Thermal Analysis of a Naturally Ventilated Building an Adaptive Comfort Algorithm:

A case study of Miele corporate headquarters, Johannesburg, Gauteng

C G JOUBERT[1]

[1]Tshwane University of Technology, Pretoria, Republic of South Africa

ABSTRACT: This paper is a follow-up to a paper submitted to the PLEA 2006 conference which described the setting up of a monitoring program to identify and quantify the most significant problems relating to occupant discomfort encountered in a commercial building in Johannesburg, South Africa. It discussed the rationale behind the program and describes some of the problems encountered. The monitoring has been completed and the data analysed. The actual performance of the building is compared to the comfort standard generated by the adaptive comfort algorithm as contained in ASHRAE RP884. The building is a corporate headquarters completed approximately four years ago. The building consists of three distinct zones, these being firstly the administration offices, secondly a showroom and thirdly workshop and spares store. The building was conceived as a passively cooled and ventilated building.
Keywords: Monitoring, thermal comfort, passive design, adaptive comfort, post occupancy evaluation.

INTRODUCTION

The South African corporate headquarters of the international Miele Kitchen appliance group completed in 2004 is a naturally ventilated building. Its design departs from the current mainstream philosophy of commercial architecture. The building consists of three different functional areas. The showroom is the most important feature and is a double volume, column free space. The offices and administrative services are located in a double storey structure which overlooks the showroom. The spares store and workshop is attached to the showroom and separated by a wall which has limited connection with the showroom by means of doors.

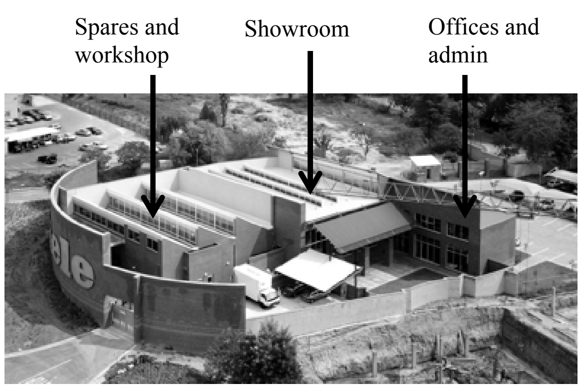

Figure 1: Aerial view showing the three functional zones

After completion, staff complained about the levels of thermal comfort experienced. These complaints were that the building was too hot in summer and too cold in winter. It is anticipated that some complaints are rooted in the expectation that air-conditioning is simply expected in a building of this nature.

An opportunity arose that allowed long term monitoring of the building. Being able to apply a thermal comfort standard to this building is significant as it provides an opportunity to evaluate, identify and quantify perceived shortcomings.

SELECTION OF A COMFORT STANDARD

Szokolay notes that, at least 30 different comfort indices have been produced by different researchers over the years all based on different studies and with different names (2004: 21). These can be grouped into two categories termed *Adaptive models* and *Static models*.

Static models can be divided into empirical and analytical models. They define comfort and its limits. Analytical indices are based on human heat transfer observations and calculations. They are premised on the deterministic logic of the heat balance equation:

Physics → physiology → comfort or discomfort

Whilst these models are based on extensive laboratory experiments and yield consistent and reproducible results, researchers are questioning whether the simplistic cause-and-effect can be applied to real world thermal perceptions (Brager and de Dear, 1998: 84).

Criticisms of the analytical models are:

- Inherent complexity and difficulty in performing calculations.
- Difficulty in estimating the variables of clo values and met rates (Brager and de Dear, 1998: 84)
- They were established with young and fit American and European subjects and do not take into account cultural, ethnic and behavioural differences and do not agree with real world observations and findings (Brager and de Dear, 1998: 85)
- They ignore adaptive opportunity and responses to thermal comfort (Nicol and Humphreys, 2002: 51).
- A larger range in the thermal comfort zone would save energy and promote sustainability of the built environment.

Adaptive comfort theory hypothesises that contextual factors and past thermal history are modifiers of building occupiers thermal expectations and preferences. Adaptive indices are premised on the rationale that people are tolerant of a much wider range of thermal sensations and that these are influenced by more than physiological factors alone. People are also active participants in their perception of thermal comfort.

BRIEF HISTORY

As early as 1975 Humphreys had uncovered a strong statistical dependence of thermal neutrality on the average air or globe temperature recorded inside buildings (Brager and de Dear, 1998: 89) and offered a comfort index based on adaptive comfort theory. It appeared that the linear regression model provided the best regression and Humphreys offered the following algorithm for NV buildings in 1978 (Szokolay, 2004: 20).

