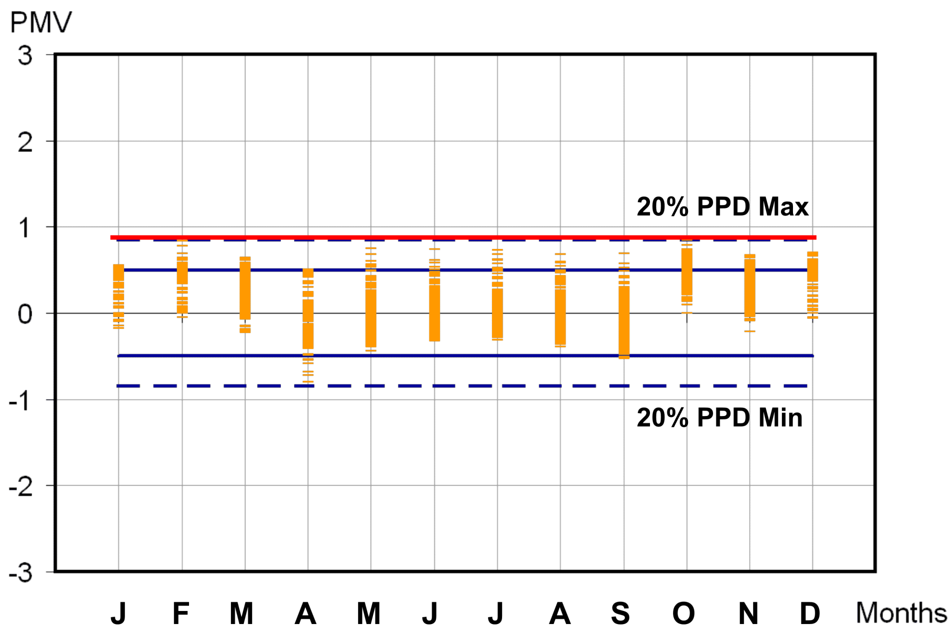

Figure 3. An example of PMV thermal comfort data shown for an active system annual simulation.

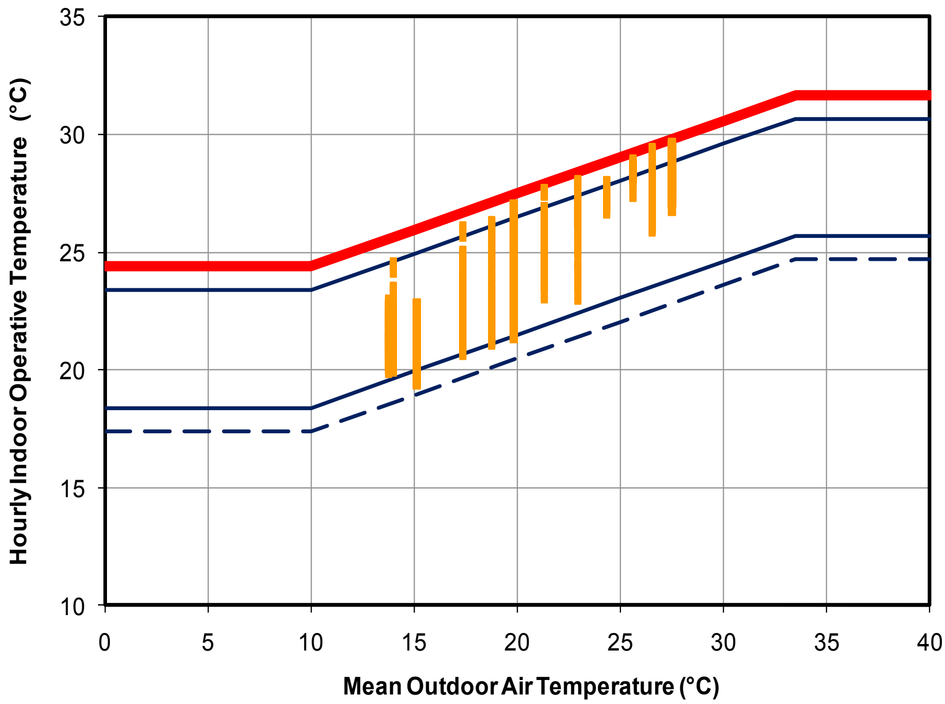

Figure 4 Operative temperatures from a mixed-mode system simulation compared with the ASHRAE Standard 55 adaptive comfort model temperature bounds.

