THE QUANTIFICATION OF SHADING FOR THE BUILT ENVIRONMENT IN SOUTH AFRICA

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ABSTRACT

A bioclimatic analysis of South African towns and cities indicates that solar protection is the single most important passive design measure to reduce energy usage and to improve internal comfort for the built environment across all climatic regions. Passive solar buildings aim to maintain interior thermal comfort throughout the sun's diurnal and annual cycles whilst reducing the requirement for active heating and cooling systems.

There is a long history of methods to calculate the shading on buildings and a significant corpus of knowledge has been built up starting with purely graphical methods 60 years ago to recent parametric simulation with energy simulation software using weather files.

This paper reviews the various shading calculation systems devised over the years. The effect of climate zones on the requirements of building shading design is also investigated. Different climate zones change the requirements of the size of horizontal overhangs on the northern façade (elevation dominated solar angles) and the periods when the eastern, western and southern facades (azimuth dominated solar angles) should be protected.

An experimental research platform has been developed to support this investigation. This method enables the calculation of required shading angles where there is a balance between the hot periods (requiring cooling) and cool periods (requiring heating). Over and above the calculation of current solar angles this method also facilitates the calculation of the increase in overhang sizes that will be required with climate change such as with the expected A2 climate change scenario (business as usual scenario) for South Africa.

This method is able to recommend different northern overhang sizes for cities and towns on the same latitude such as Upington, Kimberley and Bethlehem in South Africa. These three locations are on the same latitude but in totally different Köppen-Geiger climatic zones, i.e. respectively *BWh*, *BSh* and *Cwb* and altitudes.

The current rigid geometric solar elevation angle approach does not take account of locations on the same latitude with different climatic regions and altitudes. This method proves that it is possible to analyse and quantify solar protection on building facades resulting in a rational balance between the hot and cold periods without using the current practice of extensive parametric simulation with energy simulation software. It is also able to distinguish between cities and towns on the same latitude but in totally different climatic regions.

Keywords: Solar protection, horizontal overhangs, shading

1 INTRODUCTION

A previous bioclimatic study, by means of *Climate Consultant v6.0*, of the three main Köppen-Geiger climatic regions of Pretoria, clearly indicated the importance of protection against the summer sun by means of sun shading of windows in the predominantly hot South African set of climates (Conradie, 2017). This becomes even more important with the expected climate change in South Africa.

A bioclimatic analysis of Upington (28.433° S, 21.267° E, 814 m altitude), Kimberley (28.8° S, 24.767° E, 1 197 m altitude) and Bethlehem (28.25° S, 28.33° E, 1 682 m altitude) that are in different climatic regions and altitudes, proves this further (Table 1). These three locations are almost on the same latitude but in totally different Köppen-Geiger climatic regions, i.e. respectively desert (*BWh*), steppe (*BSh*) and warm temperate climate with dry winter (*Cwb*).

Table 1 below quantifies the actual changes in design strategy for the current climate and with an A2 climate change by the year 2100. According to recent research by Engelbrecht *et al*. (2016), the A2 climate change scenario is the closest to reality for Southern Africa. A2 is also known as the "business as usual" scenario. Projections of future global climate change such as A2 that are described in Assessment Report Four (AR4) of the Intergovernmental Panel on Climate Change (IPCC), are based on coupled global climate models (CGCMs) that simulate the coupled ocean, atmosphere and land-surface processes. By means of *Climate Consultant v6.0,* the smallest number of different passive design strategies that can potentially achieve closest to 100% or 100% comfort were determined. The surprising result is, even with an A2 climate change scenario, it is still possible to achieve 100% comfort in all cases, with a large portion totally passive and with some mechanical intervention in extreme situations by means of hybrid solutions. If hybrid intervention is not used then the theoretical passive maxima, as analysed in *Climate Consultant v6.0*, in Upington, Kimberley and Bethlehem become respectively 89.2%, 82.8% and 74.6%.

Table 1 Suggested passive and hybrid design strategies for the BWh, BSh and Cwb climatic zones, currently and with climate change. The contribution of each strategy is expressed in hours per annum. (Author)

Design strategies	BWh (Upington)		BSh (Kimberley)		Cwb (Bethlehem)	
	2009	2100[1]	2009	2100[1]	2009	2100[1]
Comfortable	2336	2102	2050	1905	1506	2065
Sun shading of windows	2017	2450	1560	2165	631	1724
High Thermal Mass					137	
High thermal Mass Night Flushed		1859	1295	1486		1236
Direct Evaporative Cooling						
Two-Stage evaporatative Cooling	2158					
Natural Ventilation Cooling		670				
Fan-Forced Ventilation Cooling						
Internal Heat Gain	2413	1844	2907	2097	3276	2683
Passive Solar Direct Gain Low Mass						
Passive Solar Direct Gain High Mass	2082	1501	2327	1669	2623	2048
Wind Protection of Outdoor Spaces		16		24		19
Humidification Only						
Dehumidification Only	116	260	279	758	256	867
Cooling, add Dehumidification if needed	133	1729	134	1445	19	403
Heating, add Humidification if needed	697	381	1095	507	1968	710

Comfort(able) (Table 1) as used in the *Climate Consultant v6.0* software is clearly defined in the ASHRAE 55-2010 (ASHRAE 55-2010) standard. This standard uses operative temperature. Operative temperature (OT) integrates the effect of air temperature and radiation, but ignores humidity and air movement. It is unsuitable for application above 27 °C (Holm *et al*., 2005). The range of operative temperatures presented is for 80% occupant acceptability. This is based on a 10% dissatisfaction criterion for general (whole body) thermal comfort based on the predicted Mean Vote/ Percentage Persons Dissatisfied (PMV-PPD) index, plus an additional 10% dissatisfaction that may occur on average from local (partial body) thermal discomfort (ASHRAE 55-2010, 2010). Two comfort zones are used, one for 0.5 clo (summer) of clothing insulation and one for 1.0 clo (winter) of insulation. These insulation levels are typical of clothing worn when the outdoor environment is warm (summer) and cool (winter) respectively. This comfort zone described in the ASHRAE 55-2010 (2010) standard differs slightly from the older new Effective temperature (ET*) delineated comfort definition used by researchers such as Givoni (1969), Watson and Labs (1993). New Effective Temperature (ET*) is described as the DBT of a uniform enclosure producing the same heat exchange by radiation, convection and evaporation as the given environment. It allows for body, clothing and space interaction. ET* lines coincide with DBT values at the 50% curve of the psychrometric chart (Holm *et al*., 2005). The quantified results in Table 1 were calculated by means of *Climate Consultant v6.0* and used the latest ASHRAE 55-2010 (2010) definitions and dual summer/ winter comfort zones.

