Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Choosing a method of thermal comfort for mixed-mode office buildings located in hot-humid summer climate

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Abstract

The objective of this paper is to assess methods of thermal comfort for use in mixed-mode office buildings located in hot-humid summer climate based on air-conditioning consumption of a predominant typology of real mixed-mode office buildings. Three methods to assess thermal comfort were analysed: (1) Givoni's chart for hot and humid climates, (2) ASHRAE 55-2010 for determining acceptable thermal conditions in occupied spaces, (3) ASHRAE 55-2010 for determining acceptable thermal conditions in naturally ventilated spaces. Different models of mixed-mode office rooms in two solar orientations and three window areas per model were analysed. Simulations were performed using the EnergyPlus computer programme. Thermal comfort was assessed applying the simulations output data into the upper acceptable ranges of each method. This work provides a way to choose a method of thermal comfort for mixed-mode office buildings that could be used where subjective assessment of thermal comfort is not available.

Keywords: Thermal comfort, mixed-mode buildings, hybrid ventilation.

1 Introduction

Nowadays there are two main lines of thought concerning thermal comfort: The steady-state model (PMV-PPD method), based on Fanger's studies (Fanger, 1970; Fanger and Toftum, 2002) and the adaptive model based on the works of Auliciems (1981), de Dear, Brager and Cooper (1997) and Nicol and Humphreys (2002). The PMV-PPD method suits well to occupants' thermal sensation in buildings with air-conditioning whereas the adaptive method describes thermal sensation of users more appropriately in naturally ventilated buildings (Fanger and Toftum, 2002; Cao et al., 2011; Deuble and de Dear, 2012).

For mixed-mode buildings a thermal comfort method is not available and more studies are required to prove that a specific method is really necessary. de Dear and Brager (2002) suggested that the ASHRAE Standard 55 (2010) method for determining acceptable thermal conditions in naturally ventilated spaces could be used in buildings operating with mixed-mode ventilation: when the maximum limits of acceptability are reached the air-conditioning is turned on just to lower the temperatures to the acceptability limit; the building operates with natural ventilation while the interior temperatures are within the limits of acceptability.

Deuble and de Dear (2012) studied a mixed-mode building in Sydney, Australia. The mixed-mode ventilation operated automatically changing from natural ventilation to air-conditioning when the indoor temperature was higher than 25ºC. Once in air-conditioning the system maintained the indoor temperature at 24ºC±0.5ºC. Measurements of environmental variables were performed at the same time that thermal comfort questionnaires were applied. The results indicated that more people were dissatisfied with their thermal environment during air-conditioning operation than during natural ventilation. The perception of the occupants changed as the building changed from natural ventilation to air-conditioning: a PMV = +1 was felt by users as much warmer than neutral in comparison with the same thermal environment during natural ventilation. Deuble and de Dear (2012) also concluded that during natural ventilation operation the adaptive method corresponded well with occupants' comfort and during air-conditioning operation the PMV-PPD model best described user's thermal sensations.

Brager and Baker (2008) compared the thermal comfort data of 12 mixed-mode commercial buildings with the data of 358 air-conditioned commercial buildings. The data are from a database created by the Center for the Built Environment, University of California, USA. These data were obtained through assessments of occupants' satisfaction with their workspace using a 7-point scale ranging from very satisfied (+3) to very dissatisfied (-3), with a neutral midpoint (0). The authors concluded that, on average, the performance of mixed-mode buildings (concerning thermal comfort) is significantly better than the other 358 air-conditioned buildings.

Classical thermal comfort field studies relating outdoor and indoor environmental variables, user's garment and metabolism with subjective assessments of thermal comfort present more valuable information than climate chamber experiments or simulation studies because field studies deal with real people in their real workplace. However, it is not always possible to perform this kind of research due to the lack of resources (researchers, funds or time). Thus, an existing method of thermal comfort could be helpful to describe in which conditions users would likely feel comfortable. But what method of thermal comfort should we use for mixed-mode buildings when subjective assessments of thermal comfort are not available?

The objective of this paper is to assess methods of thermal comfort for use in mixed-mode office buildings located in hot-humid summer climate based on air-conditioning energy consumption of a predominant typology of real mixed-mode office buildings. This work is a continuation of a previous work (Rupp and Ghisi, 2014). In that paper we considered the methods in its original publication format and we do not evaluate the prevailing mean outdoor air temperature as presented in Addendum C - ASHRAE 55 (2010). In this paper, we also evaluate the behaviour of a humidity limit for the ASHRAE 55 (2010) method for determining acceptable thermal conditions in naturally ventilated spaces.

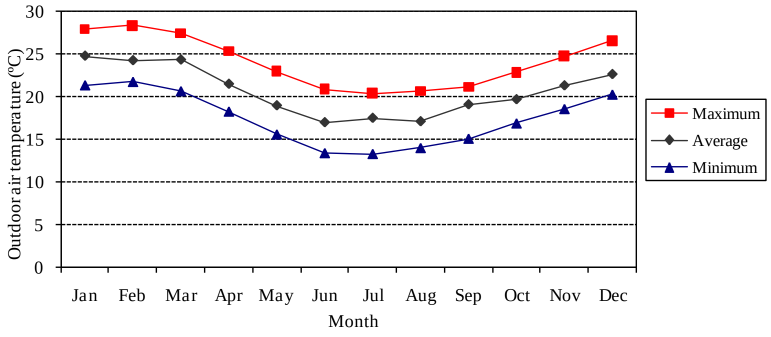
2 Method

The research is based on computer simulations performed using EnergyPlus 6.0 programme and air-conditioning energy consumption of a predominant typology of real mixed-mode office building in Florianópolis city, Brazil. The TRY (Test Reference Year) climate file of Florianópolis (LabEEE, 2011) was used for the simulations. Room models of mixed-mode office buildings located in hot and humid summer climate were simulated under two modes of natural ventilation: single-side ventilation and cross-ventilation. For each mode of ventilation, results were analysed using different methods to assess thermal comfort, considering only the heat discomfort limits imposed by such methods. No air-conditioning simulations were performed, as they are not necessary for this study.