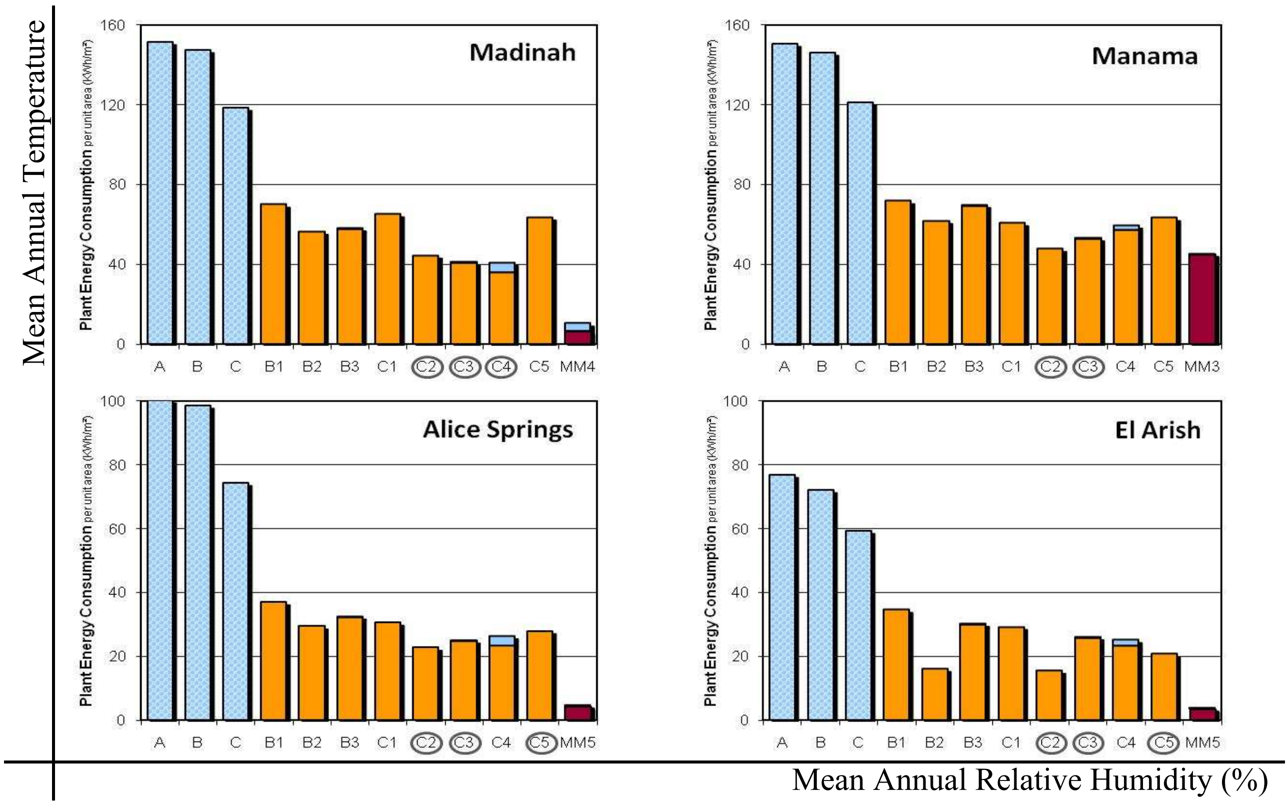

Figure 5 Plant Energy Consumption per unit area for active and mixed-mode cooling strategies with low internal gains at the four representative arid cities.

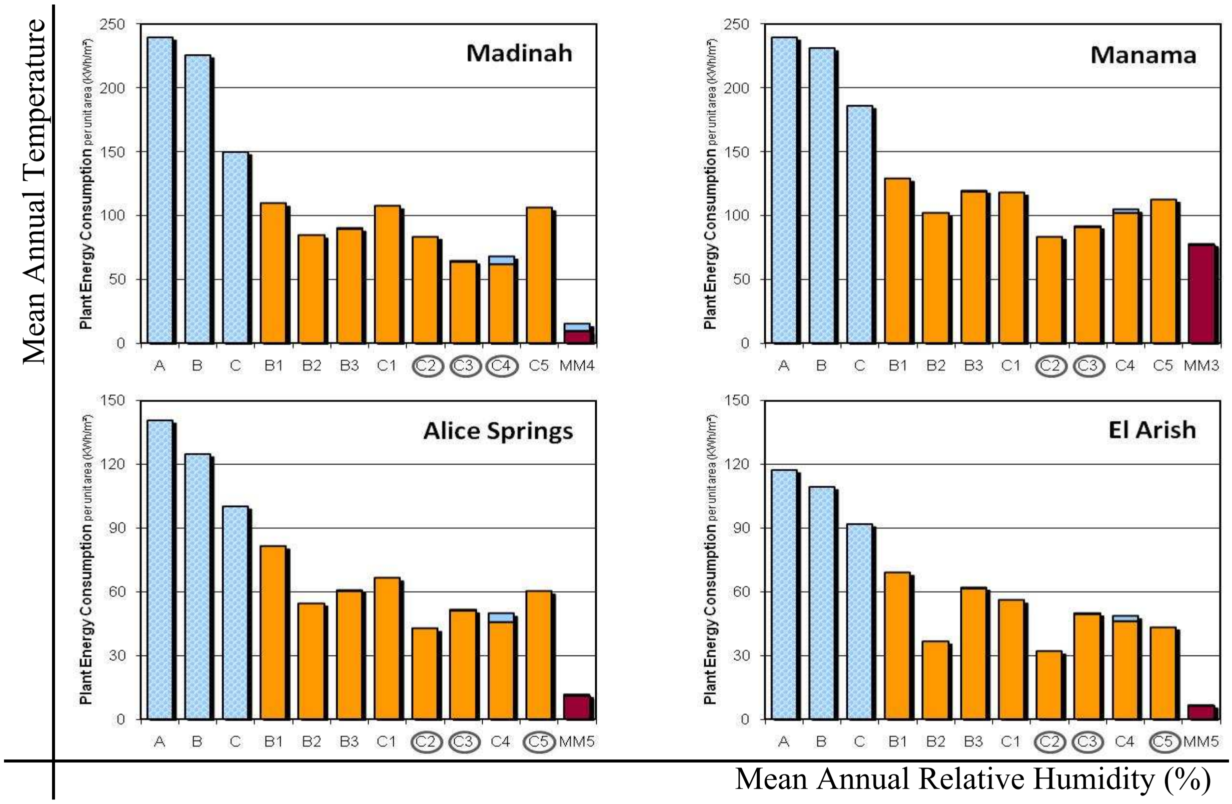

Figure 6 Plant Energy Consumption per unit area for active and mixed-mode cooling strategies with high internal gains at the four representative arid cities.

