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THE CREATION OF A SOUTH AFRICAN CLIMATE MAP FOR THE QUANTIFICATION OF APPROPRIATE PASSIVE DESIGN RESPONSES

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Summary

To design energy-efficient buildings using an optimal combination of passive design strategies it is necessary to understand the particular climate one is designing for. Predictive computational building performance requires a detailed set of quantified climatic data. Bioclimatic charts, such as the Givoni-Milne, have been used in the early design stages to define potential building design strategies.

In South Africa there is a lack of detailed weather data to support design. Benefits of climatic classification include:

- identification of areas of influence of various climatic factors
- research stimulation to identify the controlling processes of climate
- informing land-use decision-support and appropriate scientific responses to building design.

Recently the South African SANS 204-2 (2008) standard introduced six main climatic regions in an attempt to introduce a quantified view of climate into the South African National Building Standards. The question is raised whether this granularity of refinement is adequate to optimally support design decisions within the built environment for passive design strategies such as passive solar heating, thermal mass and natural ventilation. The CSIR decided to map South Africa using 20 years of precipitation and temperature data employing a Köppen-Geiger climatic classification to refine the six-zone model. The model was then extended to reflect expected South African climate changes over the next 100 years to synthetically create weather files for predicting building performance of existing and new buildings in the future.

Using the new climatic map, several bioclimatic design tools were researched to address the question of climatic responsive design. Many pre-design tools have been developed in order to help architects design buildings in the early design stages. These tools include a series of bioclimatic charts by Olgyay, Givoni and Givoni-Milne.

The team then proceeded to analyse the building performance for a typical masonry building and a recently introduced light-weight steel frame building within each of the Köppen-Geiger climatic regions in South Africa. From this a clear indicative pattern emerged as to the most appropriate passive construction response within a particular climatic region. This paper describes the process that was followed to accurately map the existing South African climate in pursuit of the quantification of appropriate passive design strategies within these climatic regions both at present and over a 100-year horizon as a useful alternative to the six-zone model currently in use.

Keywords: climatic classification, passive design responses, Köppen-Geiger map, bioclimatic chart

1. Introduction

To design energy-efficient buildings using an optimal combination of passive design strategies such as passive solar heating, thermal mass, direct evaporative cooling, indirect evaporative cooling and natural ventilation, it is necessary to understand the particular climate one is designing for. To perform a quantified predictive building performance analysis by means of simulation software a reliable and detailed set of quantified climatic data is required. In South Africa there is a lack of suitably packaged weather data (such as the tmy, tmy2 and iwec widely available in the USA) required to support design.

The climate of an area is the averaging effect of weather conditions that have prevailed there over a long period of time, such as 30 years. Earlier, researchers did not have computers or electronic databases available to research the gradual changes in climate. Wladimir Köppen and Rudolf Geiger thus regarded climate as a constant and used the sparse climatic information available to compile a single static climatic map (Rubel et al., 2010). The first quantitative hand-drawn map of climate classification was published by Köppen in 1900 and the latest version by Geiger in 1961, before Austrian researchers created a modern version in 2005 (Kottek et al., 2006).

2. Climatic classification

2.1 The climate regions of South Africa

Low et al. (1996) recognised seven vegetation biomes in South Africa that are subdivided into 68 vegetation types. These types are mainly determined by climate, but sheltering, soil type, occurrence of veld fires, browsers (wild life), elevation and inclination and other minor factors also play a role. The boundaries for these climatic regions were determined by making use of these vegetation types. Combinations were made of smaller vegetation types into larger regions, which are easier to map and described from a climatic point of view (Kruger, 2004).