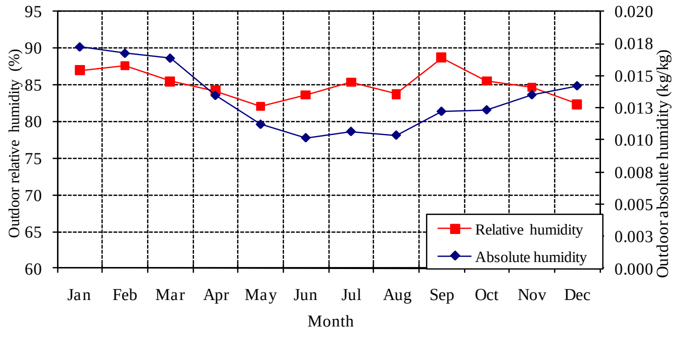
More detailed information about parameters and considerations of simulation can be found in Rupp and Ghisi (2014).

2.1 The climatic context and the simulation models of mixed-mode office buildings

Florianópolis is an island located in the state of Santa Catarina, southern Brazil (latitude -27º36’ and longitude -48º33’). The city is warm and humid during summer (December to March) as shown in Fig.1. High air humidity is common due to the proximity to the sea.



(a)



(b)

Figure 1. (a) Maximum, minimum and average outdoor air temperature and (b) outdoor air relative humidity and average outdoor air absolute humidity throughout the year in Florianópolis. Source: based on Brasil (1992).

This climate context conducts to the highest use of air-conditioning for buildings’ cooling in summer. In other periods of the year the air-conditioning is less used or turned off. Heating is not commonly used (Santana, 2006). Thus, mixed-mode buildings are usually found in Florianópolis.

For this study, different models of mixed-mode office rooms were considered to have adiabatic ceiling, floor and interior walls, because what is under assessment is the behaviour of a single model (cell) and not the whole building. The sizes of the models were based on the room index (Equation 1), as used in manuals of illumination and in Ghisi (2002). The working surface was taken as 0.75m above floor level and the overall height of the models as 2.80m.

$$K=\frac{W.D}{(W+D).h} \qquad \text{Eq. 1}$$

where K is the room index (non-dimensional); W is the overall width of the room (m), D is the overall depth of the room (m) and h is the mounting height between the working surface and the ceiling (m).

Models with geometries (Width:Depth) of 2:1 and 1:2, two room sizes per geometry (room indices of 0.8 and 5.0), two solar orientations (south and west) and three window areas (10, 50 and 100%) per room model were analysed. The window area is the total area of the façade that can be glazed. The window is located below a 60cm beam and has the width of the façade. The room dimensions for each room index and geometry can be seen in Table 1.

Table 1. Mixed-mode office room dimensions for each room index and geometry.

Room index - K	Geometry - Width:Depth			
	2:1		1:2	
	Width (m)	Depth (m)	Width (m)	Depth (m)
0.8	4.92	2.46	2.46	4.92
5.0	30.75	15.38	15.38	30.75

The models operated with artificial light and typical office equipment and occupancy, resulting in the internal thermal loads presented in Table 2. These loads were considered during occupation of the building (8am – 6pm, Monday to Friday).

Table 2. Internal thermal loads.

Room index - K	0.8	5.0	Source
Lighting Power Density (W/m^2)	13.9	8.1	lighting design performed by the authors
Occupation (m^2/person)	14.7		Santana, 2006
Metabolic activity (W/m^2)	65		ASHRAE 55, 2010
Equipment (W/m^2)	9.7		Santana, 2006

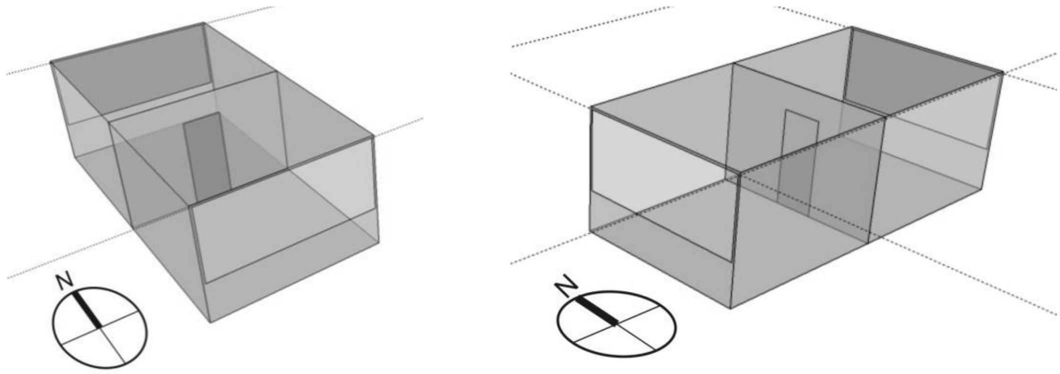
The buildings components (Table 3) were based on Santana´s work (2006), with windows composed of single glass, 6mm, 88% of light transmission.

Table 3. Properties of the building components.