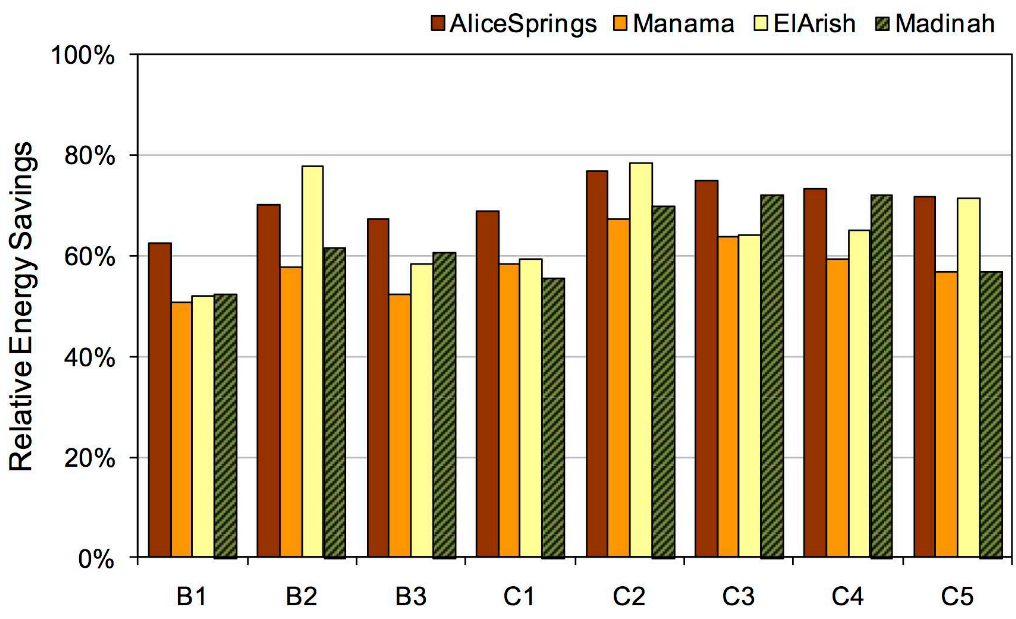

Figure 7 Savings in plant energy due to the application of mixed-mode cooling strategies for low internal heat gain cases realative to System (B, VAV).

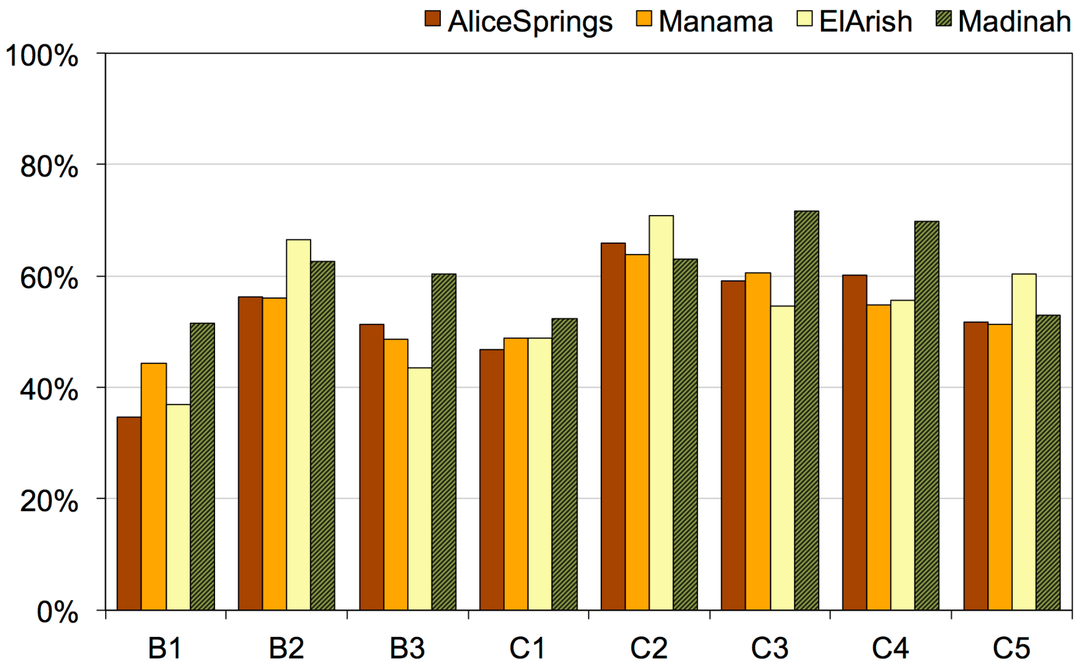

Figure 8 Savings in plant energy due to the application of mixed-mode cooling strategies for high internal heat gain cases relative to System (B, VAV).

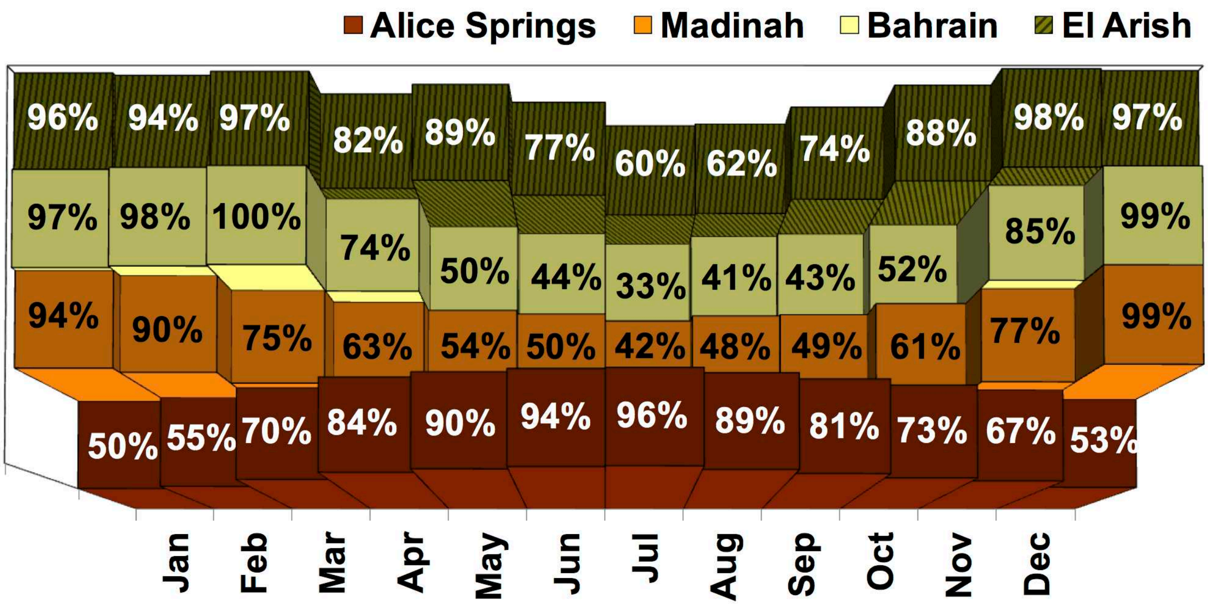

Figure 9. Monthly plant energy savings for system (B2) with low internal heat gain relative to the VAV system (B).

