USING COMFORT CRITERIA AND PARAMETRIC ANALYSIS TO DRIVE PASSIVE BUILDING DESIGN

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ABSTRACT

We present a case study of the bioclimatic design of a passively-ventilated office building in a hot and humid region. A novel adaptive, locally-orientated comfort criterion, the UTCI, was used as a key metric. The design process was a hybrid of parametric assessment and manual design. Bioclimatic features assessed in this fashion cover massing, façade design and particularly shading configuration, where parametric analysis achieved a design that blocks 100% of direct solar gain. Post-occupancy evaluation was conducted to compare the actual conditions with the predictions.

INTRODUCTION

We present an application of a hybrid design approach that combines parametric analysis with manual design. Manual elements of the process included climate analysis, ventilation and massing studies. These areas are not particularly suitable for parametric analysis. Parametric design was applied to geometric studies, particularly concerning shading configuration. The design process was entirely comfort-driven.

The case study presented concerns a processing centre in Karnataka, India, with a gross internal floor area of 6,837m² and an occupancy of 1,000 staff. The brief called for a low-cost, low-carbon, comfortable working environment. This was achieved using an entirely passive conditioning system, which can maintain acceptable conditions in a tropical climate where temperatures can reach 40C. Investigation of the feasibility of a passively ventilated building which will have a lower carbon footprint and significantly cheaper capital and operating costs. This informed the specifications for the building form, internal loads, façades and ventilation design.

BACKGROUND

Bioclimatic design approaches

Bioclimatic design is concerned with the response of people (thermal comfort) to the climate in a particular location. This is clearly most applicable when air-conditioning is to be avoided, as was required for this project. This was primarily due to budget limitations: capital and running costs for HVAC systems are prohibitively high. It is also clear that by avoiding air conditioning, a much more environmentally-friendly design can be achieved; a direct comparison is made in a later section showing that a passive design uses around half the energy of a conditioned building.

In a non air-conditioned building, the indoor average temperature is typically higher than the average ambient temperature due to the combination of external conditions and internal heat gains. Bioclimatic design uses passive factors like building material, orientation, shading and landscaping can reduce the temperature elevation (external to internal) and at best achieve zero contrast or cooler internal temperatures.

It has been applied in a wide range of climates (Yang, Lam, and Liu 2005), including tropical (Sad de Assis and Barros Frota 1999), Mediterranean (Gaitani, Mihalakakou, and Santamouris 2007) and arid (Papparelli, Kurbán, and Cúnsulo 1996) regions.

Thermal mass plays a large role in bioclimatic design (Mingozzi, Bottiglioni, and Medola 2009). It is often applied to the design of urban areas (Sad de Assis and Barros Frota 1999) or outdoor spaces (Gaitani, Mihalakakou, and Santamouris 2007).

Building precedents

This building has reinterpreted the vernacular architecture of southern India, characterized by its warm-humid climate, making use of high pitched roofs, courtyards, wide overhangs, Jali (window screens) and verandas. The following precedents illustrate the nature of local building practices that have been employed here.

The IGP Office in Gulbarga, Karnataka, was the first naturally-ventilated LEED-rated building in India. This shows that naturally-ventilated buildings are a feasible option for the state of Karnataka. It makes use, among others, of cavity walls that provide a thermal break to insulate against outer heat; wind towers that rely on evaporative cooling to promote passive down-draught ventilation; maximization of daylight; "solar lights" for night-time illumination.

The Pearl Academy of Fashion is located in a typical desert-type climate. Hot, dry weather prevails and the need for shading and daylight is still present. This building deals with this through vernacular passive control methods such as courtyards, water bodies, step wells, and double-skin façade elements called jaalis (perforated stone screen). These provide the building with shading and allow air to flow between the outer and inner skins. The temperature is further decreased by drip channels, enhancing evaporative cooling. Sliver courts provide daylight and thermal regulation inside classrooms. The building is raised above the ground, allowing air to flow underneath and promoting evaporative cooling and connection to earth's thermal.

CLIMATE ANALYSIS

The climatic conditions used in the dynamic thermal modelling (DTM) contain more than twenty variables, but the most influential are external temperature, solar radiation, humidity, prevailing winds and precipitation. Key trends are discussed below, and shown graphically in Figure 1 and Figure 2. The weather data used was obtained from the Meteonorm program.