[1] A weather file with an A2 climate change scenario as defined by the IPCC (2000) has been used to calculate these values.

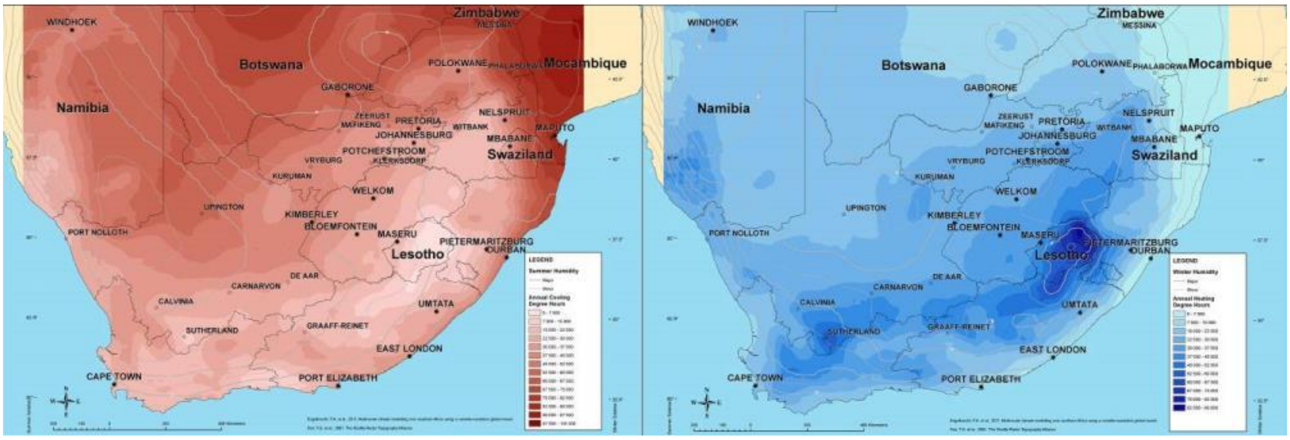

Figure 1 Separate Cooling and Heating degree hour maps before combination into a single map (Conradie et al., 2015)

In all cases the benefit of proper “Sun shading of windows” increases significantly with climate change. It is evident what the effect of climate change is in the significant reduction of the number of “comfortable” hours due to the significant increase in temperature and solar radiation.

An analysis of Figure 1 above indicates that Upington currently requires between 52 500 and 60 000 annual cooling degree hours (CDH) and only between 7 500 and 15 000 annual heating degree hours (HDH). Kimberley requires between 37 500 and 45 000 annual CDH and between 15 000 and 22 500 annual HDH hours. Lastly Bethlehem, being very cold in winter requires only between 15 000 and 22 500 annual CDH and between 30 000 and 37 500 annual HDH.

2 PRECEDENTS FOR THE CALCULATION OF SUNLIGHT AND SHADE

Over the past 66 years, many different methods have been devised to determine the amount of sunlight and shade on building facades. Initially, the focus was solely to determine the extent of shade for a given time of day and specific latitude. There was no established methodology to accurately determine when solar protection should really take place and the determination of shade was mostly qualitative. In one of the earlier systems developed at the former National Building Research Institute (Richards, 1952) a set of accurately printed solar charts and a special transparent protractor was developed for South African latitudes of 20° to 34° (2° spacing) south. *Inter alia* the same publication included suggested periods for maximum shading, summer cooling period and the winter heating period. For example in Bloemfontein (close to Kimberley in the present study) the winter heating period was suggested as from 1 May to 31 August, summer cooling period from 29 September to 2 April and the suggested period for maximum shading 6 October to 8 March. In an improved reprint of the original publication in 2004 (CSIR Building and Construction Technology, 2004), the suggested solar protection and winter period should remain unaltered, although a significant amount of climate change has already taken place.

Olgyay (1963; 2015) extensively discusses various solar control measures including a discussion of shading effectiveness. The shading effects of trees and vegetation are also discussed. The concept of overheated period charts, methods to determine the position of the sun and methods to determine the type and position of the shading device are described and illustrated. Olgyay (2015) has already noted that inside shading protection devices can only intercept the solar energy which has just passed through the glass surface and can eliminate only that portion of the radiant energy which can be reflected through the glass again. It is evident from Olgyay’s analysis that horizontal overhangs on the northern or southern side (depending on the earth’s hemisphere) and outside moveable vertical louvres/ fins on the eastern and western side are very efficient with shading coefficients of respectively 0.25 and 0.23 to 0.10.