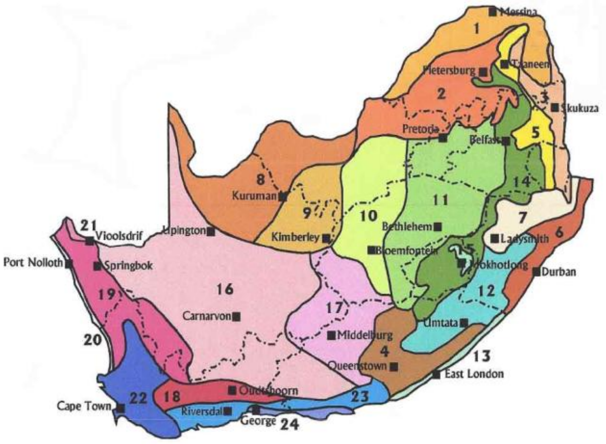

Figure 1 1. Northern Arid Bushveld 2. Central Bushveld 3. Lowveld Bushveld 4. South-eastern Thornveld 5. Lowveld Mountain Bushveld 6. Eastern Coastal Bushveld 7. KwaZulu-Natal Central Bushveld 8. Kalahari Bushveld 9. Kalahari Hardveld Bushveld 10. Dry Highveld Grassland 11. Moist Highveld Grassland 12. Eastern Grassland 13. South-eastern Coastal Grassland 14. Eastern Mountain Grassland 15. Alpine Heathland 16. Great and Upper Karoo 17. Eastern Karoo 18. Little Karoo 19. Western Karoo 20. West Coast 21. North-western Desert 22. Southern Cape Forest 23. South Grassland 23. South-western Cape 24. Southern Cape

Figure 1 illustrates these climatic regions. Regions identified are nine Savannah-type climatic regions, six Grassland-type ones, five Karoo-type, two Fynbos-type, one Forest-type and one Desert-type regions.

2.2 The South African National Standard (SANS 204-2)

The new SANS 204-2 (2008) standard recognises six main climatic regions in South Africa (Figure 2). It is an attempt to introduce a quantified view of the South African climate into the National Building Standards. For each of the six climatic zones tables are provided that give the solar exposure factors and coefficients (SHGC) for various overhang/height (P/H) factors for eight main orientation sectors. The standard is useful for initial desktop calculations such as determining the possible beneficial impact of fenestration design in combination with appropriate sun protection. This should be quantified with more detailed calculations, preferably using simulation software once the designer has determined which sun protection devices will be used.

If this classification is compared with more detailed research work of undertaken by the CSIR team over the past two years, it is clear that much more refinement would be required to support designers within the built environment.

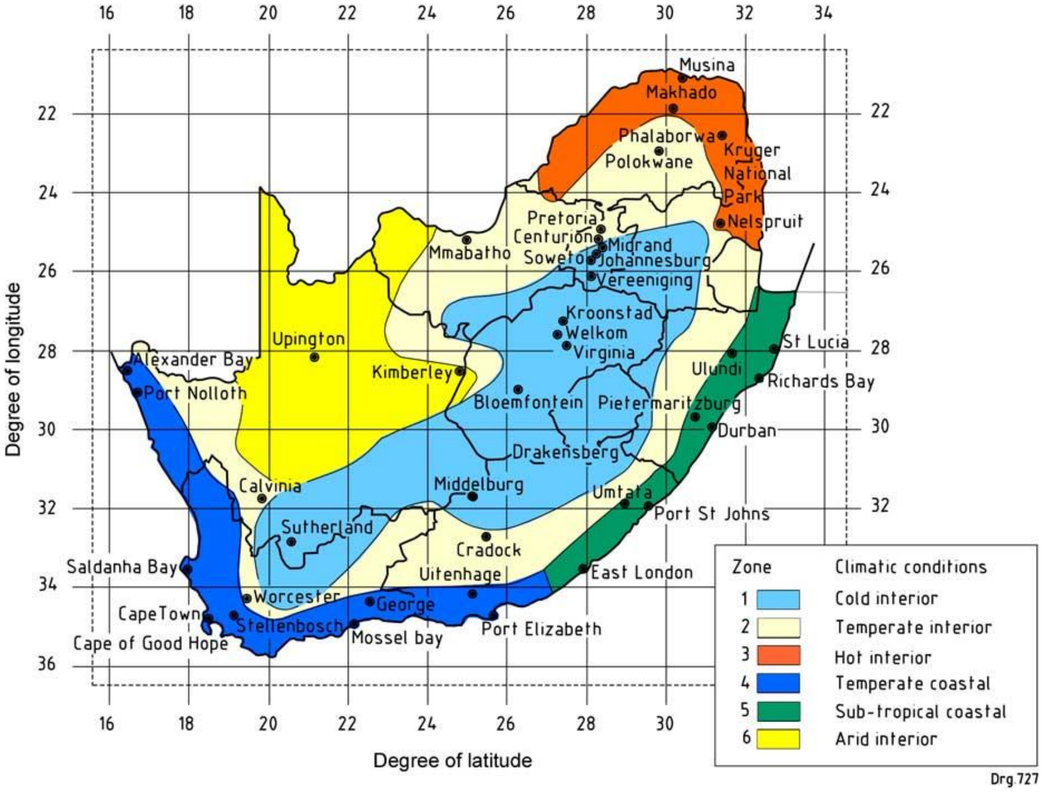

Figure 2 Climatic zone map (SANS 204-2, 2008)