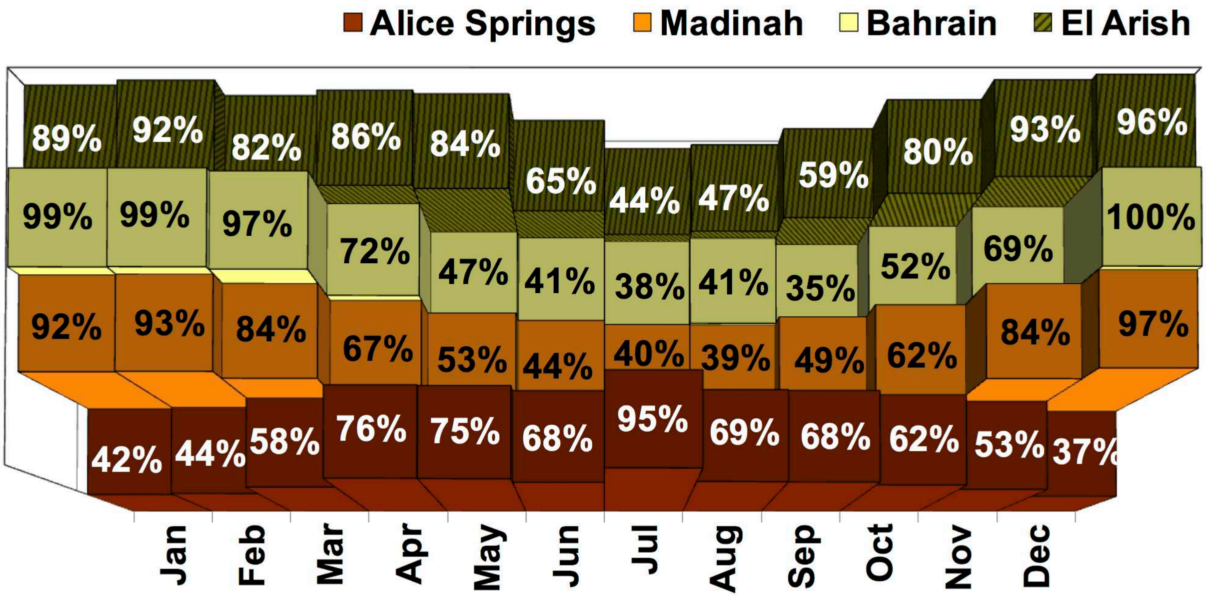

Figure 10. Monthly plant energy savings for system (B2) with high internal heat gain relative to the VAV system (B).

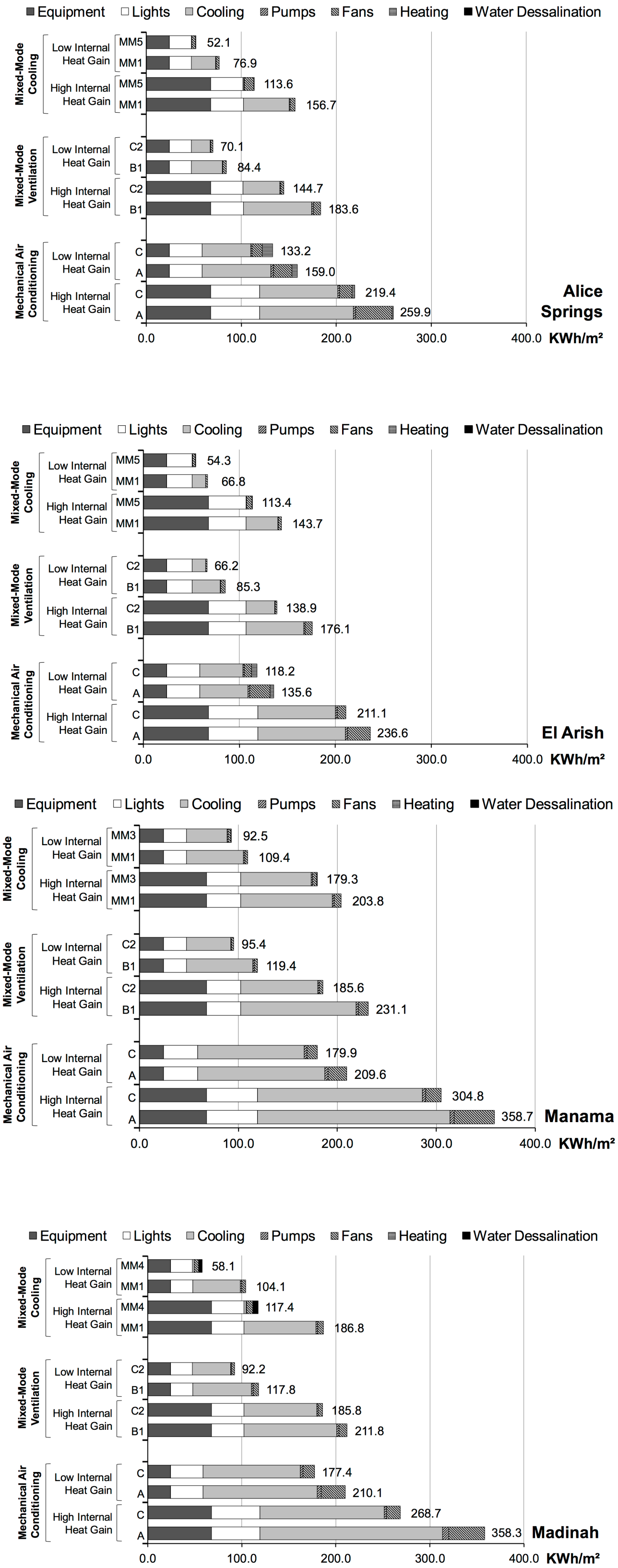

Figure 11 Annual energy use indices (EUIs) for air conditioned, mixed-mode ventilated and mixed-mode cooled office buildings in either warm or hot arid sub-climates with either low or high internal heat gain.