Element	Material	Roughness	Conductivity (W/m.K)	Density (kg/m^3)	Specific heat (J/kg.K)	Thickness (m)	Total thickness (m)
Walls	Plastering mortar	rough	1.15	2000	1000	0.025	0.200
	Ceramic 6-hole brick	rough	0.90	1600	920	0.150	
	Plastering mortar	rough	1.15	2000	1000	0.025	
Floor	Concrete slab	rough	1.75	2200	1000	0.150	0.185
	Plastering mortar	rough	1.15	2000	1000	0.025	
	Ceramic floor	rough	0.90	1600	920	0.010	
Ceiling	Ceramic floor	rough	0.90	1600	920	0.010	0.185
	Plastering mortar	rough	1.15	2000	1000	0.025	
	Concrete slab	rough	1.75	2200	1000	0.150	
Door	Wood	smooth	0.15	614	2300	0.030	0.030

2.2 Natural ventilation simulation

The multi-zone Airflow Network model from EnergyPlus was used for the simulation of natural ventilation. The simulations were performed for each room model, in pairs, according to Fig. 2. There is a door measuring 0.9 x 2.2m separating the rooms. Model 1 is used for the North-South orientations and Model 2 for the East-West orientations.



Model 1: North-South — Model 2: East-West

Figure 2. Examples of simulation models of natural ventilation.

The windows were considered operable and the natural ventilation control strategy adopted was based on temperature. In EnergyPlus this means that the windows were opened when three requirements were fulfilled: (1) the zone temperature was greater than the outdoor temperature, (2) the zone temperature was greater than the setpoint temperature of natural ventilation and (3) the schedule control of natural ventilation allowed ventilation. The setpoint temperatures for natural ventilation were 22ºC (autumn and winter, from March 21 to September 20) and 20ºC (spring and summer, from September 21 to March 20). The schedule control of natural ventilation allows ventilation from Monday to Friday. Two modes of natural ventilation were simulated throughout the simulation period: single-sided ventilation (the interior door was closed) and cross-ventilation (the interior door was opened).

For each simulation, outdoor and indoor environmental variables were obtained on an hourly basis throughout the year.

2.3 Methods to assess thermal comfort

Three methods to assess thermal comfort were analysed: (1) Givoni’s chart (Givoni, 1992) for hot and humid climates (Fig. 3), (2) ASHRAE 55 (2010) for determining acceptable thermal conditions in occupied spaces (Fig. 4), (3) ASHRAE 55 (2010) for determining acceptable thermal conditions in naturally ventilated spaces (Fig. 5). Method 3 was assessed considering the 80% and 90% upper acceptable temperature threshold (Eq. 2 and Eq. 3) and also: (3-i) the outdoor mean monthly air temperature (original publication), (3-ii) the prevailing mean outdoor air temperature (daily temperature 7-days ago) (Addendum C - ASHRAE 55, 2010), (3-iii) the outdoor mean monthly air temperature with a suggested 80% limit of relative humidity and (3-iv) the prevailing mean outdoor air temperature (daily temperature 7-days ago) with a suggested 80% limit of relative humidity. The proposal of a relative humidity threshold was based on results of the mentioned previous work (Rupp and Ghisi, 2014) and on the work of Emmerich, Polidoro and Axley (2011).

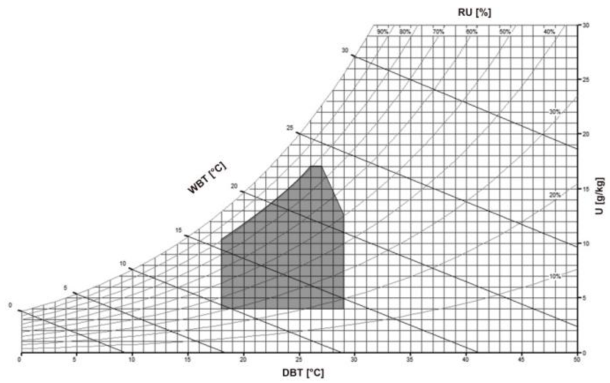


Figure 3. Givoni's chart for hot and humid climates marking the thermal comfort zone. DBT=dry bulb temperature; WBT=wet bulb temperature; RU=relative humidity; U=humidity. Based on Givoni, 1992.

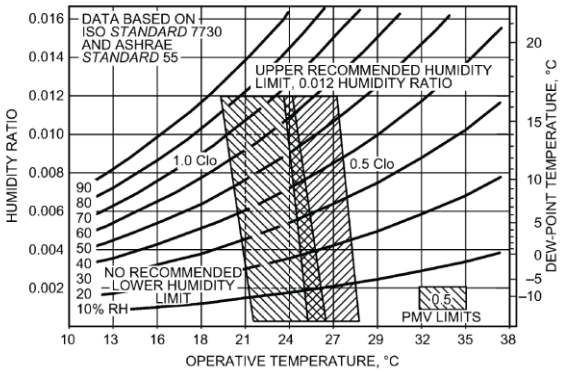


Figure 4. Acceptable range of operative temperature and humidity for spaces. Source: ASHRAE Handbook Fundamentals, 2009.

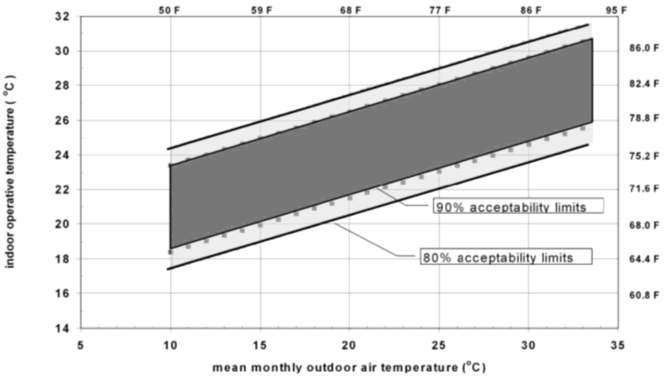


Figure 5. Acceptable operative temperature ranges (80% and 90%) for naturally ventilated spaces. Source: ASHRAE 55, 2010.