External temperatures

Shimoga has an equatorial desert climate characterised by reasonably constant hot temperatures and humid conditions. Peak temperatures regularly exceed 35ºC between March to May, before the monsoon rain cools the air. For the rest of the year temperatures are usually in the high 20s to low 30s. Figure 2 gives the hourly external temperatures over a year along with monthly statistics.

Solar gain

Solar gain to the internal environment is undesirable for offices that are in a hot ambient condition for most of the year due to high external temperatures and internal loads. Solar heating in the winter is not a concern. Initial parametric analysis of the 360º range of possible façade orientations determined the optimal solar massing. Figure 1 shows the peak incident solar gain on the spectrum of façade orientations, with the four building facades highlighted (note only north and south facades have high glazing ratios).

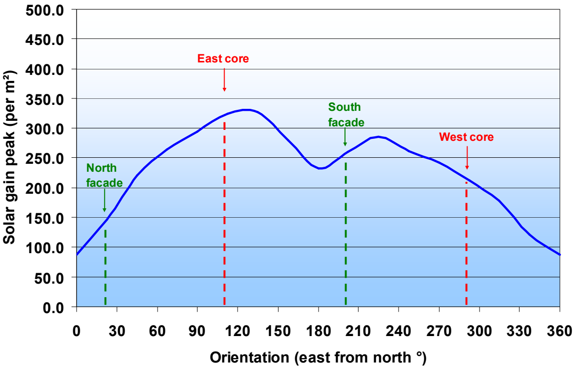


Figure 1: Solar gain by orientation.