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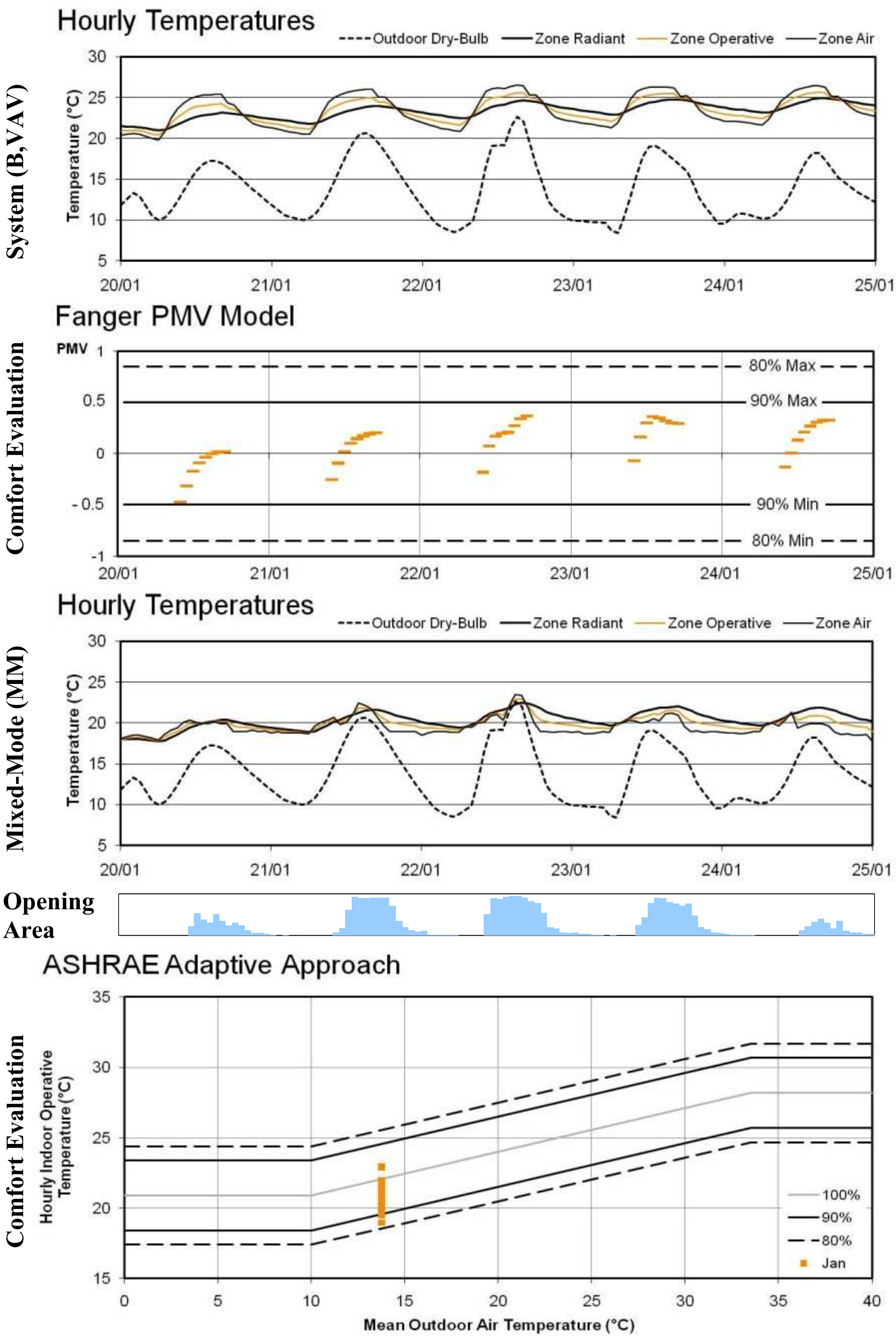

Figure 12 Performance of active and optimal mixed-mode proposal for five winter days at El Arish.