Upper 80% acceptable temperature limit (ºC) = $0.31\ t_{a(out)} + 21.3$ Eq. 2

Upper 90% acceptable temperature limit (ºC) = $0.31\ t_{a(out)} + 20.3$ Eq. 3

where $t_{a(out)}$ is the mean monthly outdoor air temperature used for 3-i and 3-iii; on a daily basis $t_{a(out)}$ was replaced with $t_{pma(out)}$, which is the prevailing mean outdoor air temperature (daily temperature 7-days ago) for 3-ii and 3-iv.

The prevailing mean outdoor air temperature (daily temperature 7-days ago) was calculated as presented in de Dear (2006) and de Dear and Candido (2010), Eq. 4:

$$t_{pma(out)} = 0.34t_{od-1} + 0.23t_{od-2} + 0.16t_{od-3} + 0.11t_{od-4} + 0.08t_{od-5} + 0.05t_{od-6} + 0.03t_{od-7} \quad \text{Eq. 4}$$

where t_{od-1} is the mean daily outdoor temperature from the previous day, t_{od-2} is the mean daily outdoor temperature from the day before that, and so forth.

2.4 Number of hours of heat discomfort

The results of simulations of natural ventilation were applied in each method to assess thermal comfort. Thus, it was possible to determine the number of hours of heat discomfort throughout the year for each method. This number of hours represents the number of hours per year that the use of air-conditioning (in cooling mode) is necessary to bring thermal comfort to the users. The number of hours was compared among each evaluation method. Graphs with the number of hours for each method and for the same room were developed to ease the comparison.

2.5 Correlations

Correlations between the total number of hours in the year in which the air-conditioning will be necessary, and the number of hours of use of air-conditioning of the predominant typology of office building in Florianópolis, as defined by Santana (2006), were performed. Santana (2006) defined a predominant typology from an analysis of 35 real mixed-mode office buildings located in Florianópolis. Her analyses were performed in relation to the constructive characterization and to the occupation pattern and equipment use. Through simulation of such predominant typology in EnergyPlus, Santana (2006) obtained the air-conditioning energy consumption throughout the year (Fig. 6).

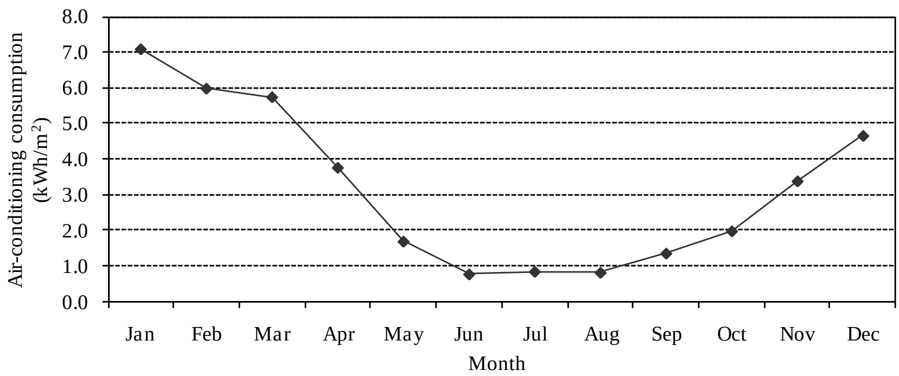


Figure 6. Air-conditioning energy consumption of the predominant typology of office buildings in Florianópolis. Based on Santana, 2006.

From the EnergyPlus file of the predominant typology of office buildings of Santana´s study (2006) we obtained the number of hours of air-conditioning use on an hourly basis. Thus, we performed correlations between the number of hours of air-conditioning use obtained from the three methods and the number of hours of air-conditioning use of the predominant typology of office buildings in Florianópolis and the results were shown in graphs. The bisection was also drawn in each of these graphs in order to consider the real behaviour of air-conditioning use. Thus, methods with results above the bisector consume more air-conditioning electricity than a typical office building in Florianópolis and may not be adequate to be used with the mixed-mode ventilation strategy. On the other hand, methods with results below the bisector consume less air-conditioning electricity than a typical office building in Florianópolis and are more adequate to be used with the mixed-mode ventilation strategy.

The decision on the most adequate method to assess thermal comfort to be used in mixed-mode office buildings was made from such comparisons and from the pattern of air-conditioning use, as defined by Santana (2006). The highest use of air-conditioning for cooling office buildings located in Florianópolis occurs from December to March, and there is scarcely any use from June to August (Santana, 2006).

3 Results

3.1 Number of hours of heat discomfort of the predominant typology of mixed-mode buildings

The number of hours of the predominant typology of mixed-mode office buildings located in Florianópolis, calculated using the EnergyPlus file of Santana (2006) is presented in Fig. 7. Even in winter, there are hot days with high solar radiation, resulting in the use of the air-conditioning for cooling. The greatest number of hours of air-conditioning use occurs between January and March. From March on, the number of hours decreases, being slightly above zero between June and August. Between August and December there is a gradual increase in the number of hours.

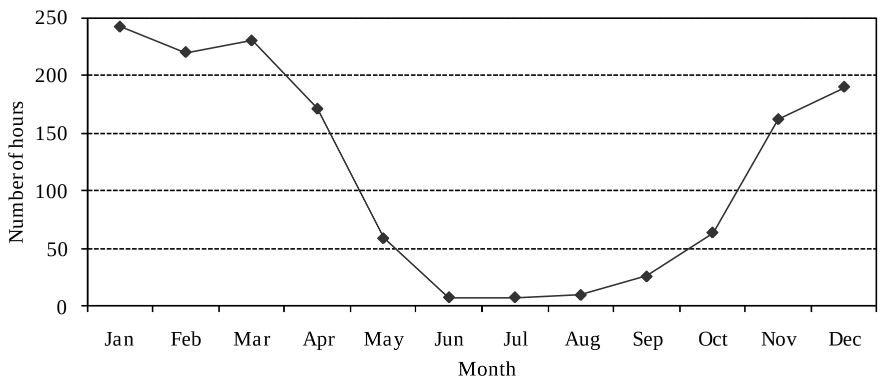


Figure 7. Number of hours per month of use of air-conditioning calculated for the predominant typology of mixed-mode office buildings. Based on Santana, 2006.