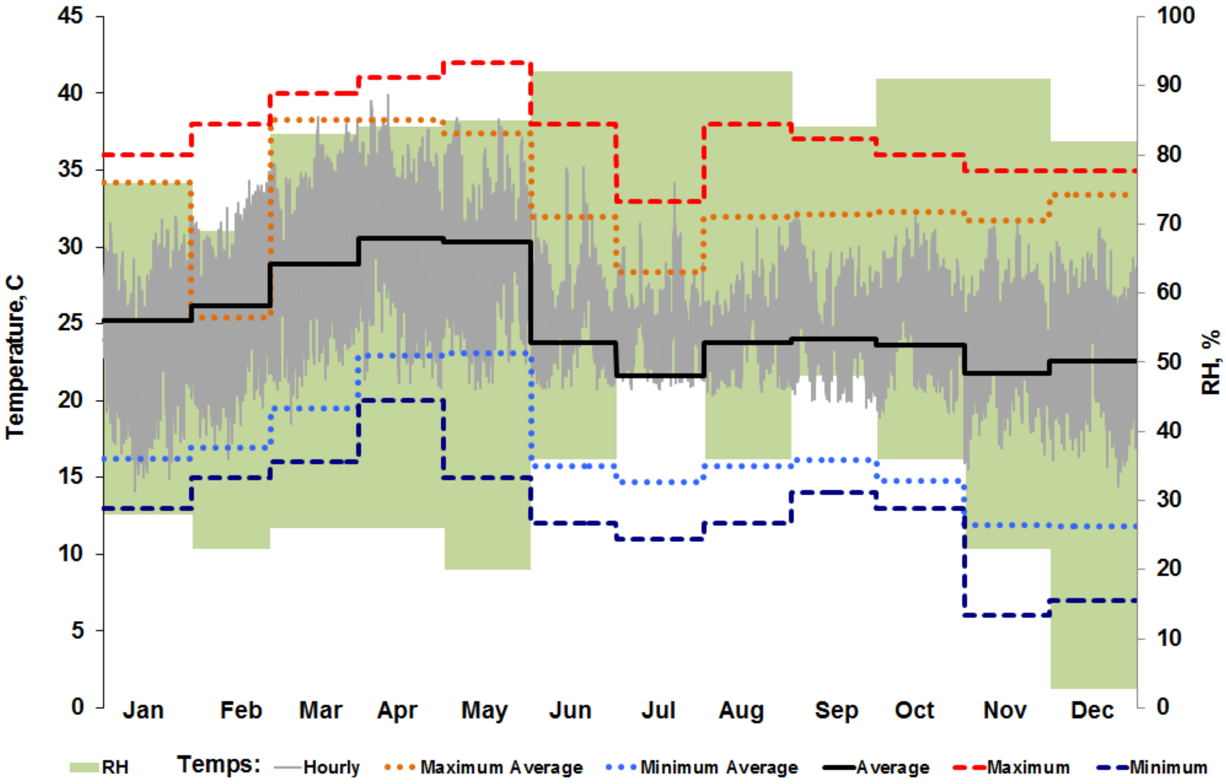


Figure 2: External temperatures

Humidity

Shimoga is classed as ‘tropical wet and dry’ under the Köppen climate classification system (Peel, Finlayson, and McMahon 2007). It is located on the boundary between regions that are wet (costal, to the west) and dry (inland, east). Relative humidity variations are out of phase with temperature variations, such that high humidity months have lower temperatures and vice versa (see Figure 2). This is beneficial in terms of comfort, but requires both factors to be taken into account to calculate an accurate comfort metric.

Prevailing winds

Shimoga, like much of India, is subject to seasonal wind reversal due to the Asiatic monsoon wind system. From late November to early March, north-easterly winds bring dry cool air; from June to August south-westerly wind brings monsoon rain.

Rainfall

Average annual precipitation for Shimoga is around 1,300mm, the majority occurring during the monsoon (June to October). However, rainfall can vary significantly from year-to-year depending on the quality of the monsoon.

COMFORT CRITERIA

The thermal comfort conditions within the building have to be satisfactory for the occupants. However, the conditions that occur will be highly correlated to the external climate due to the natural ventilation strategy. There are many ways of assessing the thermal comfort of building occupants (Blazejczyk et al. 2012). Figure 3 compares three comfort criteria for the Shimoga climate. The Fanger PMV model is the most commonly-used, but also the most narrowly defined. The CIBSE adaptive criteria includes information on past temperatures (hours and days) to account for adjustments in clothing etc. However, the only variable is air temperature. The Universal Thermal Comfort Index (UTCI) is explained in more detail in the next section.

Assessment of comfort based on western standards like PMV (often used globally by international architects and engineers) would have resulted in an air-conditioned building. For the purposes of this work, the UTCI metric was used with the bands of ‘no heat stress’ and ‘moderate heat stress’ deemed to be acceptable.

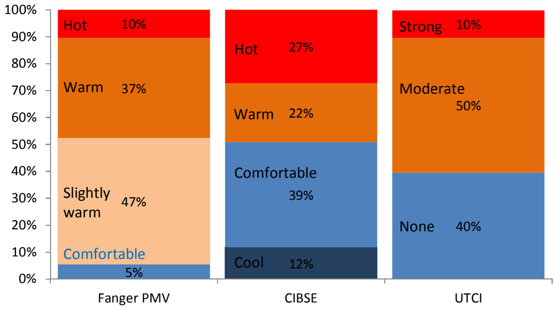


Figure 3: Comparison of comfort criteria.

Universal Thermal Comfort Index (UTCI)

The Universal Thermal Climate Index (UTCI) has been adopted for this study. This thermal comfort criterion is a recently developed, internationally accepted procedure for the assessment of human thermal comfort in any climate. The UTCI combines the key factors associated with human comfort (temperature, humidity, radiation, air speed) into one a single equivalent temperature (ET). The UTCI has been developed for external environments, but is equally applicable to naturally-ventilated internal spaces. The equivalent temperature is assessed against a scale derived from simulated physiological responses.

For the purposes of this study allaying to the extreme external conditions it has been determined that the design solutions implemented should aim to increase the frequency of time within the no thermal stress band and the moderate heat stress band.

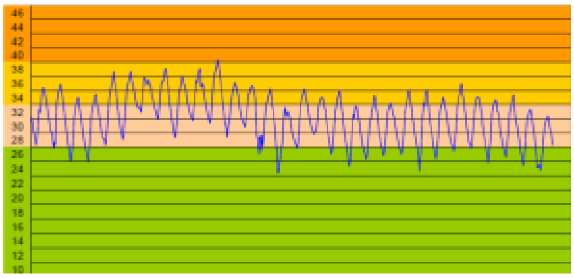


Figure 4: Summer week, UTCI. Bands show no heat stress (green), slight (pink), moderate (orange) and strong (orange) heat stress.