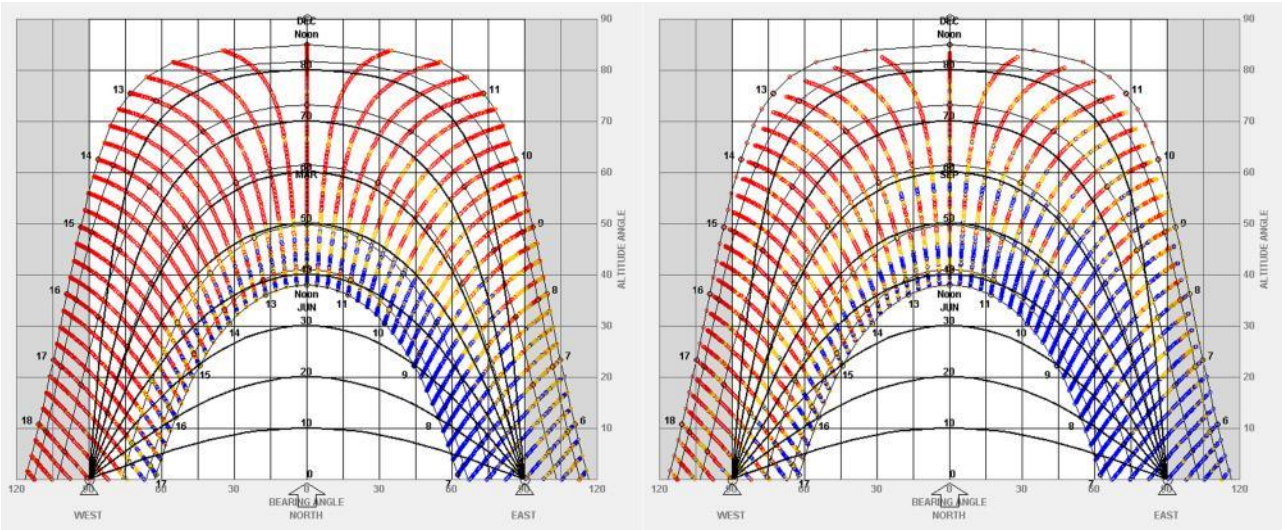

Figure 2 A Climate Consultant v6.0 implementation of the original Mazria (1979) solar chart. The two halves of the year are illustrated for the hot climate of Upington. The image on the left is for 21 December to 21 June and the right hand for 21 June to 21 December.

Mazria (1979) made a significant contribution in the further understanding and quantification of solar protection. His biggest contribution was the invention of a special solar chart with a horizontal axis marked in degrees (azimuth) and a vertical axis marked from 0° to 90° (elevation or altitude). This enabled him to introduce a shading calculator that was used to generate a shading mask. The curved lines that run from the lower right-hand corner are used to plot horizontal obstruction lines parallel to a window and the vertical lines on the calculator serve to plot vertical obstruction lines parallel to the window. This original on-paper concept is currently used in the modern *Climate Consultant v6.0* software. One of the refinements in said software is the introduction of the display of the two halves of the year. The one half spans from 21 December to 21 June and the other half from 21 June to 21 December (Figure 2). This became necessary as the two halves of the year are not symmetrical from a climatological point of view.

Closer inspection of Figure 2 reveals that the 21 December (Summer solstice) to 21 June (Winter solstice) half is significantly hotter than the 21 June to 21 December half. This was not recognized by Mazria as weather files were not freely available.

Another complication in the use of this particular solar chart system is that it is really not suitable for use in the tropical band, i.e. north of the Tropic of Capricorn and south of the Tropic of Cancer. This was practically tested with the South African town of Musina that is just north of the Tropic of Capricorn (22.338° S, 30.042° E, 543 m) (Figure 3). The December 21 to 21 June part of Figure 3 (left hand image) appears is a correct presentation of the weather file data. However the 21 June to 21 December part (right hand figure) does not correctly reflect the amount of solar radiation on the southern façade. The only way a Mazria type chart can show a town north of the Tropic of Capricorn is to distort the diagram by adding additional projecting “ears”. A similar technique than the Mazria chart is used by the University of Oregon Solar Radiation Laboratory in the generation of a diagrammatic solar chart (University of Oregon, 2018).

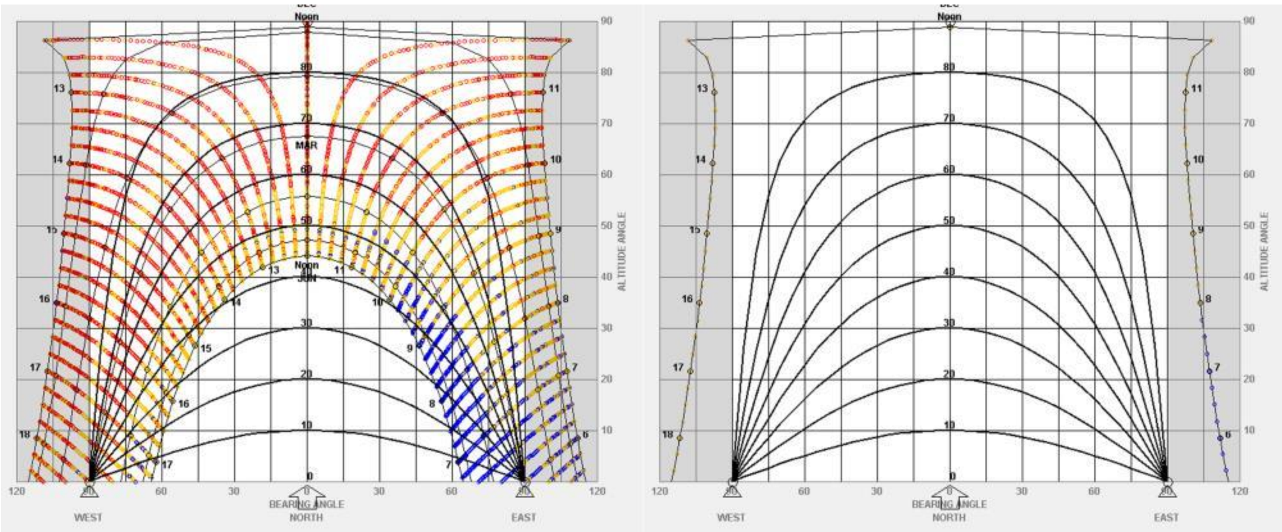

Figure 3 A Climate Consultant v6.0 analysis for the South African town of Musina The image on the left is for 21 December to 21 June and the right hand degenerated one for 21 June to 21 December.