2.3 Köppen-Geiger classification

Many different approaches exist to classify climate empirically, as discussed above. However, the Köppen-Geiger classification is still the most widely used (Kottek et al., 2006). Köppen was a trained plant physiologist and realised that plants are indicators of many climatic elements. His effective classification was constructed on the basis of the five main vegetation groups determined by the French botanist De Candolle, who referred to the original climate zones of the ancient Greeks (Kottek, 2006). The five vegetation groups of the Köppen classification distinguish between plants of the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E). A second letter in the classification considers the precipitation and a third letter the air temperature. The Köppen classification therefore essentially uses combinations of temperature and precipitation.

The CSIR decided to create a detailed new Köppen-Geiger map to quantify the current climatic conditions as accurately as possible in South Africa (Figure 3). This classification uses a concatenation of a maximum of three alphabetic characters that describe the main climatic category, amount of precipitation and temperature characteristics. A detailed dataset of 20 years of temperature and precipitation spanning 1985 to 2005, based on a 1 km x 1 km grid, was obtained from the South African Agricultural Research Council (Agrometeorology staff, 2001). *ArcMap* GIS was used to compile a climatic map using the algorithms (Tables 1 and 2) as described by Kottek (2006) (Figure 3).

Table 1 lists the formulae that were used to derive the first two letters of the classification. The annual mean temperature is denoted by T_{ann} and the monthly mean temperature of the warmest and coldest months by T_{max} and T_{min}, respectively. P_{ann} is the accumulated annual precipitation and P_{min} is the precipitation of the driest month. The values P_{smin}, P_{smax}, P_{wmin} and P_{wmax} are defined as the lowest and highest monthly precipitation values for the summer and winter half-years for the particular hemisphere considered. All temperatures are calculated in °C and monthly precipitation in mm/month and P_{ann} in mm/year.

In addition to the temperature and precipitation values, a dryness threshold P_{th} in mm is introduced for the arid climates (B), which depends on $\{T_{ann}\}$, the absolute measure of the annual mean temperature in °C and on the annual cycle of precipitation.

$$P_{th} = \begin{cases} 2\{T_{ann}\} & \text{if at least 2/3 of the annual precipitation occurs in winter,} \\ 2\{T_{ann}\} & \text{if at least 2/3 of the annual precipitation occurs in summer,} \\ 2\{T_{ann}\} + 14 & \text{in all other cases.} \end{cases}$$

Table 2 indicates how the additional temperature conditions, i.e. the third letter, was determined for arid climates (B) as well as for warm temperate (C) and snow climates (D). In this table T_{mon} is the mean monthly temperature in °C.