Improving UTCI through bioclimatic design

UTCI calculates the equivalent temperature from 4 key variables. Bioclimatic design features aiming to improve the performance of each of these variables are summarised below.

Ambient temperature

Ambient temperature will be correlated to the external climate, but buffering via the thermal mass of building, minimising internal heat gains and passive cooling from surrounding vegetation can reduce the temperature.

Mean radiant temperature

Greater control can be had over radiant temperatures through minimising solar gain by optimising shading.

Thermal mass also has a stabilizing effect on surface temperatures.

Wind speed

In hot and humid climates, high air flow increases evaporation from occupants' skin and reduces thermal stress. Passive ventilation design can assist this by channelling outdoor airflow through the building as effectively as possible. This is assisted by ceiling fans.

Humidity

Humidity is the most difficult parameter to improve via passive design. Form and façade have little effect. Water features can increase mosquito risk. The only effect available is vegetation transpiration and the associated local evaporative cooling effect.

PARAMETRIC STUDIES

Methodology

The key to parametric modelling is automation of geometry adjustment and analysis. In this manner many options can be rapidly assessed. For this work Excel VBA was used to script geometry creation; simulations were then conducted in bulk using the IES dynamic thermal modelling program. The parameters shown in Table 1 and Figure 5 were sequentially altered to produce a large array of different geometries, using a range of possible values agreed with the architect.

Table 1

Parameters of the parametric model

d1	Horizontal shading projection
d2	Vertical shading projection (per façade)
d3	Vertical shading offset from façade line
d4	Vertical shading offset from next shade
d5	Length of angled shading elements
d6	Glazing height
d7	Glazing width
d8	Glazing vertical offset
d9	Glazing horizontal offset
a1	Angle between adjoining shades
a2	Façade orientation

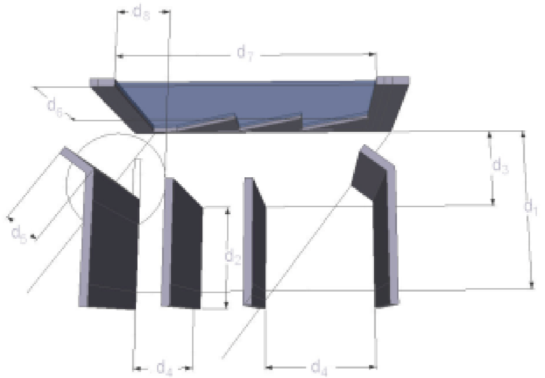
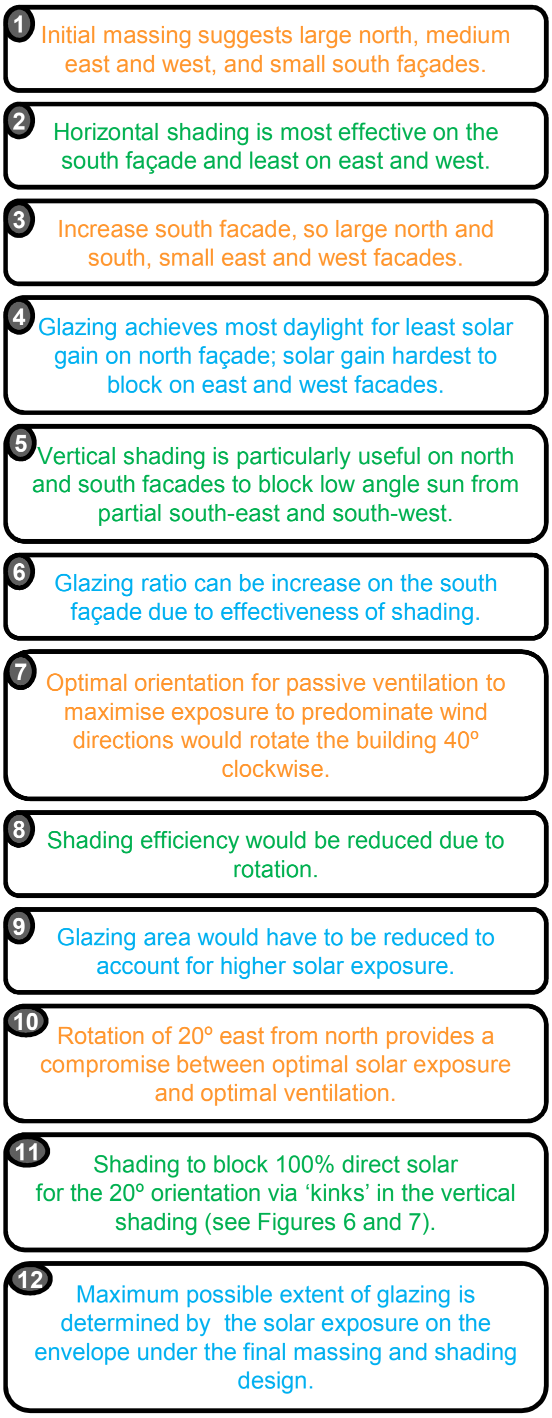