3.2 Number of hours of heat discomfort calculated by the different thermal comfort methods

Monthly results of the sums of the number of hours of heat discomfort for one geometry, one room index, three window areas, two orientations, with single-sided ventilation, by the methods of Givoni, ASHRAE 55 for occupied spaces (ASHRAE 80%), ASHRAE 55 for naturally ventilated spaces (using the outdoor mean monthly air temperature) with 80% of acceptability (ASHRAE NV 80%) and with 90% of acceptability (ASHRAE NV 90%), ASHRAE 55 for naturally ventilated spaces (using the outdoor mean monthly air temperature with the proposal of relative humidity threshold) with 80% of acceptability (ASHRAE NV

80_RH_limit) and with 90% of acceptability (ASHRAE NV 90_RH_limit), ASHRAE 55 for naturally ventilated spaces (using the prevailing mean outdoor air temperature) with 80% of acceptability (ASHRAE NV 80_Tpma) and with 90% of acceptability (ASHRAE NV 90_Tpma), ASHRAE 55 for naturally ventilated spaces (using the prevailing mean outdoor air temperature with the proposal of relative humidity threshold) with 80% of acceptability (ASHRAE NV 80_Tpma_RH_limit) and with 90% of acceptability (ASHRAE NV 90_Tpma_RH_limit), can be seen in Fig. 8.

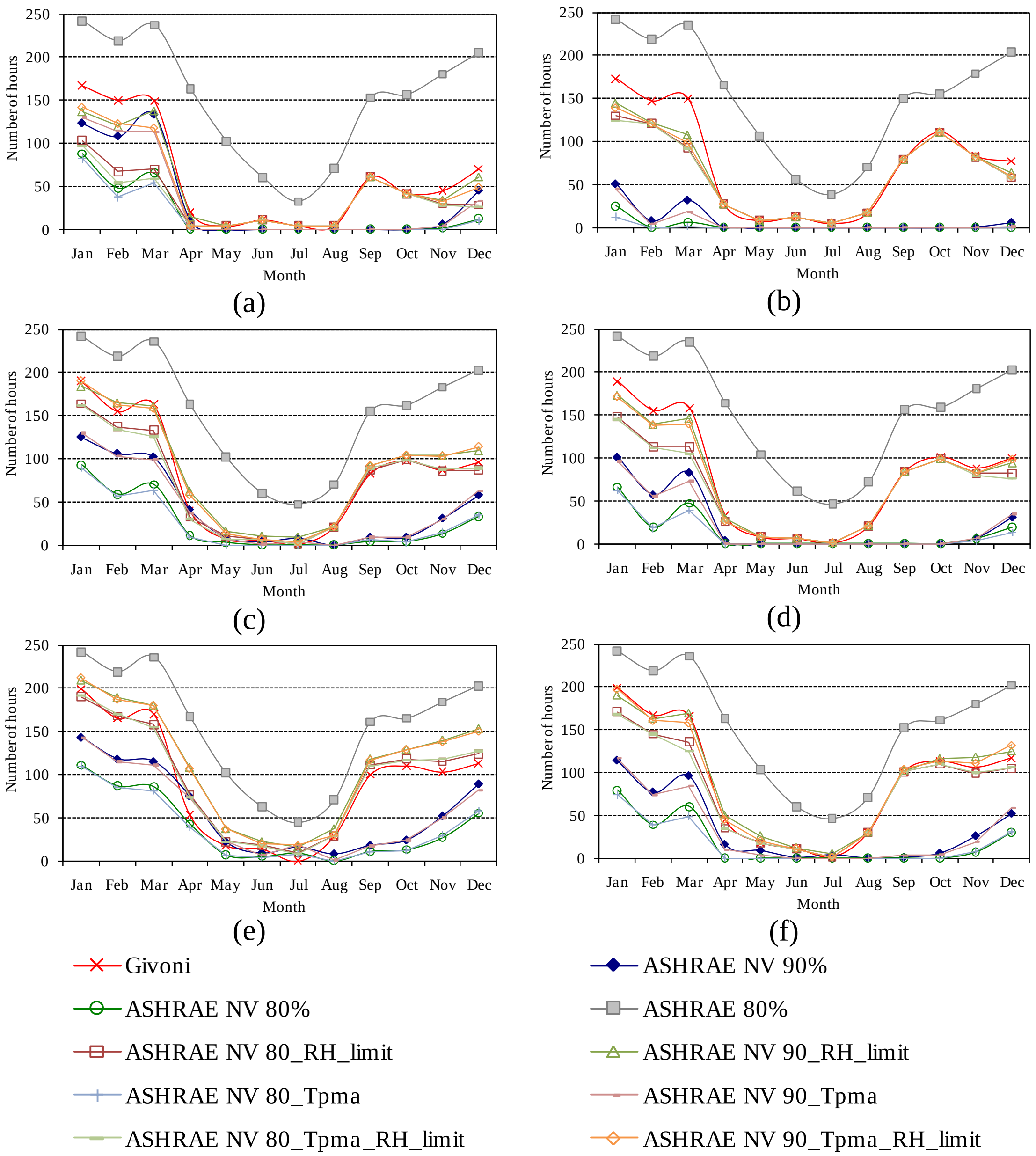


Figure 8. Number of hours of heat discomfort for the model with single-sided ventilation, geometry of 2:1, room index equal to 0.8, west and south orientations and window areas of 10, 50 and 100%. (a) West orientation, 10% of window area; (b) South orientation, 10% of window area; (c) West orientation, 50% of window area; (d) South orientation, 50% of window area; (e) West orientation, 100% of window area; (f) South orientation, 100% of window area.