Since then, several researchers have reviewed this or similar data and proposed modifications to this algorithm. The algorithms have commonalities in that they are all linear functions, they all have a constant and they all have a variable linking the outdoor temperature to adaptive thermal neutrality.

In 1997 ASHRAE commissioned a very large study which culminated in the ASHRAE RP884 report. This study proposed the following algorithm:

Tcomf = 0.31 x Ta,out + 17.8 (deg C)…… (De Dear and Brager)

Where
Tcomf is thermal comfort
Ta,out is mean outdoor dry bulb temperature

Suitability for South African conditions The question arises as to which of these is the most suitable for use in South Africa. A recent comparison and evaluation was published by Holm and Engelbrecht (2005: 12). They compared two commonly used algorithms. These are where Tn is usually calculated by using either ET* or DBT as the input for the equations. They make the recommendation that the following algorithm TnDBT be used in the Adaptive Comfort Standard algorithm for South African climatic conditions

TnDBT = 17,6°C + 0,31 x To.ave

This algorithm is used as the standard for the determination of comfort levels in the case study

They base it on the following arguments:

- There is general access to DBT and the effort to calculate TnDBT is much less than that required to calculate TnET*.
- DBT is in general use and easily understood by the general public while ET* is only accessible to specialists.
- The difference between the effect of outdoor ET* and DBT is negligible within the recommended comfort range of 17,8°C to 29,5°C
- The degree of accuracy in achieving design temperatures in the real world context of South Africa’s naturally ventilated buildings does not justify the additional work in using ET* instead of commonly understood DBT temperature units.
- ET* and DBT calculations are both valid up to an altitude of 3000m above mean sea level. The majority of the South African population fall within these altitudes. The Miele Headquarters is located in Johannesburg at 1694m above mean sea level.
- The input data to the calculation consist of interpolations which introduce a level of inaccuracy.

MONITORING PROCESS AND DATA ACQUISITION

Administrative offices In the office areas, use was made of self contained loggers mounted at approximately 1700mm high. These were simply attached to mullions of the partitions between offices using double sided adhesive tape.

On both the ground and 1st floor the locations selected were situated at the extreme ends of the building and in a middle position.

Showroom The showroom was monitored in the form of a grid pattern both on plan and in section. The thermometers were placed on the same horizontal plane and suspended from the trusses above. The thermometers / thermocouples were mounted on steel chains, the mass of which ensured that the thermometers were suspended in a straight line.

WORKSHOP AND STORE

The workshops’ and stores’ areas are not open to the public and Miele management accepted an installation where the wiring and thermometers were fixed to PVC electrical conduits for support. As in the showroom the thermometers were placed on the same horizontal plane and formed a grid pattern both on plan and in section.

The thermocouples were placed at three different positions on each chain. In both the showroom and the workshops the heights were:

A low position (300mm from the floor)
A middle position (approx. 3850 from the floor)
A high position (approx. 8000mm from the floor and placed in the middle of the fixed louvre grille above the windows).

EXTERIOR DATA – WEATHER STATION

All external temperatures were obtained from a Davis Vantage Pro-2 weather station. It was decided to mount the weather station to the North of the building as the vegetation and buildings on the Northern and western side of the building would have a significant effect on the microclimate.

BIAS

The fact that measurement of the temperatures are not random samples, but are essentially planar (both in the horizontal and vertical planes) and therefore stratified, probably does introduce some form of bias into the design. The requirement of management that the equipment could not detract from the building, dictated to some degree the positioning of the temperature sensors.

Further factors that were considered in the design of the layout were:

- Possible radiation from lighting
- Draughts or wind currents
- Radiation from windows close to sensors.

The values used for determining the mean temperature are interpolations of values from different heights and are the means of values from different positions. Thus the combined effect does tend to ameliorate bias.

POPULATION, SAMPLING AND SAMPLING RATE

The statistical population of measurable temperature is theoretically infinite for both outdoor and indoor conditions. A large enough sample had to be gathered to allow for reasonable inference of the indoor conditions relative to changing weather over a reasonable period of time. The approach used was to consider how rapidly the exterior and interior temperatures of a building may possibly react to changes in weather. For outdoor changes it was decided that, due to weather conditions being able to change rapidly, the smallest practical interval or sampling rate was 30 minutes.

Building interiors do not normally react to variations in temperature as rapidly as outdoor conditions due to a combination of thermal capacitive (thermal mass), infiltration and resistive insulation.