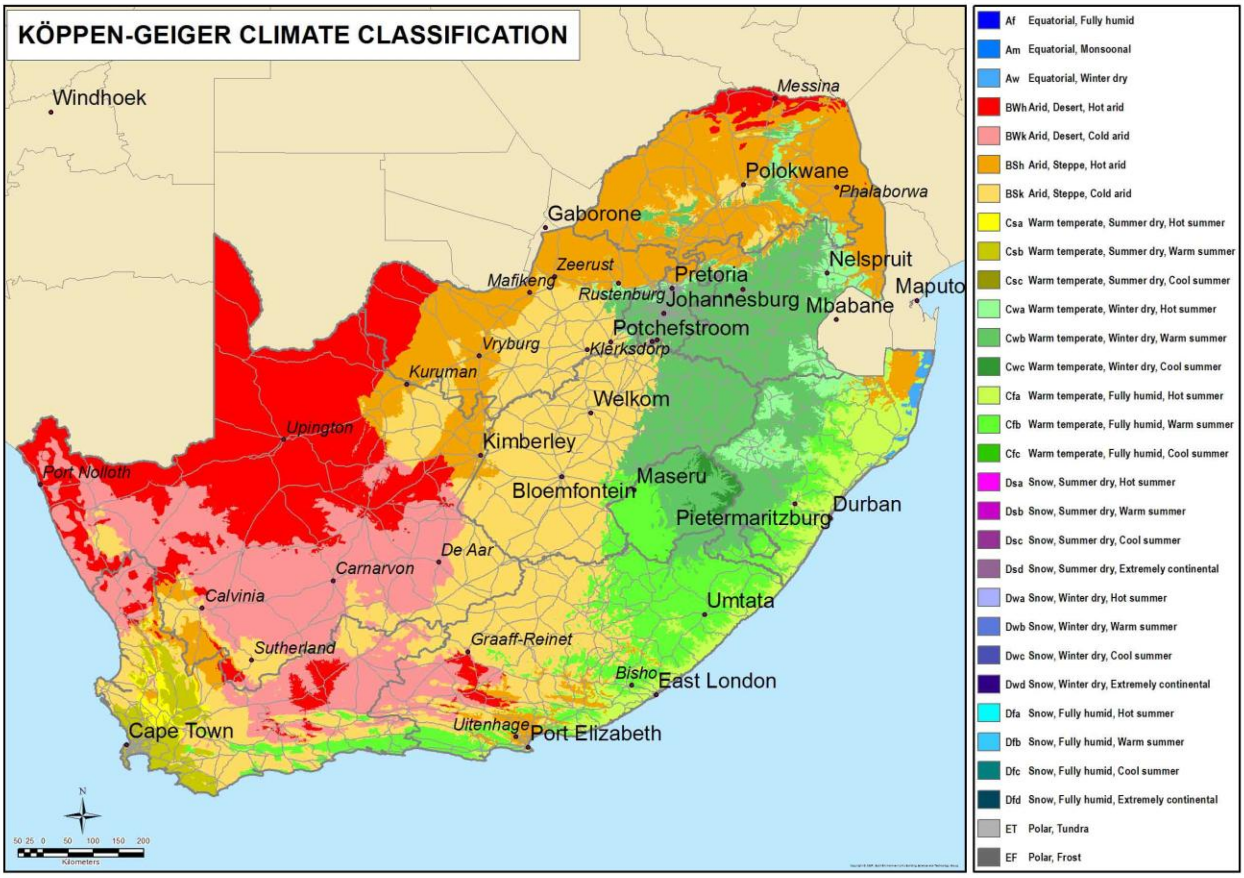

Figure 3 CSIR Köppen-Geiger map based on 1985 to 2005 Agricultural Research Council data on a very fine 1 km x 1 km grid (authors)

3. Current climate and climate change

All indications are that South Africa can expect a significant change in climate. This will have a profound impact on the built environment and how buildings should be designed in future. It became clear to the research team that, if climate change could be expressed in terms of Köppen category changes and the current building performance in a particular location could be related to a particular Köppen classification, it would become feasible to predict future building performance characteristics within that particular location. Another implication of this ambitious hypothesis is that, if existing weather files are known and connected to a particular Köppen classification, it could be reasonably assumed that buildings in other areas that have the same Köppen classification would perform in a similar way. With climate changes over time, a particular building is very likely to end up in a different Köppen category. Due to the fact that particular weather files are connected to a particular Köppen region, it becomes feasible to predict over time what the impact will be on a particular building's thermal performance. Although it is not the main theme of this paper, the team investigated the thermal performance of two different test buildings in different Köppen categories, using reliable. known weather files. This was the first step in an attempt to quantify the building performance in terms of Köppen climatic regions. This is discussed below.

Table 1 Key to calculating the first two letters of Köppen-Geiger climate classification for the main climates (Kottek et al., 2006)

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18$ °C
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25(100-P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\ P_{th}$
BS	Steppe climate	$P_{ann} > 5\ P_{th}$
BW	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperate climates**	-3 °C < T_{min} < +18 °C
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperate climate, fully humid	Neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3$ °C
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climate, fully humid	Neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10$ °C
ET	Tundra climate	0 °C ≤ T_{max} < +10 °C
EF	Frost climate	$T_{max} < 0$ °C

Table 2 Key to calculating the third-letter temperature classification in the Köppen-Geiger classification (Kottek et al., 2006)