Comparing the monthly number of hours of heat discomfort with the pattern of air-conditioning use in Florianópolis (Fig. 7) some statements may be pointed out: (a) the trends obtained for the method of ASHRAE 55 for occupied spaces are different from the pattern of air-conditioning use in Florianópolis during winter (June to August); (b) the trends obtained for the other methods are similar to the pattern of air-conditioning use in Florianópolis (with some exceptions among the methods); (c) the number of hours obtained for the method of ASHRAE 55 for naturally ventilated spaces (90% of acceptability) and Givoni were similar; even for models with cross-ventilation; (d) the number of hours obtained for the method of ASHRAE 55 for naturally ventilated spaces using the outdoor mean monthly temperature and the prevailing mean temperature are similar with each other, with the first leading to slightly greater number of hours.

The number of hours of heat discomfort along the year was also obtained for all models, for each method to assess thermal comfort, with single-sided ventilation (Table 4) and cross-ventilation (Table 5). In general, the number of hours is greater for models with room index equal to 5.0 than for room index equal to 0.8. As for Givoni's and ASHRAE 55 for naturally ventilated spaces (with the proposal humidity limit) methods, the opposite trend was observed in some situations. Another factor is that the increase of window area increases the internal thermal load of the room. Thus, the awaited trend is that there would be a greater number of hours of air-conditioning use (more hours of heat discomfort). However, for some cases in the method of ASHRAE 55 for naturally ventilated spaces (original publication) this trend was observed, but for other cases the opposite pattern occurred (the number of hours decreased).

The increase in the window area did not significantly affect the number of hours of heat discomfort for the method of ASHRAE 55 for occupied spaces. Furthermore, the number of hours per year obtained from the method of ASHRAE 55 for occupied spaces is much greater than the other methods, for all cases. This fact is due to the narrow limits established by this standard, to guarantee thermal comfort. Even in winter (June to August), due to high humidity, typical in Florianópolis, there would be a significant use of air-conditioning for cooling. This trend was the same for all models studied in this work. Thus, this method was considered not suitable to be applied to environments with high humidity and for the mixed-mode ventilation strategy studied in this paper.

The smallest number of hours were obtained for the method of ASHRAE 55 for naturally ventilated spaces (80% of acceptability, both with the outdoor mean monthly temperature and the prevailing mean temperature), followed by the same method with 90% of acceptability. By this method, in December, the number of hours of air-conditioning use was close to zero. Thus, the method of ASHRAE 55 for naturally ventilated spaces (80% and 90% of acceptability, both with the outdoor mean monthly temperature and the prevailing mean temperature) did not prove suitable for use in the climate of Florianópolis.

As a result, the methods of Givoni and ASHRAE 55 for naturally ventilated spaces with the proposal of humidity threshold remained to be assessed in detail. These methods showed a behaviour that met the pattern of use of air-conditioning in Florianópolis and are rather similar to each other. The following section will show another analysis to help choosing the method of thermal comfort for use in mixed-mode office buildings.

Table 4. Number of hours of use of air-conditioning throughout the year for each method to assess thermal comfort - interior door closed (single-sided ventilation).

Method	Comfort threshold based in	Window area	Geometry							
			1:2				2:1			
			K=0.8		K=5.0		K=0.8		K=5.0	
			West	South	West	South	West	South	West	South
			Number of hours with interior door closed							
ASHRAE NV 90%	Prevailing mean outdoor air temperature; Proposal of relative humidity threshold	10%	761	481	844	625	593	758	2062	543
		50%	798	726	793	625	1027	874	784	623
		100%	1068	917	769	651	1325	1085	970	792
ASHRAE NV 80%	Prevailing mean outdoor air temperature; Proposal of relative humidity threshold	10%	440	393	456	310	393	736	1519	432
		50%	625	611	436	330	851	762	516	437
		100%	877	811	533	490	1139	949	734	659
ASHRAE NV 90%	Prevailing mean outdoor air temperature	10%	735	165	804	564	394	68	2059	186
		50%	385	227	745	554	490	266	562	359
		100%	496	269	479	311	663	373	540	314
ASHRAE NV 80%	Prevailing mean outdoor air temperature	10%	405	35	413	242	183	13	1515	50
		50%	193	83	388	256	277	135	292	166
		100%	266	140	235	140	444	201	284	165
ASHRAE NV 90%	Outdoor mean monthly air temperature; Proposal of relative humidity threshold	10%	768	526	878	661	629	780	2053	584
		50%	825	744	819	669	1037	884	817	674
		100%	1075	929	799	689	1338	1106	983	827
ASHRAE NV 80%	Outdoor mean monthly air temperature; Proposal of relative humidity threshold	10%	475	417	495	367	427	743	1563	458
		50%	650	635	466	376	863	783	542	478
		100%	892	827	554	522	1139	961	763	677
ASHRAE NV 90%	Outdoor mean monthly air temperature	10%	741	217	839	600	425	98	2051	229
		50%	421	249	772	600	502	283	596	409
		100%	510	288	514	352	689	402	565	352
ASHRAE NV 80%	Outdoor mean monthly air temperature	10%	439	64	455	302	215	31	1559	81
		50%	219	108	418	302	290	157	318	207
		100%	283	158	257	171	454	215	315	182
ASHRAE 80%	Indoor operative temperature; Absolute humidity	10%	1840	1842	1863	1854	1820	1819	2093	1841
		50%	1840	1846	1851	1850	1842	1842	1848	1843
		100%	1842	1841	1844	1837	1858	1835	1845	1839
GIVONI	Indoor air temperature; Relative humidity	10%	782	683	809	743	727	890	1440	755
		50%	830	840	747	709	947	944	765	763
		100%	973	986	793	790	1074	1074	886	879

Table 5. Number of hours of use of air-conditioning throughout the year for each method to assess thermal comfort - interior door opened (cross-ventilation).