ANALYSIS OF THE THERMAL RESPONSE OF THE BUILDING – ADAPTIVE COMFORT ALGORITHM

The building's response to the Adaptive Comfort Algorithm is discussed separately under headings that represent the three functional areas that make up the building. These are:

- Administration block
- Showroom
- Workshop and parts store

All data were treated in the same way. Daily mean temperatures were calculated by obtaining $\overline{T}$ using all available data. Most of the data were acquired by using a frequent interval of 15min (only the weather station was set at an interval of 30min) and it was considered that there was a large enough sample to negate the effects of outlier values. The mean monthly temperature was calculated by obtaining the mean of the daily temperatures for the particular month.

LEVEL OF ACCEPTABILITY

As the Miele building is a corporate headquarters and the level of accommodation is synonymous with "A" grade office space, it was decided to use the 90% level of acceptability. This corresponds to a PMV of ±0,5. The daily swing or variances from TnDBT is thus TnDBT ±2,5K.

Overheating and overcooling For this study the number of Kelvin-days of overheating and overcooling was calculated from a variable base. This variable base was determined from the TnDBT for any given day. The actual interior temperature was then compared to TnDBT and the difference was expressed as the number of degrees of either heating or cooling required to affect thermal comfort (that is TnDBT). This is referred to as "Kelvin-days" in this document.

General description of the construction The floor is a concrete surface bed which is in direct contact with the ground. In the showroom and workshop areas the surface bed is neither carpeted nor tiled and provides for some thermal mass. In the office areas the concrete floor is covered with a thin carpet.

- The western wall is perforated by only one double door which is well protected from western sun. The eastern wall has large windows which are fixed glazed and have no operable sections
- The roof structure consists of exposed steel trusses which support a sheet steel roof and the ceiling consists of rigid insulated ceiling boards

- The roof has roof lights which face south. These are equipped with fixed aluminium louvres
- Ventilation is only possible by means of air that can enter the building via the administration block or from the occasional opening of the entry or the doors to the workshop and stores area
- The showroom and workshop area have a large volume compared to surface area of the envelope.

ANALYSIS OF THE THERMAL RESPONSE OF THE BUILDING – ADAPTIVE COMFORT ALGORITHM

Each of the three functional areas are, for most purposes, thermally discreet and exhibit an identifiable thermal response. It was decided to separate the data to illustrate the thermal response of the three zones of the building.

Administration block – analysis As illustrated by the drawings, the offices that house administrative functions form a unit that is, for most purposes, thermally discreet and exhibits an identifiable thermal response. It was decided to separate the data to illustrate the thermal response of the lower and upper floors individually for the following reasons:

Comparison of interior temperature to the adaptive comfort algorithm The following graph illustrates the response of the administration block by comparing the TnDBT to interior temperatures using the monthly means. This summarized view of the upper floor of the administration block is subjected to a marked degree of overcooling during the winter months. From approximately September to December 2005 both the upper and lower floors tended towards TnDBT.

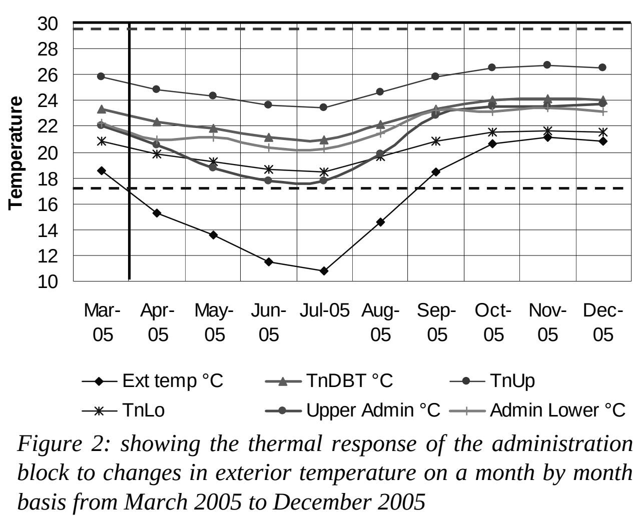

Figure 2: showing the thermal response of the administration block to changes in exterior temperature on a month by month basis from March 2005 to December 2005

Diurnal range in temperature The following table shows that on a considerable number of days the internal temperature swing exceeds the recommended 5K range. The number of occurrences tends to increase in the colder months of the year. This indicates a lack of thermal damping probably caused by a lack of envelope resistance. This is exacerbated by the inability to control the in- and ex-filtration of air.

Table 1: Maximum and minimum swings for the months reviewed.