Figure 5: Parametric model.

The iterative process of addressing massing, façade design and shading configuration is given in Figure 6. The process is a hybrid between manual design (informed by existing approaches, climate analysis etc) and parametric analysis based on simulation.



1. Initial massing suggests large north, medium east and west, and small south façades.
2. Horizontal shading is most effective on the south façade and least on east and west.
3. Increase south facade, so large north and south, small east and west facades.
4. Glazing achieves most daylight for least solar gain on north façade; solar gain hardest to block on east and west facades.
5. Vertical shading is particularly useful on north and south facades to block low angle sun from partial south-east and south-west.
6. Glazing ratio can be increase on the south façade due to effectiveness of shading.
7. Optimal orientation for passive ventilation to maximise exposure to predominate wind directions would rotate the building 40° clockwise.
8. Shading efficiency would be reduced due to rotation.
9. Glazing area would have to be reduced to account for higher solar exposure.
10. Rotation of 20° east from north provides a compromise between optimal solar exposure and optimal ventilation.
11. Shading to block 100% direct solar for the 20° orientation via 'kinks' in the vertical shading (see Figures 6 and 7).
12. Maximum possible extent of glazing is determined by the solar exposure on the envelope under the final massing and shading design.

Figure 6: Iterative design process. Massing: orange; shading: green; façade: blue.

Massing

The first priority for the building massing strategy was to allow passive ventilation, in order to avoid the need for a mechanical ventilation system. This suggested thin massing orientated perpendicular to the predominant wind directions, and precluded deep-plan offices. However, the high envelope-to-floor ratio of thin massing would cause high solar and ambient gains. A compromise between these two opposing effects was achieved with a large central atrium. This had a low (exposed) envelope-to-floor ratio but allowed passive ventilation via the atrium. The north and south blocks act as two separate buildings, ventilated to the outside and into a common atrium space. In this way the atrium is similar to the courtyard of traditional architecture, providing neighbouring areas with light and ventilation. The atrium protrudes above the height of the roof of the office slabs to increase the wind exposure and draw clean, fresh air into the building.

Substantial external zones on the north and south facades which are thermally broken from the main building act as buffer zones, limiting solar and conduction gains while allowing passive air movement into the 'inner' building. The depth of the buffer zones are a result of the solar exposure: the south is very deep (5.5 metres), while the north is thinner (2.6 metres).

The orientation of the building was also a key part of the massing study, but is discussed under the façade and shading headings.