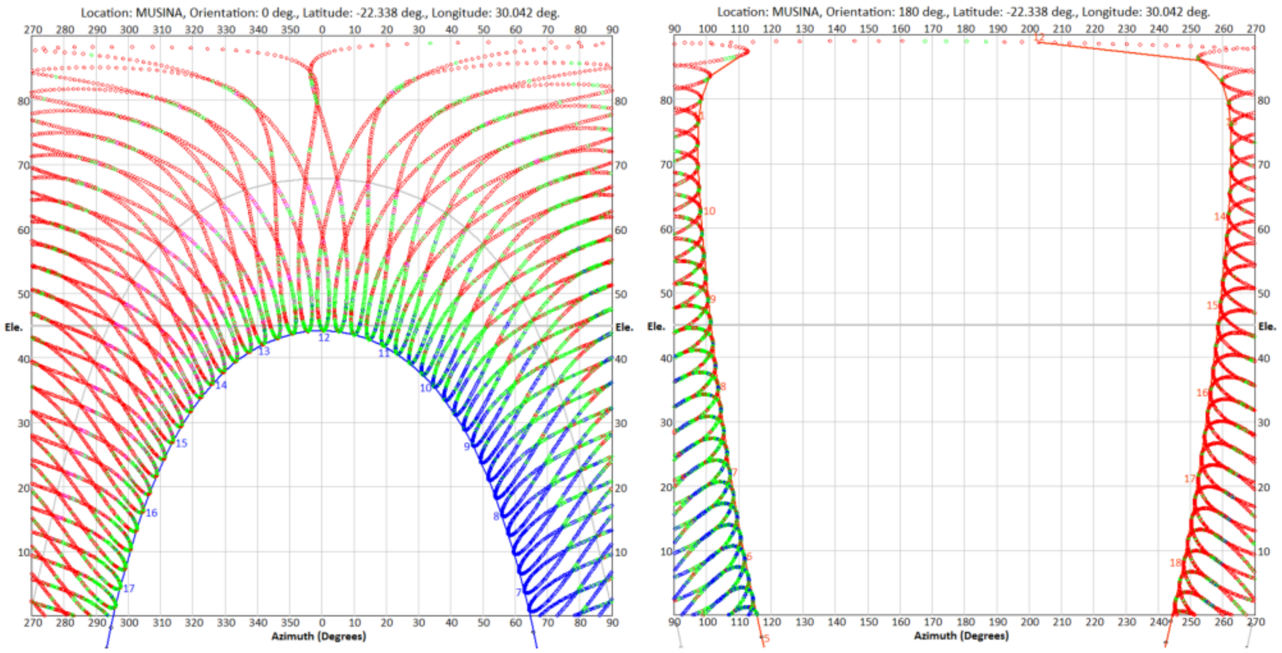

Figure 4 The experimental research platform analysis for the South African Town of Musina (slighty north of the tropic of Capricorn) using the same weather file as in Figure 3. The image on the left is for the whole year with a bearing of 0° (north). The image on the right is also for the whole year with a bearing of 180°. It correctly shows that, during noon on summer solstice, the sun do fall on the southern façade.

Szokolay (2004) also describes various solar design aspects and alludes to two important aspects for designers, i.e. the apparent movement of the sun (the solar geometry) and the energy flows from the sun and how to design for it (exclude it or make use of it). Sun path diagrams or solar charts are the simplest practical tools for visualising the sun's apparent movement. The sky hemisphere is represented by a circle (the horizon). *Azimuth* angles (i.e. the direction of the sun) are indicated on the perimeter and altitude (also called elevation) angles (from the horizon up) are indicated by a series of concentric circles, 90° (the *zenith*), being in the centre. Several different methods are used in the construction of these charts. The *orthographic*, or parallel projection method is the simplest, but it produces very compressed altitude circles near the horizon. The *equidistant* method is in general use in the USA, however it is not a true geometrical projection. The most widely used type is the *stereographic* chart. These are constructed by a radial projection method, in which the centre of the projection is vertically below the observer's point, at a distance equal to the radius of the horizon circle (the *nadir* point).

According to Szokolay (2004) solar radiation can be measured in two ways:

1. Irradiance is a measure in W/m² and is the instantaneous flux- or energy flow density or power density.

2. Irradiation expressed in J/m² or Wh/m² is an energy quantity integrated over a specific period of time.

The latter irradiation was used below to calculate the critical solar angles along with a specific temperature threshold described in detail below. Szokolay (2004) suggested the use of a shading mask, which can be constructed with the aid of a shadow angle protractor. He improved somewhat on the ideas of Mazria (1979).

At least 12 different generic shading devices can be identified (Figure 5). Generally speaking shading types that exclude the sun externally during the overheated period and allow it in during the cold period are more efficient. In contrast fixed screens, although they are very efficient, have the disadvantage that they exclude the sun even during the cold period and hence the energy saving opportunity by balancing the overheated with cold period is unfortunately lost.

2.1 A: Horizontal overhang (fixed)

This type of overhang is mostly suitable for altitude/ elevation (sun is far above the horizon) dominated solar angles, typically on northern (or near northern) facades. It can take various forms such as illustrated in A to E. This could also be in the form of a projecting awning or sun blind.

2.2 B: Fixed vertical screen

This configuration is a variation of A and is intended to exclude the lower rays of the sun, thereby reducing the glare problem.

2.3 C: Side fin/ vertical projection (fixed)

The side fin used on its own is suitable for use on facades where the solar altitude/ elevation is mostly azimuth dominated, i.e. low solar angles above the horizon. This option is often combined with A for facades that are not due north and where there is a mix of altitude/ elevation and azimuth dominated solar angles that need to be excluded.

2.4 D: Light Shelf (fixed)

This is another variation of A and is used to improve the natural light penetration in a space by means of a reflecting light shelf.

2.5 E: Horizontal louvres (fixed or moveable)

This is a variation of A and if it is moveable it is more flexible than A. Is typically used with altitude/ elevation dominated solar angles. This have the advantage of permitting air circulation near the façade. Slanted louvres give better protection than vertical ones.

2.6 F: Vertical louvres (fixed/ moveable)

This protection device is found in different forms. In its simplest form it could be a fixed vertical screen some distance away from the building façade. In a more complex form it could consist of multiple louvres set right in front of the window or some distance away from the façade. The most sophisticated variation would be a moveable system with or without computer control.