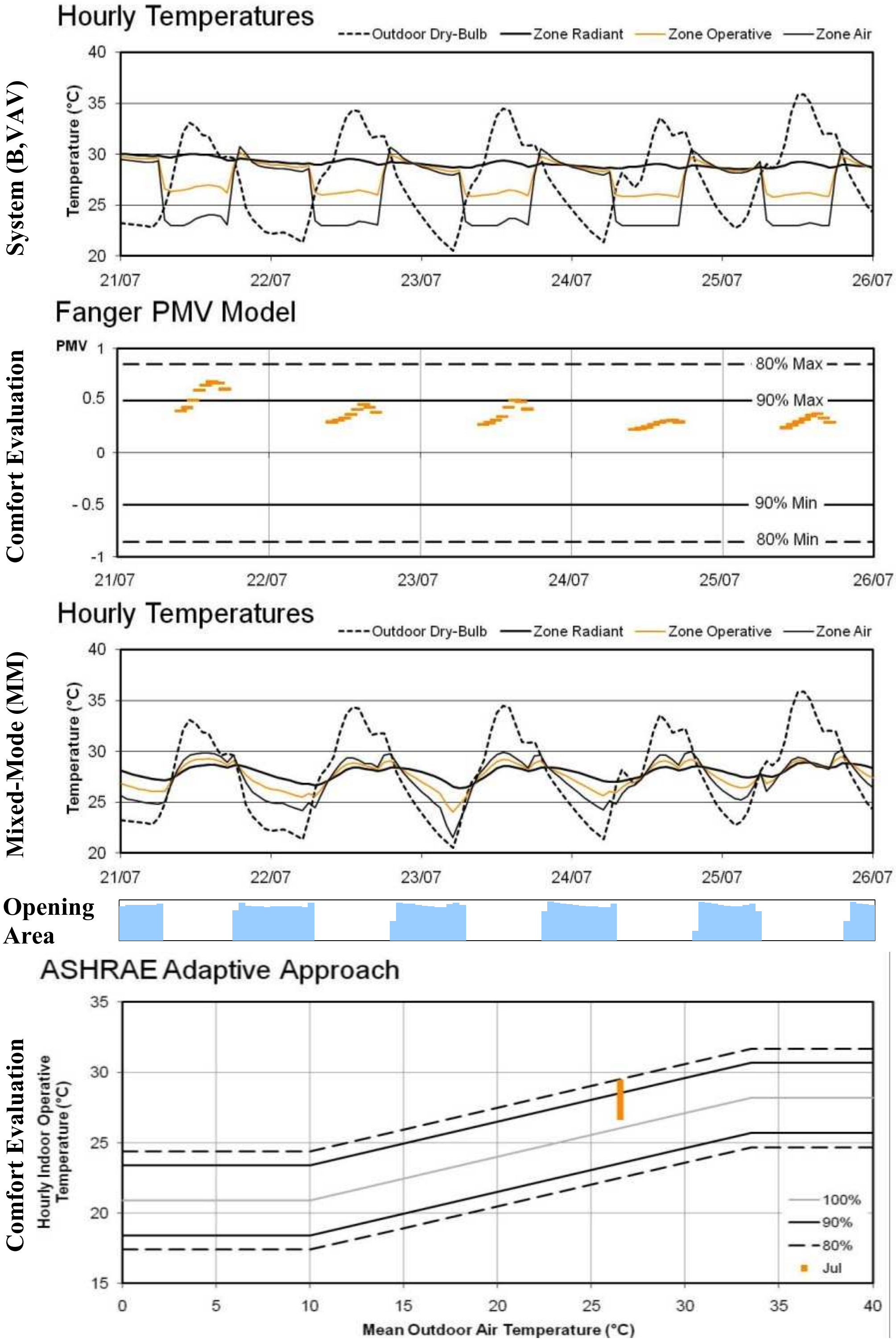

Figure 13 Performance of active and optimal mixed-mode proposal for five summer days at El Arish.

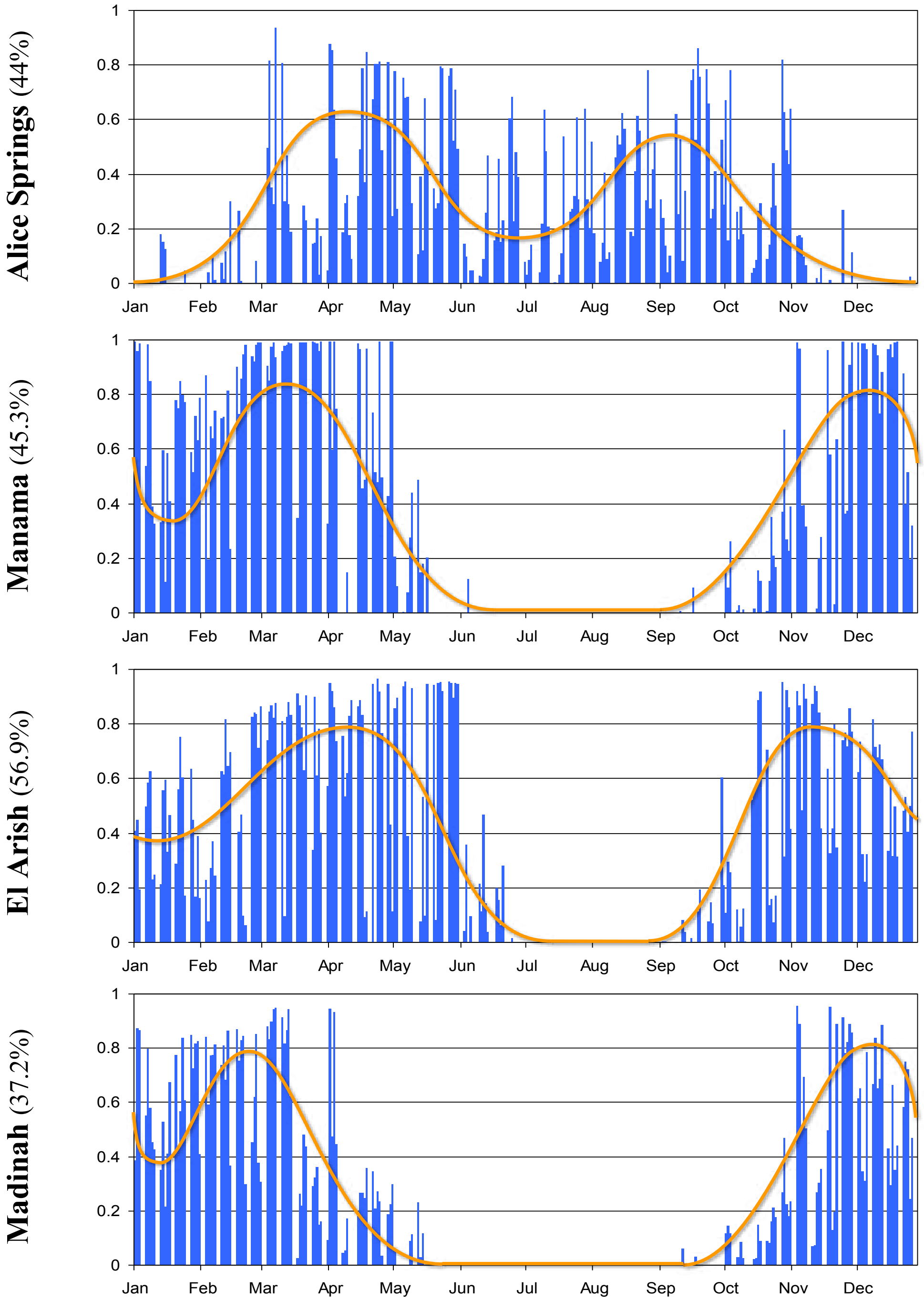

Figure 14 Window opening area of the optimal designs during the occupied hours (Natural Ventilation). The annual proportion of natural ventilation is noted in the vertical axis caption.