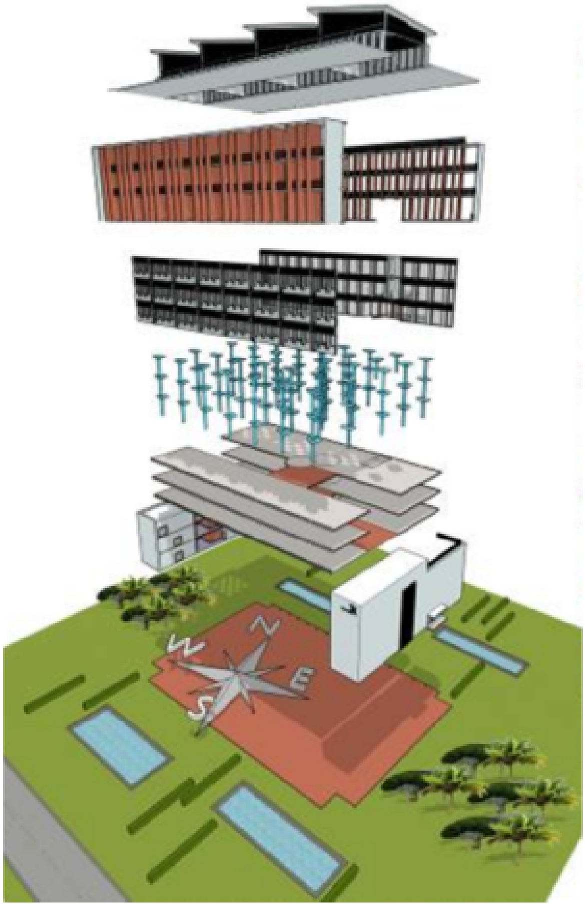


Figure 7: Exploded diagram of passive design features. From top: wind catcher atrium roof; north and south shading zones; optimised façade glazing; smaller south floor slab; east and west bookend design; surrounding vegetation and water features.

Facade design

Due to the intense climate and the need to avoid air conditioning, the façade design must be highly functional. The façade has two key functions: to allow air movement and to provide daylight into the offices. The challenge in providing daylight in a climate with intense solar gain is that glazed elements tend to cause overheating. It is particularly difficulty to reduce solar gains from low angle sun to the east and west facades, therefore these are almost entirely unglazed. Glazing is instead placed on the north and south facades, where low angle sun can be more easily blocked using external shading.

The atrium roof performs slightly differently, as solar gains are not to occupied spaces and are more easily passively extracted via the roof vents. The vertical elements at the top of the atrium are unglazed vents to aid ventilation; the horizontal elements are polycarbonate, allowing diffuse light into the atrium while limited solar gain.

The use of cavity walls (which is not widespread in India) has been used, and rigid foam insulation further reduced conduction gains. This is particularly important for the east and west walls, which are unshaded and have high surface temperatures in direct sunlight.

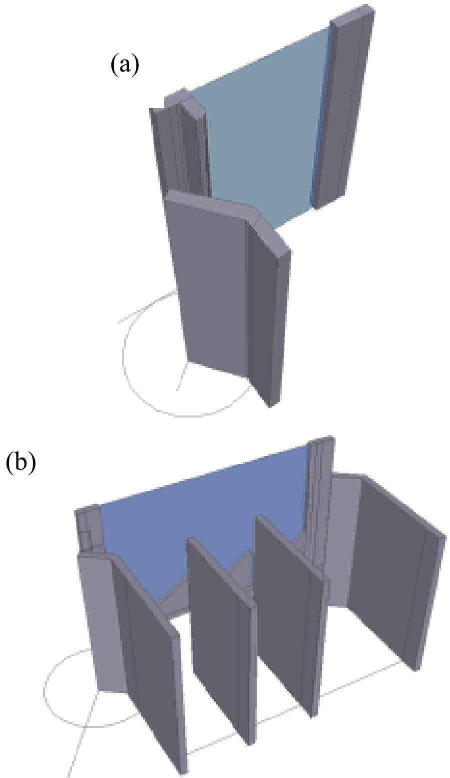


Figure 8: Final shading and glazing design. (a) North. (b) South.

Shading

Shading is used to reduce solar gain to internal areas by placing horizontal and vertical elements close to glazed surfaces. Parametric studies were used to optimise the shading to block 100% of direct sunlight. The glazed elements receive only diffuse light, thereby reducing heat gains and problems relating to glare. There is also a shading canopy for the roof, reducing gains to the building and creating an external space that is protected. The shading also serves to keep rain, often very heavy during the monsoon, away from the roof. Wide overhangs protect walls from damage and staining from constant falling rain.

Overall performance

Figure 9 gives the performance of the optimised designs using the UTCI metric. It is clear that without internal gains, the buffering effects of the building reduce the occurrence of uncomfortable conditions considerably. With internal gains the benefit is minimal, but when shading is included the improvement is notable. However, if internal gains were to rise this would be negated.