2.7 G: Integral blinds

In this system blinds are built into a double glass system. This has some advantages such as the protection of the blind. These systems are normally moveable.

2.8 H: Special glass such as heat absorbing, reflective and photochromic.

This is the weakest type of shading device as it depends on the treatment of the glass and can ultimately not avoid heat gains in the interior.

2.9 I: Vertical external screen

There are many types of this screen. In its simplest form it could be a fixed fine woven metal mesh. More complex systems consist of special screens that can be opened and closed when desired.

2.10 J: External louvres, insulated louvres, louvered blind and vertical roller blind

These types are mentioned by CIBSE (2014) and there are many variations with varying degrees of durability. Some researchers even suggested the integration of screens with flexible photovoltaics (Sampatakos, 2014). Insulating blinds are mentioned by Kristinsson (2012).

2.11 K: Internal screen, louvre drapes, blinds or curtains.

This family of solar protection devices are not that efficient to reduce heat in a space as it is not excluding the solar radiation from the outside. This causes the gradual built up of heat in the space due to the hot house effect. However it is useful as a means to control solar glare with low solar angles in the early morning and late afternoon. Ideally these types of devices should be used in conjunction with well-engineered external solar protection devices. This type of screening could venetian blinds, vertical louvered retractable blinds, fabric roller blind and fabric curtains.

2.12 L: Double-skin façade

This the most sophisticated type of façade. This façade takes many forms depending on the specific façade application and is successfully used in hot climates. Three fundamental types can be recognized, such as Buffer Façade, Extract-air Façade and Twin Face Façade.

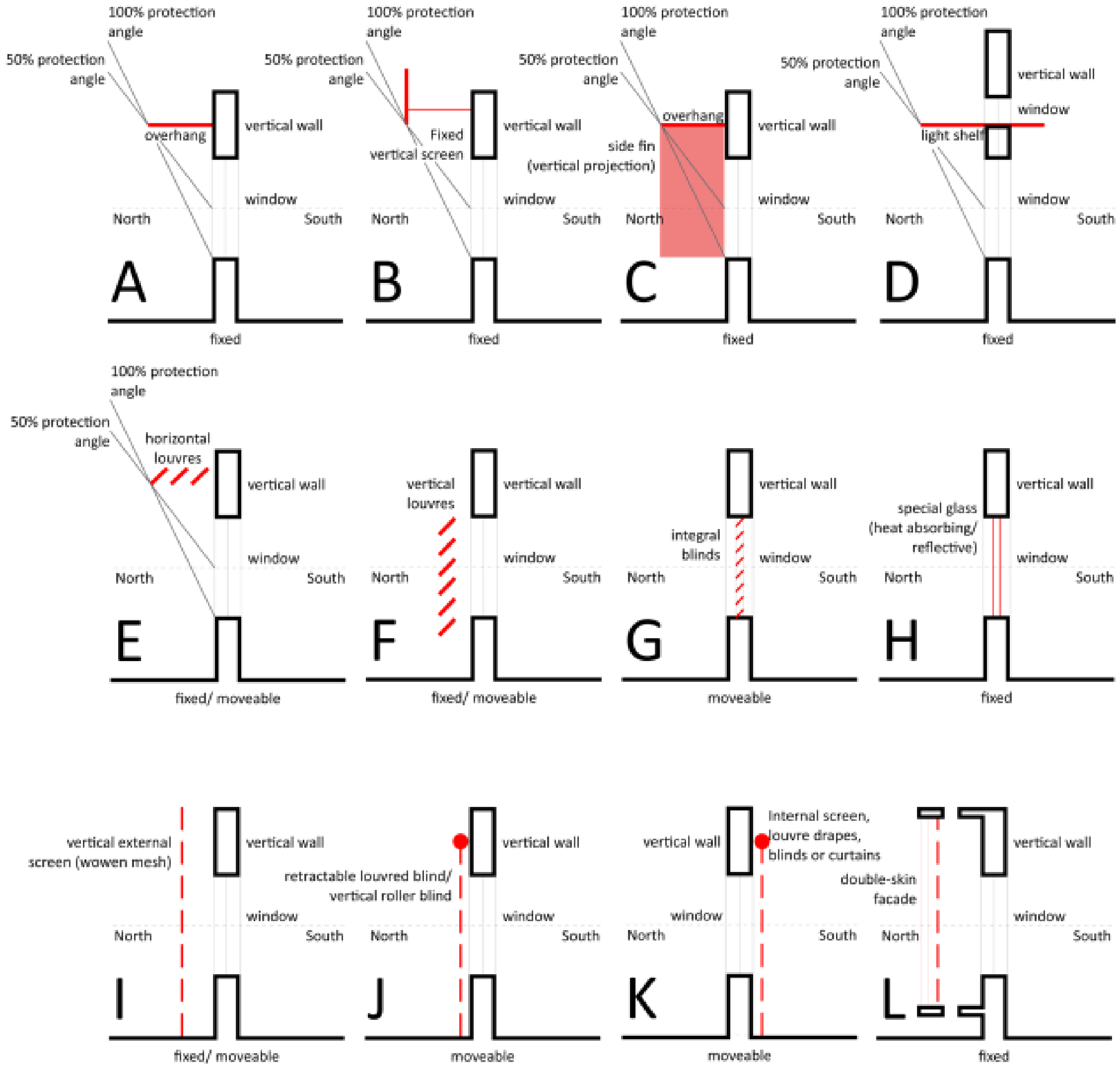

Figure 5 Different types of shading devices (Author after Olgyay 2015; Bellia et al. 2014; CIBSE, 2014)

3 METHODOLOGY

The primary aim of this paper is to investigate the effect of climate zones on building shading design, by means of quantifying the size of horizontal overhangs on the northern façade, using weather files, and also to provide a quantitative indication of the periods and time of day when the eastern, western and southern facades should be protected. It is clear from Figure 5 that types A to E would benefit from a quantification of horizontal overhangs if the overheating problem was solar elevation related as would typically be the case on the northern façade and parts of the eastern and western facades. If the solar radiation was azimuth dominated such as found on the eastern, western and southern facades types F to L would be applicable and the platform should be able to provide a set of azimuth angles when these façades should be protected.