Month	Monthly ave. swing	No days exceeding 5K swing
Mar 2005*	4,57	8
Apr	5,25	19
May	5,82	23
Jun	5,52	27
Jul	5,94	29
Aug	4,62	12
Sep	5,51	18
Oct	5,06	14
Nov	4,54	11
Dec *	3,89	2

* Partial month – recording of temperatures began on 12 March 2005 and ended on 20 Dec 2005

Quantification of overheating and over cooling The following tables quantify the amount of overheating and overcooling of the administration block of the period under review. The values were calculated over the full daily 24 hour period and not over the period that the building is occupied

Table 2: The table quantifies the extent of the overheating and overcooling expressed in Kelvin-days of the upper floor.

Upper floor – Administration (°days)

	K-D<Tn	K-D>Tn
Totals	**527.53**	**11.20**
Mar 05	25.86	0.00
Apr 05	68.82	0.00
May	94.13	0.00
Jun	101.58	0.00
Jul	97.92	0.00
Aug	70.64	0.00
Sep	18.64	2.88
Oct	19.87	5.05
Nov	20.62	1.15
Dec	9.45	2.13

Showroom – analysis The showroom is a unit that is connected to the workshop and stores area by three doors. It shares the passage of the administration block. It was decided to show its thermal response separately as it forms a functional unit on its own and has a unique thermal response.

Comparison of interior temperature to adaptive comfort algorithm Temperatures were measured from May 2005 to approximately November 2006. A full year of data were used for the determination of the thermal response of the building compared to the adaptive comfort algorithm. This was summarised for each month of the year and each day of the year under review.

The following graph illustrates the response of the showroom based on monthly temperatures.

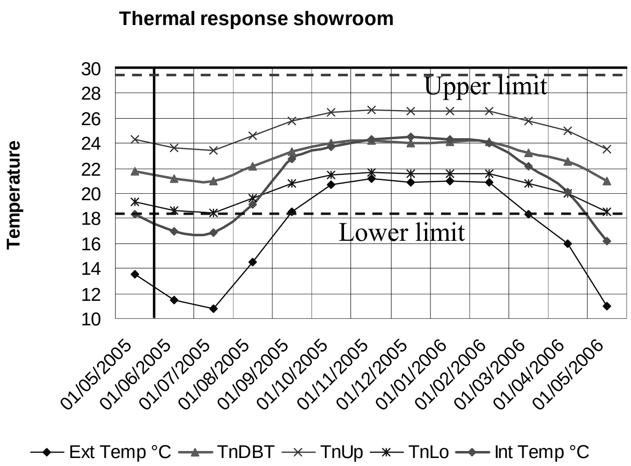

Figure 3: showing the thermal response of the showroom to changes in exterior temperature on a month by month basis from May 2005 to May 2006.

It can be noted that, from approximately the months of April to August, the showroom shows evidence of severe overcooling when the average indoor temperature is below both the lower limit of the range of acceptability for 90% of the population and the absolute lower limit of 17,8°C. For the rest of the year the showroom exhibits a tendency to be somewhat higher than TnDBT but average temperatures remain within the 90% band of acceptability.

Diurnal range in temperature The following table shows that on a considerable number of days the internal temperature swing exceeds the recommended 5K range whilst during some months the swing is almost double the 5K range (Refer to table 3). As with the administration block the number of occurrences tends to increase in the colder months of the year. The showroom has even less thermal capacity relating to the volume of the room as the effect is even more pronounced than in the administration block. Again the inability to control the in- and ex-filtration of air is considered to worsen the thermal swing.

Quantification of overheating and overcooling The following table quantifies the amount of overheating and overcooling of the showroom for the period under review. The values were calculated over the full daily 24 hour period and not over the period that the building is occupied (Refer to table 4).

Table 3: The maximum and minimum swings of the Showroom for the months reviewed.

Month	Monthly ave. swing	No days exceeding 5K swing
May 2005*	5,77	19
Jun	5,82	22
Jul	6,34	26
Aug	5,38	20
Sep	6,57	23
Oct	6,09	23
Nov	5,76	21
Dec	5,67	23
Jan 2006	3,92	3
Feb	3,89	5
Mar	4,07	10
Apr	5,19	19
May	5,95	23

* Partial month – recording of temperatures began on 6 May 2005

Table 4: The table quantifies the extent of the overheating and overcooling of the Showroom expressed in Kelvin-days

	Showroom	
	DD<Tn	**DD>Tn**
Totals	**641.99**	**47.29**
May 05	89.80	0.00
Jun 05	124.61	0.00
Jul 05	125.35	0.00
Aug 05	91.65	0.00
Sep 05	38.64	1.02
Oct 05	20.30	3.33
Nov 05	9.37	12.42
Dec 05	1.71	14.40
Jan 06	3.54	10.03
Feb 06	7.01	6.09
Mar 06	37.49	0.15
Apr 06	73.70	0.00
May 06	18.82	0.00

Stores and workshop – analysis The stores and workshop is a unit that is connected to the showroom area by three doors. It was decided to show its thermal response separately as it forms a functional unit on its own and has a unique thermal response.