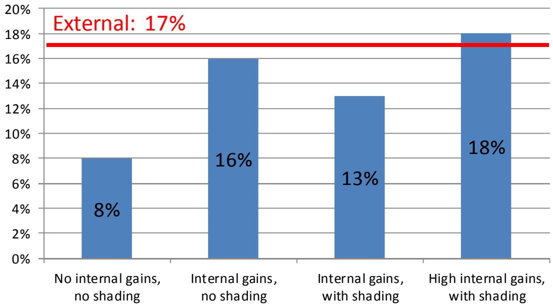


Figure 9: UTCI performance of shading.

AIR-CONDITIONED ALTERNATIVE

To illustrate the cost savings represented by the passive ventilation strategy for the Shimoga Processing Centre a modelling run assuming air conditioning to 26 degrees has been considered. Relative humidity was limited to 70%. Outdoor air ingress through infiltration and auxiliary ventilation was assumed to be 21l/s/m^2. The model used the same geometry as the passive design, but all vents were closed and replaced with mechanical ventilation.

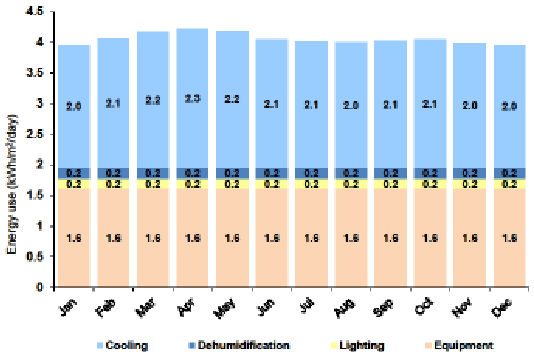


Figure 10: Energy used in passive and air-conditioned alternatives.

The graph illustrates the huge energy penalty associated with air conditioning to 26°C (approximately 130% increase in energy consumption).

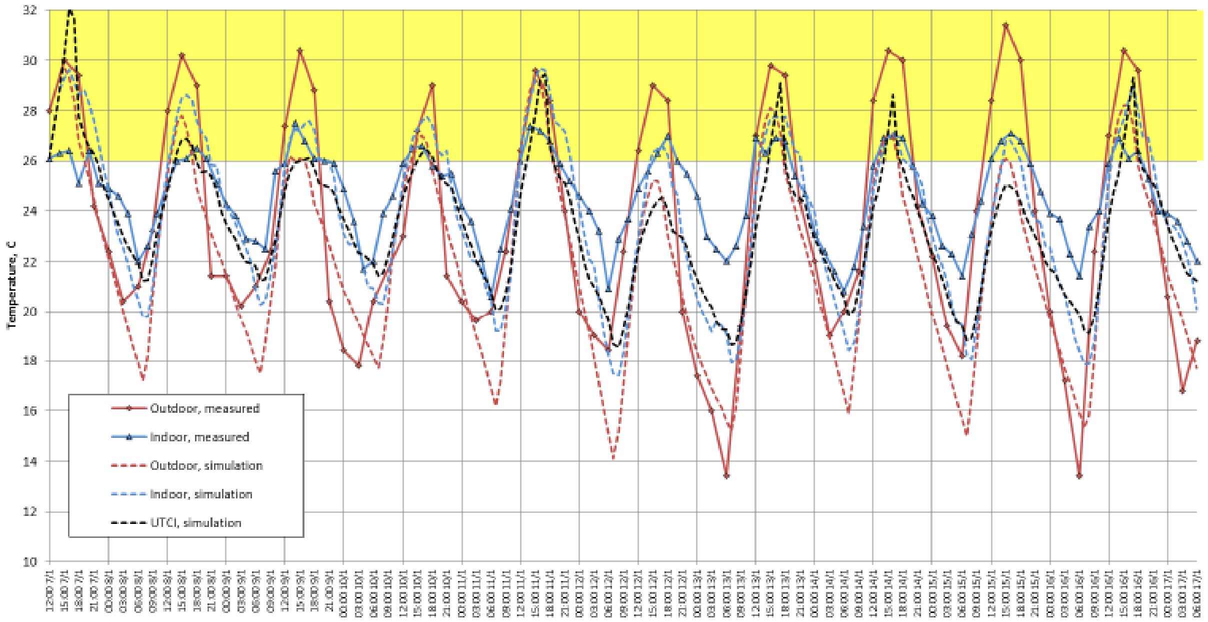


Figure 11: Comparison of measured and simulated performance.
The yellow area denotes moderate heat stress for UTCI (see Figure 4).