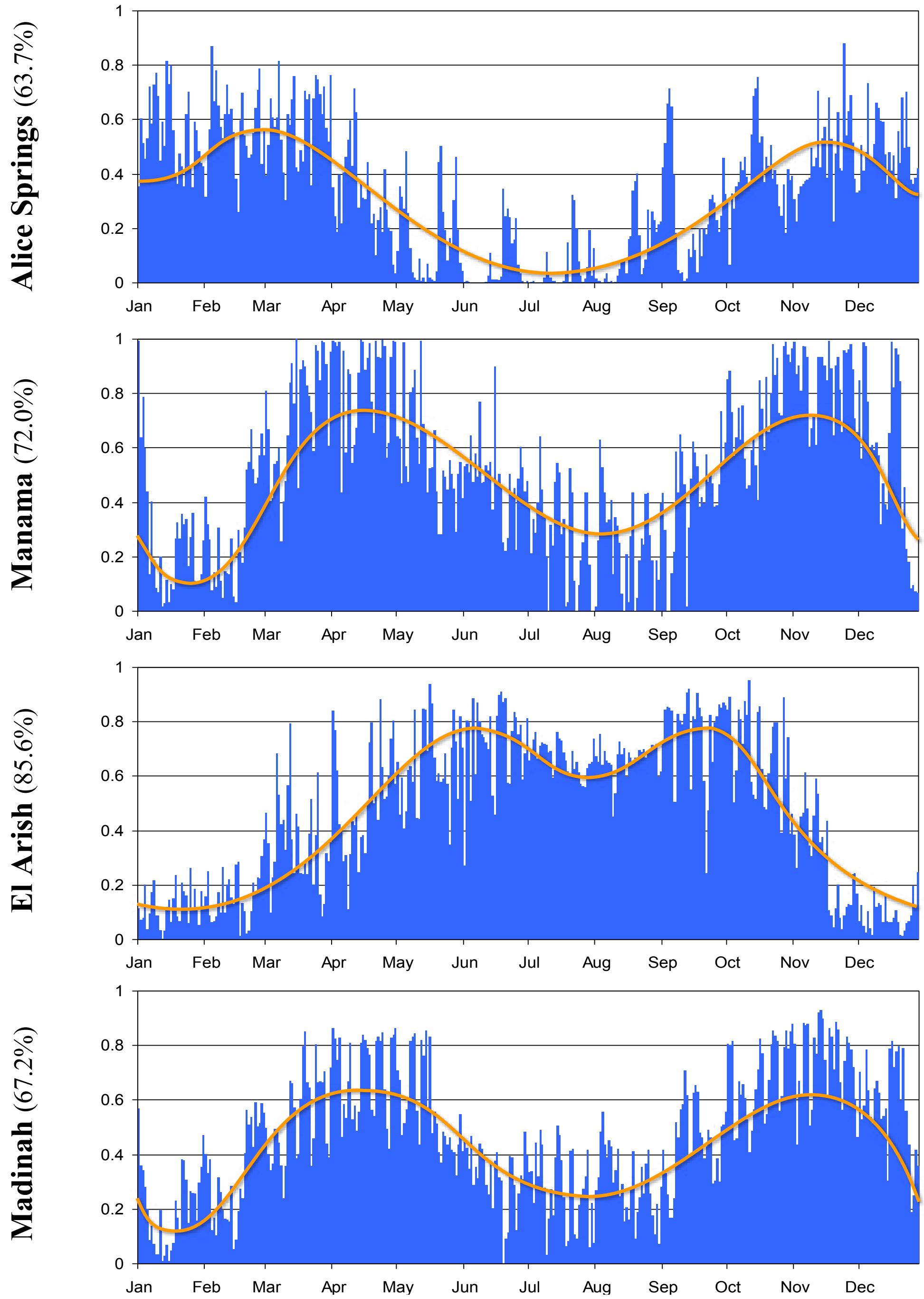

Figure 15 Window opening area of the optimal designs during the non-occupied hours (Night Ventilation). The annual proportion of night ventilation is noted in the vertical axis caption.

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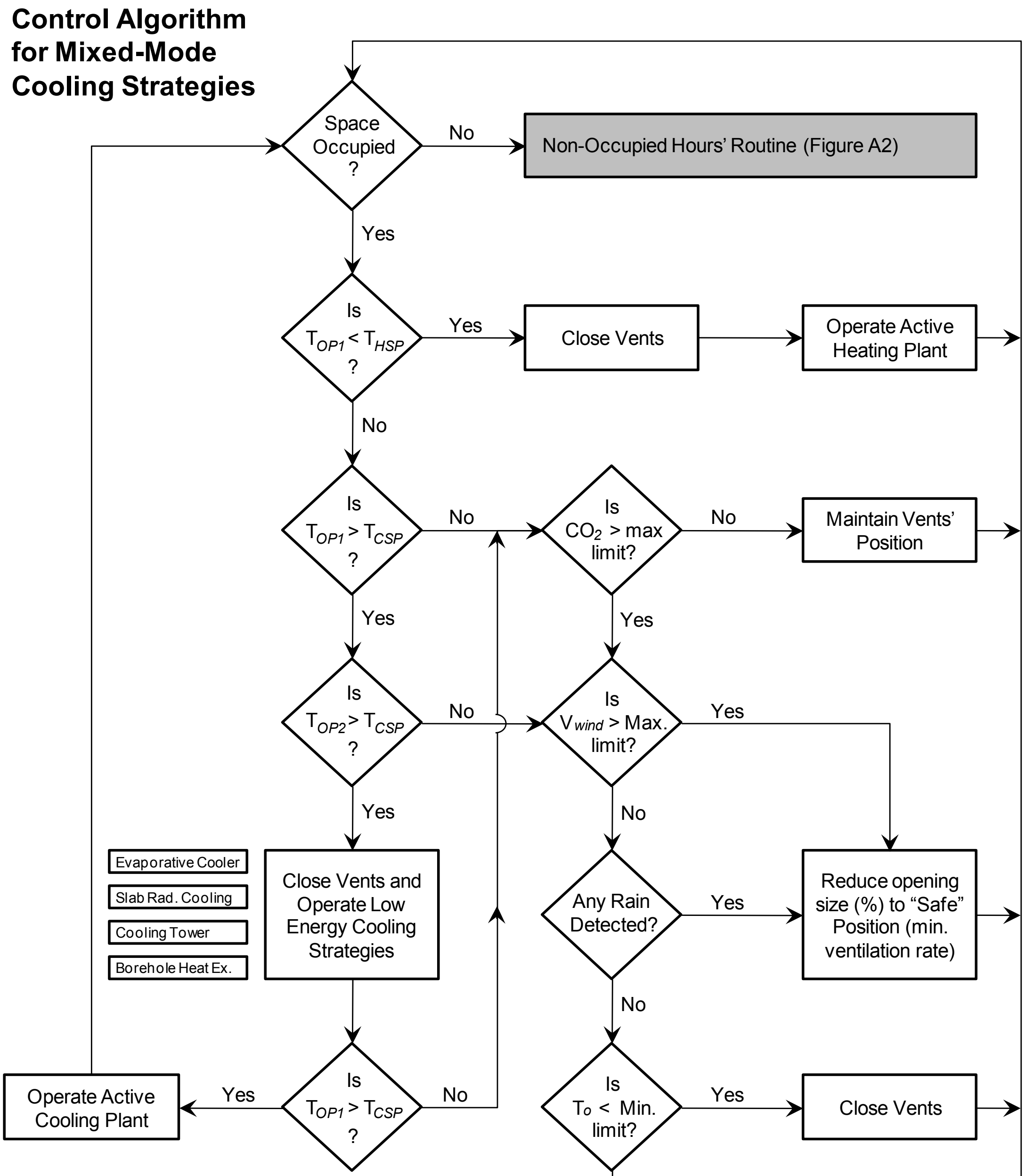