Method	Comfort threshold based in	Window area	Geometry							
			1:2				2:1			
			K=0.8		K=5.0		K=0.8		K=5.0	
			West	South	West	South	West	South	West	South
			Number of hours with interior door opened							
ASHRAE NV 90%	Prevailing mean outdoor air temperature; Proposal of relative humidity threshold	10%	529	660	822	539	724	894	1389	558
		50%	892	884	763	565	1070	963	808	612
		100%	1099	979	781	643	1321	1106	967	798
ASHRAE NV 80%	Prevailing mean outdoor air temperature; Proposal of relative humidity threshold	10%	419	635	434	279	636	877	917	452
		50%	781	799	435	319	908	874	528	439
		100%	915	873	542	496	1133	962	728	667
ASHRAE NV 90%	Prevailing mean outdoor air temperature	10%	173	62	780	461	150	51	1382	181
		50%	270	155	709	479	415	214	578	345
		100%	452	240	490	300	652	369	546	314
ASHRAE NV 80%	Prevailing mean outdoor air temperature	10%	41	1	389	197	49	4	907	54
		50%	135	49	381	227	224	107	293	166
		100%	234	111	243	143	431	193	286	168
ASHRAE NV 90%	Outdoor mean monthly air temperature; Proposal of relative humidity threshold	10%	575	684	852	584	753	909	1408	591
		50%	916	909	807	619	1076	982	833	662
		100%	1094	991	808	693	1332	1115	981	837
ASHRAE NV 80%	Outdoor mean monthly air temperature; Proposal of relative humidity threshold	10%	440	642	477	323	654	886	947	476
		50%	794	815	458	358	922	898	564	468
		100%	934	903	562	528	1137	975	757	686
ASHRAE NV 90%	Outdoor mean monthly air temperature	10%	228	98	812	506	185	73	1401	215
		50%	298	183	753	533	433	241	603	397
		100%	454	258	520	351	677	390	570	358
ASHRAE NV 80%	Outdoor mean monthly air temperature	10%	66	17	434	242	66	21	937	80
		50%	149	67	404	266	237	130	330	195
		100%	256	143	263	175	443	208	318	186
ASHRAE 80%	Indoor operative temperature; Absolute humidity	10%	1836	1832	1849	1846	1826	1821	1892	1842
		50%	1839	1831	1846	1849	1843	1833	1845	1845
		100%	1841	1835	1845	1843	1857	1827	1845	1838
GIVONI	Indoor air temperature; Relative humidity	10%	699	800	808	687	866	1006	1086	761
		50%	941	999	729	671	1011	1044	778	752
		100%	1017	1042	799	791	1075	1083	884	891

3.3 Correlations between the number of hours of heat discomfort of the predominant typology of mixed-mode buildings and the calculated number of hours

The number of hours of air-conditioning use obtained from the three methods was also correlated with the number of hours of the predominant typology of office buildings located in Florianópolis, calculated using the EnergyPlus file of Santana (2006).

Fig. 9 shows the correlations for the models with single-sided ventilation, geometry of 2:1, room index equal to 0.8, west and south orientations and window areas of 10, 50 and 100%. Fig. 9 also contains the bisector. Based on such graphs, it was verified which method had results below (the method could be considered adequate) or above (the method is considered not adequate) the bisector.