To achieve this, a bespoke research analysis platform was developed. The first step was to generate detailed weather files for the current climate with the *Meteonorm* software for Upington, Kimberley and Bethlehem using typical meteorological years specifically based on measured data. A second set of weather files were also generated to quantify the effects of climate change up to the year 2100 using an A2 climate change scenario of the Special Report on Emission Scenarios (SRES) for the period 1961-2100 using the first set as a baseline. Although typical meteorological years are currently used for energy simulations a significant amount of research is currently taking place to improve the accuracy of weather files and also to have more specialized weather files available (Herrera, 2017).

The second step was to develop a software parser to read the weather files in *Energy Plus* weather file format (.epw) into *MS Access* (U.S. Department of Energy, 2018). For each of the 8 760 records (number of hours in a year) the following fields were read (A total of 19 data fields):

A1: City
A2: State Province Region
A3: Country
A4: Source
N1: WMO
N2: Latitude [-90,90]
N3: Longitude [-180,180]
N5: Elevation
N1: Year
N2: Month [1,12]
N3: Day [1,28] $\wedge$ [1,30] $\wedge$ [1,31]
N4: Hour [1,24]
N5: Minute [1,60]
N6: Dry Bulb Temperature (°C)
N7: Dew point temperature (°C)
N8: Relative humidity [0,110]
N14: Direct Normal radiation in (Wh/m²)
N15: Diffuse Horizontal radiation (Wh/m²)
N22: Total Sky Cover [0,10] (Amount of sky dome in tenths covered by clouds or obscuring phenomena at the time indicated.)

Three special fields were added to contain calculated values for solar azimuth, elevation/ altitude and a single date record transcribed from the separate year, month, day fields (Fields N1 to N3).

Table 2 Verification of the accuracy of the analysis platform compared against values generated with the NREL solar position algorithm. α is the sun topocentric azimuth, measured eastward (clockwise) from North in decimal degrees. γ is the sun topocentric elevation angle, with atmospheric refraction correction, in decimal degrees.

	Upington				Bethlehem			
	Analysis Platform (Based on NOAA)		NREL		Analysis Platform (Based on NOAA)		NREL	
Date and Time	α	γ	α	γ	α	γ	α	γ
Summer Solstice (21 December)								
08h00	102.43	29.26	102.4329	29.2681	99.95	35.32	99.95258	35.3245
12h00	57.97	81.05	57.96346	81.0554	12.94	85.07	12.90543	85.0722
16h00	263.72	43.59	263.726	43.5859	260.92	37.41	260.9242	37.4055
Autumnal Equinox (20 March)								
08h00	80.58	17.08	80.58627	17.0756	76.84	23.19	76.8504	23.1926
12h00	21.47	59.86	21.48589	59.8584	7.43	61.59	7.451924	61.5968
16h00	292.21	34.90	292.2156	34.9071	287.42	29.12	287.4337	29.1264
Vernal Equinox (23 September)								
08h00	78.60	20.34	78.596	20.3463	74.70	26.41	74.69621	26.4255
12h00	14.19	61.02	14.17527	61.0198	359.49	61.94	359.4749	61.9450
16h00	289.36	31.96	289.3592	31.9541	284.89	26.08	284.8911	26.0741
Winter solstice (21 June)								
08h00	59.49	5.74	59.4946	5.7408	55.67	11.02	55.67584	11.0242
12h00	10.61	37.39	10.60568	37.3983	2.47	38.28	2.465389	38.2883
16h00	311.34	18.73	311.3458	18.7277	306.8	14.03	306.799	14.0313

The third step was to accurately calculate solar azimuth and elevation angles for each of the 8 760 hours per annum and merge it with the weather file data. This was the most challenging part as a large number of rather complicated astronomical calculations need to be performed. The detailed documentation of these complicated mathematical formulae is beyond the scope of this paper. There are various algorithms for sun position calculations available (Blanc *et al*., 2012) such as the sun position algorithm from the National Renewable Energy Laboratory (NREL) (Reda *et al*., 2008), Algorithm Solar Geometry from the European Solar Radiation Atlas (ESRA, 2000), Algorithm from the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) (Grena, 2008), Algorithm from Michalsky (1988), the SG2 algorithm (Blanc *et al*., 2012) and finally an algorithm from the National Oceanic and Atmospheric Administration (NOAA). The calculations in the NOAA Sunrise/Sunset and Solar Position Calculators are essentially based on equations by Meeus (2015). The original code is written in Java. The most accurate known algorithm is the NREL one that achieves a standard deviation of only 0.0003° (1”) for the period -2000 to 6000 (Reda *et al*., 2008). This very high accuracy is achieved by means of tables containing the Earth Periodic Terms in addition to a set of astronomical equations found in most of the abovementioned solar position algorithms. These so called secular factors are irregular and can only be obtained by means of direct astronomical observation. It was decided to use the less accurate and sophisticated NOAA algorithm as a basis as it would be more than adequate for built environment shading applications (Table 2). An implementation of the NREL algorithm was obtained and compared with the NOAA based algorithm for a number of critical points at 08h00, 12h00 and 16h00 for the annual solstices and equinoxes (Table 2). Hours closer to sunset and sun rise were excluded in this comparison as solar refraction has a large impact at these low solar elevation angles. Table 2 compares the accuracy of the research platform using algorithms based on NOAA and Meeus (2015) against the very accurate NREL solar angle calculation. Once the platform was established the experimental part of the research could start.