Where:

T_o : Hourly outdoor dry-bulb temperature

T_a : Zone air temperature

T_r : Zone radiant temperature

T_{OP1} : Zone operative temperature = $\frac{T_a + T_r}{2}$

T_{OP2} = $\frac{T_o + T_r}{2}$

V_{wind} : Outdoor wind speed

$T_{HSP} = 0.31\ T_{mdb} + 14.3$ and $T_{CSP} = 0.31\ T_{mdb} + 21.3$

T_{mdb} : Average of the mean monthly minimum and maximum daily air temperatures for the month

Figure A1 The mixed-mode/hybrid cooling control algorithm for occupied periods.

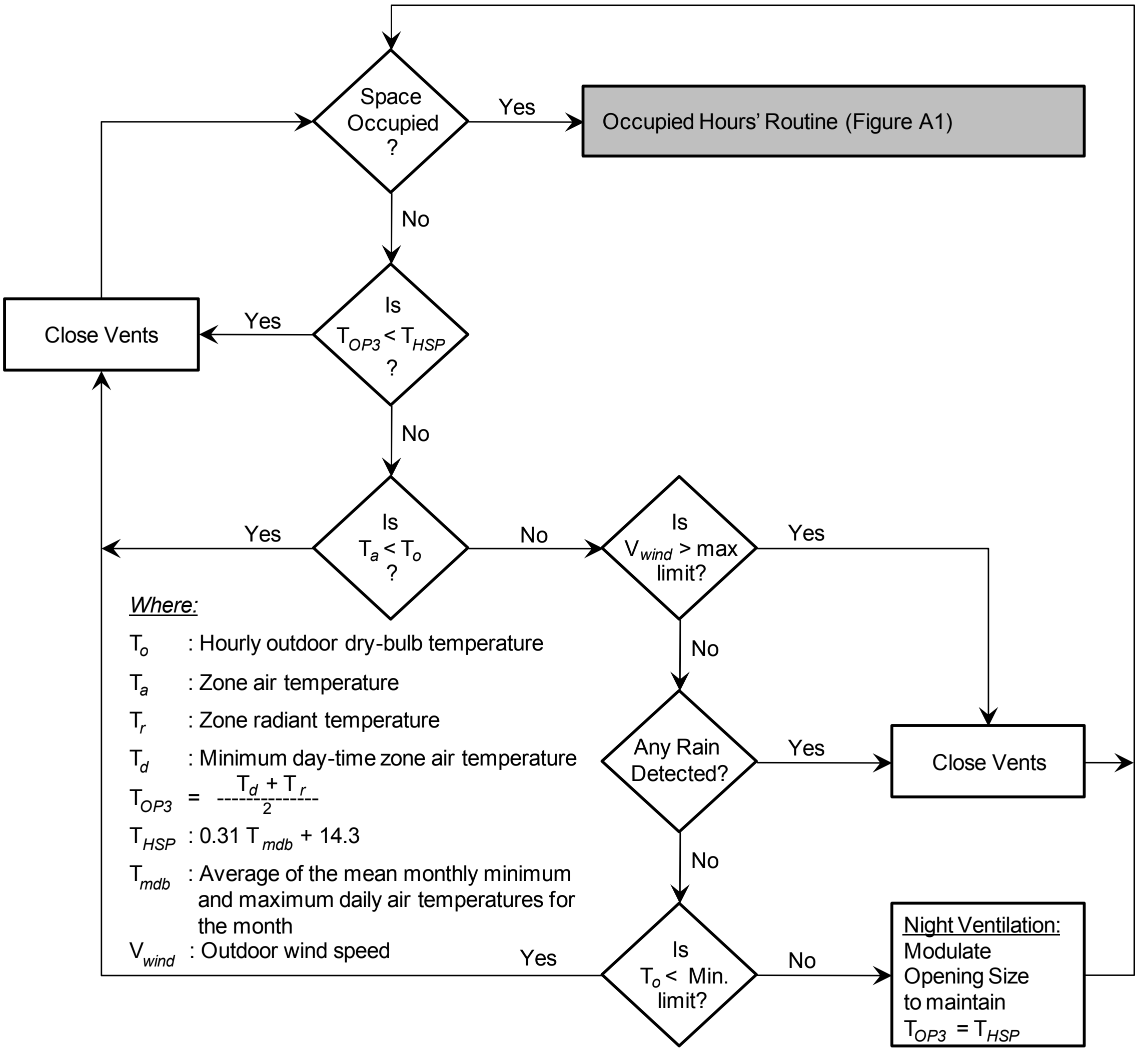

Figure A2 The mixed-mode/hybrid cooling control algorithm for non-occupied periods.