POST-OCCUPANCY EVALUATION

Figure 12: The north façade and building entrance.

Figure 13: The completed building (from northwest)

Measurements have been conducted in the occupied building in order to verify the performance of the design. Climate information for the period of interest as obtained from the National Climatic Data Center[1] for a nearby location.

Figure 11 compares the measured and simulated performance of the building for 10 days in January. The simulation used the same weather file as the design-stage simulations. The graph shows reasonable agreement with measured outdoor temperatures: the average absolute discrepancy was 2.2C.

There is good agreement between the simulated and measured zone temperatures: the average absolute discrepancy was 1.6C. The greatest discrepancy (5.5C) occurred at 8am on the 12th, when 17.4C was predicted but 22.9C was measured. This is despite the measured outdoor temperature being 2 degrees lower than that used in the simulation. The greatest over-prediction (3.5C) occurred in the middle of the first day, when 28.6C was predicted by 25.1C was measured. The outdoor temperatures were less than 1 degree different between simulation and measurement.

In general, measured indoor temperatures were similar to the simulation during the day, but warmer during the night. This is despite measured outdoor temperatures often being higher at all times of day. This shows that the building is performing better than expected, since higher outdoor temperatures during the day have not caused a corresponding increase in daytime indoor temperatures.

The UTCI effective temperature has been plotted for the simulated zone conditions. This predicted that moderate heat stress would occur on five out of the ten days for between 3 and 4 hours in the middle of the day. UTCI cannot be calculated from the

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[1] http://www.ncdc.noaa.gov

measured data because this requires mean radiant temperatures, which were not measured. However, simulated dry bulb temperatures were higher than measured values for all occasions when moderate heat stress is predicted (average over-prediction of 1.7C). Therefore, there is a high degree of confidence that UTCI for the measured case will have fewer occurrences of moderate heat stress than the simulation.

CONCLUSIONS

Passive design features

- 100% shading of direct solar gains to minimise overheating.
- Maximised daylight from diffuse solar gains, particularly by enlarging the north facade.
- East and west facades largely opaque to block low angle incident solar, whereas north and south facades have large glazed elements (giving good views) but large vertical and horizontal external shading to block high-angle sun.
- The facade design then informed the floorplate design: ‘bookends’ on the east and west containing the building cores, and a deep plan with high ceilings.
- Internal atrium to improve daylight penetration, with four wind-collecting stacks to channel fresh air into the building.
- A slight rotation of the building into the prevailing wind improved passive cross-ventilation through the north and south facades.
- High thermal mass, minimised internal loads and external landscaping helped to reduce peak temperatures.

Future proofing

Climate change may cause temperature increases in the future. It is therefore important to consider possible ways of mitigating this. The reduction in heat gains from improved lighting units and IT equipment could balance the increase in ambient heat gains. Landscaping will channel wind into the building and larger vegetation will provide shade to the building façade. These effects are likely to be minimal at first due to the size of newly planted vegetation but over time the impact will increase. If necessary, small cooled areas should be provided where people with lower thermal adaptability (e.g. visitors from cooler climates) can adjust. This will allow temperature gradients to be created across the space, reducing thermal shock.

Appraisal of design approach

The hybrid, iterative process outlined in Figure 6 provided a highly effective means of achieving a functional design in difficult conditions. This work has drawn on vernacular design elements, and assessed their viability via comfort-driven simulations. In parallel, sophisticated computational analysis has enabled the parametric design of a high-performance shading system.

The focus on occupant comfort was driven by the need to avoid air conditioning. This was achieved using a comfort metric that is able to accurately capture occupant conditions, and by the deliberate relaxation of that criteria in line with local norms. Post-occupancy evaluation has confirmed that both the simulation and the UTCI comfort metric have successfully delivered a building which is performing above expectations.

Many studies either concentrate solely on parametric analysis, at great computational expense, or attempt to derive very complicated analytical approaches to address problems best handled numerically. Neither are suited to situations in which a challenging problem must be solved with very limited time and resources. For this work, the design approach was tailored to be as efficient as possible, using expert input and computational power in balance as appropriate in order to derive the greatest benefit for end-users.

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