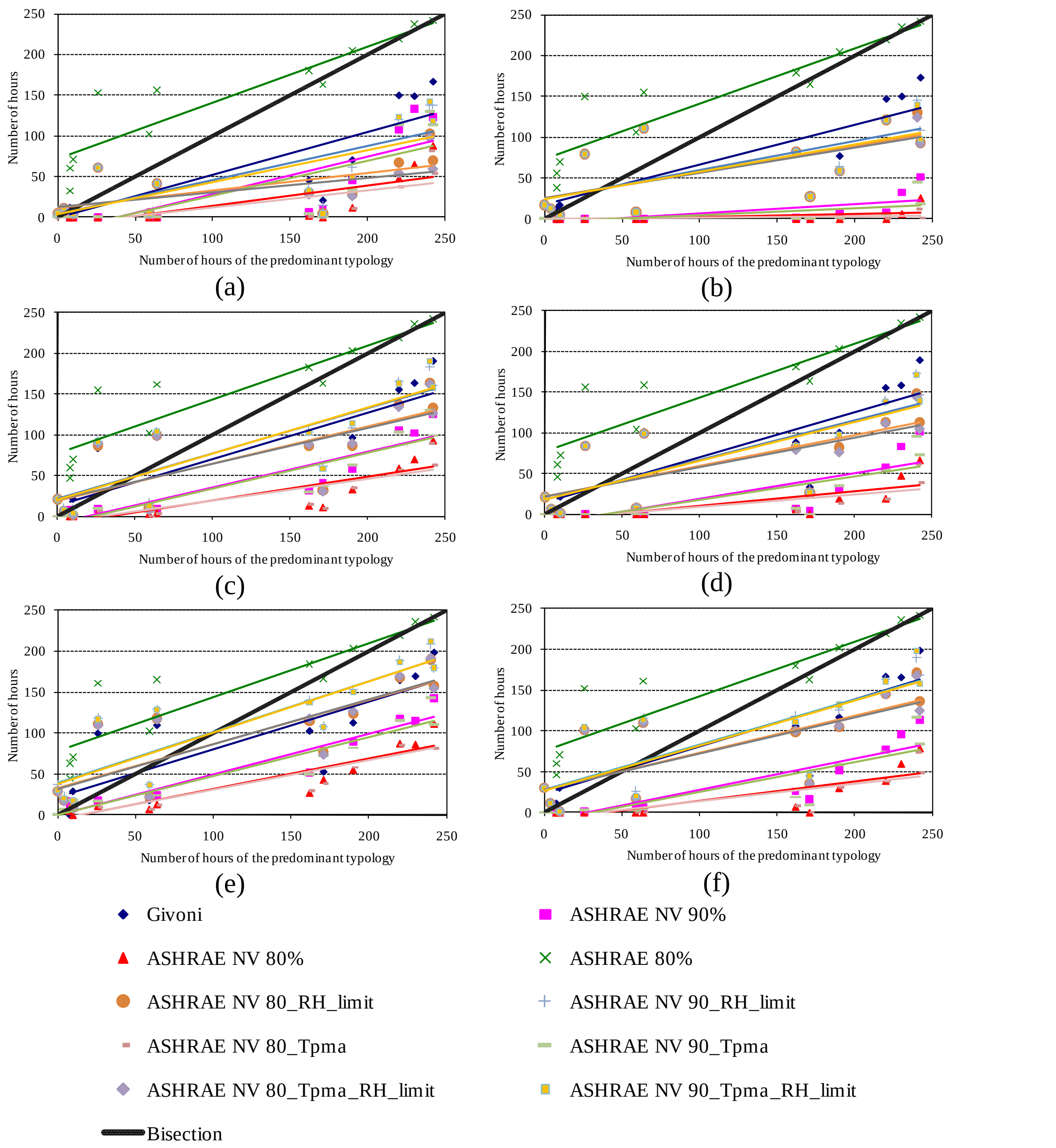


Figure 9. Correlation between number of hours of use of air-conditioning and the number of hours of use of air-conditioning estimated from the predominant typology of mixed-mode office buildings for the model with single-sided ventilation, geometry of 2:1, room index equal to 0.8, west and south orientations and window areas of 10, 50 and 100%. (a) West orientation, 10% of window area; (b) South orientation, 10% of window area; (c) West orientation, 50% of window area; (d) South orientation, 50% of window area; (e) West orientation, 100% of window area; (f) South orientation, 100% of window area.

The ASHRAE 55 method for naturally ventilated spaces (both 90% and 80% of acceptability, with the outdoor mean monthly temperature and the prevailing mean temperature) and the ASHRAE 55 method for occupied spaces were the ones with results more distant to the bisector in all cases. Thus, for the ASHRAE 55 method for naturally ventilated spaces (both 90% and 80% of acceptability, with the outdoor mean monthly temperature and the prevailing mean temperature), the straight lines always showed lower values than the values of the bisector, while for ASHRAE 55 method for occupied spaces, the straight lines always showed higher or equal values than those of the bisector.

In general, Givoni's method and the ASHRAE 55 90% of acceptability method for naturally ventilated spaces (both with the outdoor mean monthly temperature and the prevailing mean temperature, with the proposal of relative humidity limit) were the ones with results closer and below to the bisector for all cases with either single-sided ventilation or cross-ventilation. Such methods also presented the most consistent number of hours of heat discomfort compared to the pattern of air-conditioning use in Florianópolis. Therefore, these methods were considered the most appropriates to be used in climates similar to the one observed in Florianópolis, i.e., hot and humid summer climate.

4 Conclusions

This research provides a way to choose a method of thermal comfort for mixed-mode office buildings that could be used where subjective assessment of thermal comfort is not available. Furthermore, given that there is not a specific method to assess thermal comfort in mixed-mode office buildings, this work was carried out to help choosing a method of thermal comfort for such buildings located in hot and humid summer climates.

It can be concluded that the ASHRAE 55 method for occupied spaces is not suitable for application in mixed-mode office buildings located in hot and humid summer climates like observed in Florianópolis, due to the narrow humidity limits set by this standard to guarantee thermal comfort. These limits led to a significant and unrealistic use of air-conditioning for cooling in winter months. The ASHRAE 55 method for naturally ventilated spaces (both using the outdoor mean monthly temperature or the prevailing mean temperature) led to very low use of air-conditioning in December (summer), which is not consistent with the pattern of air-conditioning use observed in Florianópolis.

No big differences were found between the ASHRAE 55 method for naturally ventilated spaces using the outdoor mean monthly air temperature or the outdoor prevailing mean air temperature, when related to hours of heat discomfort. Nevertheless, the outdoor mean monthly air temperature showed a slightly greater number of hours.

Correlations between the number of hours of air-conditioning use obtained from the simulations and from the predominant typology of office buildings located in Florianópolis were performed for each method to assess thermal comfort. By comparing these correlations, it was concluded that the most suitable methods for use in hot and humid summer climates were the method of Givoni and the method of ASHRAE 55 with 90% of acceptability for naturally ventilated spaces (both with the outdoor mean monthly temperature and the prevailing mean temperature, with the proposal of relative humidity limit of 80%).

The results presented herein do not disprove the conclusions of our previous work (Rupp and Ghisi, 2014). In that paper, it was pointed out that the method of Givoni was the most suitable to be used in mixed-mode office buildings in the studied climate. In that paper we just considered the methods in their original publications. When proposing a relative humidity limit, the method of ASHRAE 55 with 90% of acceptability for naturally ventilated spaces (both with the outdoor mean monthly temperature and the prevailing mean temperature) also could be considered suitable.

In the next step we will carry out a field research on thermal comfort to compare the results with the simulated ones.

Acknowledgements
Ricardo F. Rupp would like to thank CAPES – *Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*, an agency of the Brazilian Government for post-graduate education, for the scholarship that allowed him to carry out this research. The authors also want to thank Marina V. Santana for supplying specific information about her research.

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