The fourth step was to calculate the Degree-days and hours to discover the fundamental energy requirement differences between the three locations using the platform and compare it with the values in Figure 1 that was previously calculated with totally different method (Conradie *et al*., 2015) Degree-days are essentially a summation of the differences between the outdoor temperature and a base temperature over a specified time period. A key issue in the application of degree-days is the definition of the base temperature, which, in buildings, relates to the energy balance of the building and systems. This applies to both heating and cooling systems, which leads to the dual concepts of Cooling Degree Days (CDD) and Heating Degree Days (HDD). (CIBSE, 2006). The most rigorous and precise method of calculating degree-days is to sum hourly temperature differences to the base temperature and divide these by 24 (CIBSE TM41, 2006). This method takes the often significant diurnal temperature variation in South Africa into account. Equation 1 was used for the calculation of heating degree days and Equation 2 for cooling degree days.

$$D_h = \frac{\sum_{j=1}^{8760} \left(\theta_{o,j} - \theta_b\right)_{\left(\left(\theta_{o,j} - \theta_b\right) > 0\right)}}{24} \qquad (1)$$

$$D_c = \frac{\sum_{j=1}^{8760} \left(\theta_b - \theta_{o,j}\right)_{\left(\left(\theta_b - \theta_{o,j}\right) > 0\right)}}{24} \qquad (2)$$

Where:

D_h	is the heating degree-days for a year
D_c	is the cooling degree-days for a year
θ_b	is the base temperature. 18 °C is used.
$\theta_{o,j}$	is the outdoor temperature in hour *j*

In both formulas the subscripts denote that only positive values are taken into account in the relevant calculation. Using a 2005 typical meteorological year weatherfile from *Meteonorm*, the HDH for Upington, Kimberley and Bethlehem are respectively 18888, 25907, 44842 and the CDH for Upington, Kimberley and Bethlehem are respectively 47947, 32241, 11338. These values differ a bit from the values determined from the maps in Figure 1 (Conradie *et al*., 2015) as these maps already factored climate change. The difference is already indicative of what can be expected with climate change.

The fifth step was to develop an analytical graphical screen to display the temperature/ radiation combinations with solar azimuth on the horizontal axis and elevation above the horizon on the vertical axis. The azimuth is expressed in degrees clockwise from 0° (north). The elevation is expressed in degrees from the horizon to vertical (0° to 90°). This facilitated the study of the annual temperature and radiation distribution and to determine the times when solar protection and shading would be necessary. Four temperature categories were colour mapped on each chart to make the trends more visible:

Cold (Blue):	Drybulb temperature <= 18 °C
Comfortable (green):	Drybulb temperature > 18 °C and Drybulb temperature < 23.8 °C
Warm (Magenta):	Drybulb temperature >= 23.8 °C and Global Horizontal Irradiation < 315.5 Wh/m²
Hot (Red):	Drybulb temperature >= 23.8 °C and Global Horizontal Irradiation >= 315.5 Wh/m²

Unlike the Mazria (1979) and the *Climate Consultant v6.0 method* the new research platform supports a bearing of any angle including due south. The diagram initially only used the 8 760 points from the weather file leading to a very course diagram with only hour values. It was therefore decided to create more data points with 15 minute intervals by means of a Lagrange formula for polynomial interpolation (Press *et al*., 1990). This produced a much larger smoothed dataset of 35 037 points.

Once this was achieved six solar analysis charts were generated for Upington, Kimberley and Bethlehem. Three of the charts are for current climatic conditions and three are for climate change with A2 climate change scenario. To simplify comparison only a northern façade orientation was used.

The sixth and last step was to devise an algorithm to calculate recommended elevation and azimuth angles for horizontal and vertical fixed solar protection devices for the three towns. Various statistical methods were studied and tried. Initially it appeared that histograms might give an indication when solar protection might be required. During testing it was determined that it is rather difficult to determine a recommended solar angle using histograms as climate is a complex mix of cold, comfortable, warm and hot periods. It was decided to use a *K-means clustering* method originally proposed by MacQueen (1967) to cluster the different overheated areas into representative clusters with representative centroids. *K-means clustering* is an unsupervised learning technique used to automatically partition a given dataset into *k* representative clusters/ groups. It proceeds from an initial set of *k* clusters that are predefined or programmatically allocated and then iteratively refine them as follows (Wagstaff *et al*., 2001: 577-578):

1. Each data instance i is assigned to its closest cluster centre.
2. Each cluster centre j is updated to be the centroid of its constituent instances.
3. The algorithm converges when there are no further changes in the assignment of instances to clusters.

The general formula can be written as:

$$J = \sum_{j=1}^{k} \sum_{i=1}^{n} \left\| x_i^{(j)} - c_j \right\|^2 \quad (3)$$

Where:

J	is an objective function.
k	is the number of clusters where k is predefined.
n	is the number of cases or hot points in the weather file being analysed as defined above.
$\left\| x_i^{(j)} - c_j \right\|^2$	is a function to determine the Euclidian distance between case *i* and the centroid for cluster *j*.

Seven clusters were used for the elevation and two sets of four clusters each for the azimuth angles, i.e. one set for the morning and one set for the afternoon.

The last step was to determine which elevation and azimuth angles should be protected for a given façade orientation and to draw red lines to indicate the recommended angles. The previous step created a set of cluster centroids numbered E1 to E7 in elevation and A11 to A14 and A21 to A24 in azimuth that are the best representatives of a surrounding set of hot points. There are three types of mean, i.e. arithmetic, geometric and harmonic mean. Initially arithmetic mean was used. However during simulation it was noticed that an outlier centroid tends to distort the calculated average angles significantly. The lesser known Harmonic mean method was therefore used (Formula 4) as this reciprocal form of mean resists outliers more efficiently.

$$H = \frac{n}{\frac{1}{x_1} + \frac{1}{x_2} + \ldots + \frac{1}{x_n}} = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}} = \left(\frac{\sum_{i=1}^{n} x_i^{-1}}{n} \right)^{-1} \quad (4)$$

Where:

H	is the harmonic mean.
n	is the number of cluster points (7 has been used for the elevation and two pairs of 4 for the azimuth).

$x_1 \ldots x_n$ are the elevation and azimuth cluster points used in the various solar angle calculations.