Comparison of exterior temperature to adaptive comfort algorithm Temperatures were measured from May 2005 to approximately November 2006. A full year of data (May 2005 – May 2006) was used for the determination of the thermal response of this part of the building compared to the adaptive comfort algorithm. This was summarised for each month of the year and each day of the year under review.

The following graph (Fig 4) illustrates the response of the stores and workshop based on monthly temperatures.

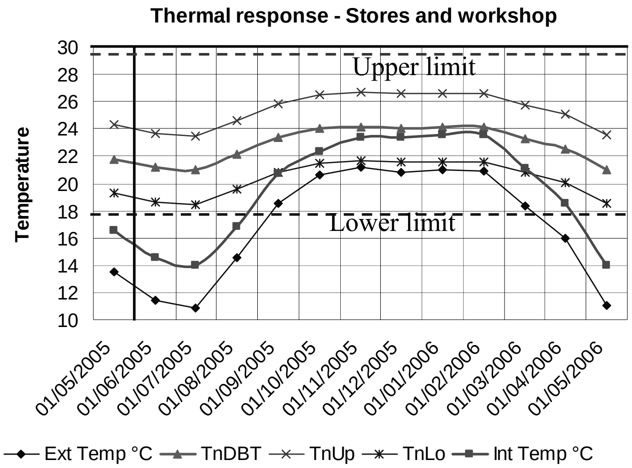

Figure 4: showing the thermal response of the stores and workshop to changes in exterior temperature on a month by month basis from May 2005 to May 2006.

It can be noted that, from approximately late March to September, the stores and workshop show evidence of severe overcooling when the average indoor temperature is below both the lower limit of the range of acceptability for 90% of the population and the absolute lower limit of 17,8°C. For the rest of the year the stores and workshop are within the 90% band of acceptability and from November to mid March the mean approximately coincides with TnDBT.

Diurnal range in temperature The following table shows that, on a considerable number of days, the internal temperature swing exceeds the recommended 5k range whilst during some months the swing is almost double the 5k range. As with the administration block and the showroom, the number of occurrences tends to increase in the colder months of the year. The overall number of days that the 5K range is exceeded is highest in this area.

Table 5: Maximum and minimum swings for the months reviewed for the stores and workshop.

Month	Monthly ave. swing	No days exceeding 5K swing
May 2005*	5.88	18
Jun	5,84	21
Jul	6,27	22
Aug	5,50	21
Sep	7,15	29
Oct	6,70	26
Nov	5,90	23
Dec	6,05	25
Jan 2006	4,24	9
Feb	3,87	10
Mar	4,23	11
Apr	4,71	17
May	5,74	22

* Partial month – recording of temperatures began on 6 May 2005

Table 6: quantifies the extent of the overheating and over-cooling of the Stores and workshop expressed in Kelvin-days

	Stores and workshop	
	DD<Tn	**DD>Tn**
Totals	**1149.38**	**438.99**
May 05	135.87	70.87
Jun 05	197.68	122.68
Jul 05	216.53	139.03
Aug 05	163.20	85.70
Sep 05	76.87	13.55
Oct 05	53.37	6.09
Nov 05	28.09	1.06
Dec 05	23.72	0.00
Jan 06	18.61	0.00
Feb 06	16.84	0.00
Mar 06	70.20	8.67
Apr 06	120.50	45.91
May 06	27.91	15.41

SUMMARY AND CONCLUSIONS

Various strategies can be used to obtain a satisfactory thermal response for a naturally ventilated building in this particular climatic zone. The building envelope is fundamental in obtaining satisfactory thermal performance. The product of envelope resistance and thermal capacity should be high whilst lower resistance can be countered by higher thermal capacity and vice versa. It is evident that the Miele building reacts rapidly to changes in the external environment. This indicates a lack of thermal mass and a lack of control over air in- and ex-filtration. When the Adaptive Comfort Algorithm is applied it can be noted that the degree of overcooling is most pronounced in the stores and workshop area. The internal diurnal range in temperature is greater than a reasonable range of 5K for most months of the year. This would contribute significantly to feelings of thermal discomfort.

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