4 RESULTS

Table 3 Result of the solar angle calculations for Upington, Kimberley and Bethlehem. The elevation and azimuth solar angles were calculated by means of arithmetic mean (AM) and harmonic mean (HM) averages. The values were also calculated for an A2 climate change scenario by the year 2100.

	BWh (Upington)		BSh (Kimberley)		Cwb (Bethlehem)	
	2005	2100[2]	2005	2100[1]	2005	2100[1]
Elevation (Degrees) (AM)	62.9°	62.9°	64.1°	63.1°	67.5°	64.1°
Azimuth 1 (Degrees) (AM)	57.3°	64.4	65.7	50.9°	n/a	55.2°
Azimuth 2 (Degrees) (AM)	291.1°	297.3	289.3°	296.5°	295.4°	291.2°
Elevation (Degrees) (HM)	61.7°	61.7°	63°	61.9°	66.5°	63°
Azimuth 1 (Degrees) (HM)	54.3°	61.1°	63.2°	46.6°	n/a	49.3°
Azimuth 2 (Degrees) (HM)	287.2°	292.1°	285.4°	291.4°	287.3°	287°
Heating Degree Hours	18 888	10 045	25 907	12 656	44 842	18 000
Cooling Degree Hours	47 947	70 365	32 241	55 915	11 338	35 433
Daylight hours on surface	3 918.25	3 918.00	3 929.00	3 930.00	3 913.00	3 913.75

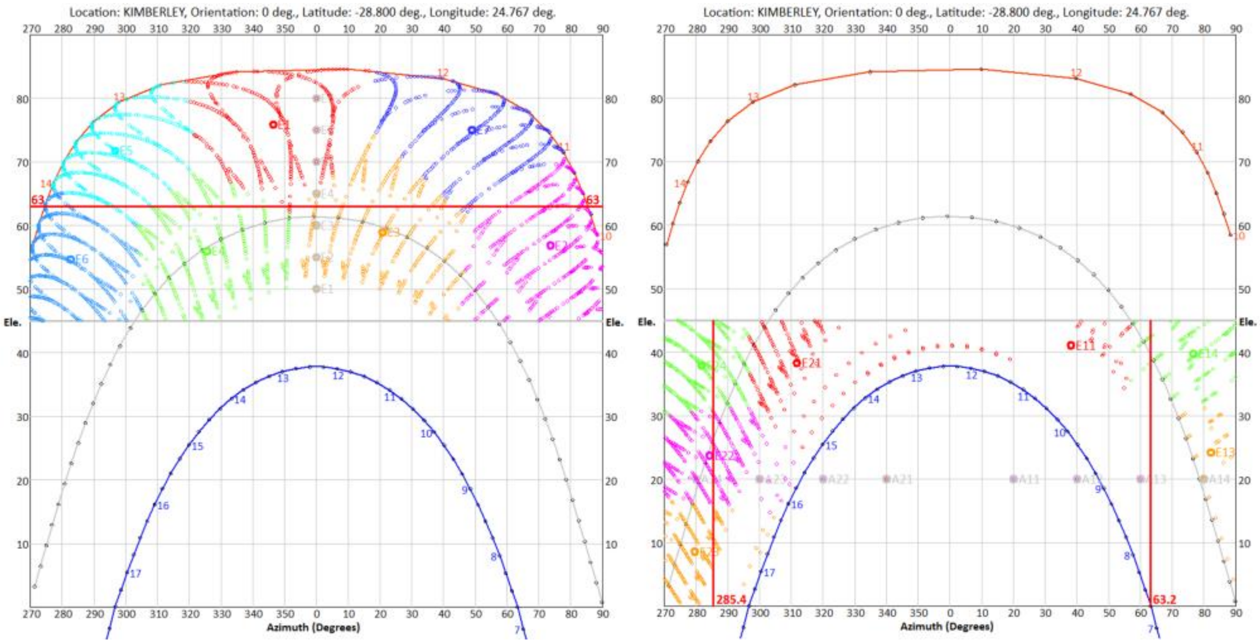

Figure 6 The recommended elevation and set of azimuth solar protection angles for Kimberley calculated with the experimental research platform analysis by means of K-means clustering and the application of harmonic mean to determine the final recommended angles.

5 CONCLUSIONS AND FURTHER RESEARCH

The research indicated the importance of appropriate solar protection within the predominantly hot South African climatic zones. A bioclimatic analysis indicates that all the South African climatic zones still have a very high passive design potential. This will reduce with climate change, however solar protection will continue to remain the single most important measure.

It is possible to calculate solar position angles very accurately. In this research the author's algorithms were compared with the most accurate solar position algorithm currently available. On the other hand weather files are not yet that accurate due to many technical reasons. However the accuracy and specialization of weather files are currently rapidly increasing with better remote sensing and advanced statistical methods being applied. Weather files are increasingly required for many different types of specialized energy

[2] A weather file with an A2 climate change scenario as defined by the IPCC (2000) has been used to calculate these values.

simulation applications beyond just the typical meteorological year applications that do not take account of extreme conditions that could potentially have a devastating effect on structures.

The research indicated that it is possible to quantify and recommend solar protection angles for the different facades of a building turned at any bearing for both elevation and azimuth dominated solar angles. These calculated angles vary significantly between different climatic regions and altitudes as indicated by an analysis of Upington, Kimberley and Bethlehem that are all on almost the same latitude. Climate change will have a very significant impact on the recommended solar protection angles and significantly more shading will be required. Climate change will also significantly change the amount of heating and cooling degree hours.

The unsupervised *K-means clustering* algorithm used in the prototype research platform was able to recommend solar angles in combination with a harmonic mean average calculation. Further research would have to be undertaken to make the algorithm more efficient as a significant amount of processing time is currently required. A comparison between the arithmetic and harmonic mean method of calculating the solar protection angles indicated that the latter is less sensitive to outlier values and therefore gives a more appropriate mean.

For the first time an early design stage platform is now able to correctly draw solar shading charts for any bearing and location within the tropics even close to the equator.

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