Type	Description	Criteria
h	Hot steppe/desert	$T_{ann} \geq +18$ °C
k	Cold steppe/desert	$T_{ann} < +18$ °C
a	Hot summer	$T_{max} \geq +22$ °C
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10$ °C
c	Cool summer and cold winter	not (b) and $T_{min} > -38$ °C
d	Extremely continental	like (c) but $T_{min} \leq -38$ °C

One of the accessible methods used in the quantification of building performance in different climatic regions is the bioclimatic chart. Bioclimatic design is used to define potential building design strategies that utilise natural energy resources and minimise energy use (Visitsak et al., 2004). This approach to building design for maintaining indoor comfort conditions was first developed by Olgyay (1963). To address the problems of the original Olgyay chart, Givoni developed a chart for "envelop-dominated buildings" based on indoor conditions. In 1979, Milne and Givoni combined the different design strategies of the previous study of Givoni (1969) on the same chart. The Givoni-Milne bioclimatic chart is currently used by many architects.

Ecotect™ and *Climate Consultant*™, developed by Robin Liggett and Murray Milne of the UCLA Energy Design Tools Group, were used to determine appropriate passive design strategies (Table 3). Both software packages have psychometric charts with Givoni-Milne overlays that enabled the CSIR to relate a particular Köppen region to a set of passive design responses. The method that researchers used was to identify a city in a particular Köppen region for which they had a weather file. They then analysed the weather file in said software to determine the set of appropriate passive design responses. This related Köppen region, weather file and passive design response are illustrated in Table 3. At the moment the CSIR team is researching the relationship between the psychometric chart, the Köppen region and the passive design response and is in the process of developing their own generic climate software research platform. Table 3 below suggests some passive design strategies using the principles of the Givoni-Milne approach that could be used to improve the comfort of buildings in the context of various different climatic regions in South Africa, as well as the current percentage distribution of Köppen categories in South Africa calculated in the CSIR study.

4. Building thermal performance simulations

These simulations aimed to evaluate the performance of masonry and light steel frame (LSF) houses regarding energy consumption for space heating and cooling for six Köppen regions in order to relate actual building performance to climatic region. The methodology adopted included air infiltration rate measurements, development of *Ecotect*™ simulation models and simulation with base case characteristics and various energy-efficient measures.

Table 3 Current % of Köppen categories in South Africa and suggested passive design strategies (authors)

Climatic characteristics				Passive design strategy					
Description	**Köppen-Geiger class.**	**Area in km²**	**Percent (%)**	**Passive solar-heating**	**Thermal mass**	**Exposed mass and night purge ventilation**	**Natural ventilation**	**Direct evaporative cooling**	**Indirect evaporative cooling**
Equatorial climates (0.2%)	Aw	2296	0.20	■			■		
Arid climates (70.89%)	Bsh	192 269	16.59	■	■	■	■	■	■
	Bsk	275 927	23.81						
	Bwh	188 784	16.29	■	■	■	■	■	■
	Bwk	164 629	14.20						
Warm temperate climates (28.91%)	Cfa	42 918	3.70	■			■		
	Cfb	93 405	8.06	■	■		■		■
	Cfc	84	0.01	■	■		■		
	Csa	5 120	0.44	■	■		■		
	Csb	18 395	1.59						
	Cwa	31 162	2.69	■	■	■	■		
	Cwb	140 405	12.11	■	■		■		
	Cwc	3 564	0.31	■	■		■		
	Total	**1 158 958**	**100.00**						

Table 4 Description of the thermal mass (Case A) and light-weight (Case B) reference houses (authors)

Element	**Low thermal-mass house**	**High thermal-mass house**
Roof	30 mm concrete tiles[1], 38 mm air gap and 0.2 mm polyethylene (high density). U_{value} = 2.59 W/m^2.K, thermal lag = 0.82 hours	30 mm concrete tiles, 38 mm air gap and 0.2 mm polyethylene (high density). U_{value} = 2.59 W/m^2.K, thermal lag = 0.82 hours
External walls	9 mm fibre cement sheet, 0.2 mm vapour membrane, 30 mm OSB board, 102 mm glass wool insulation in combination with 0.8 mm steel studs and 15 mm gypsum board. U_{value} = 0.5402 W/m^2.K, thermal lag = 2.6 hours	15 mm cement plaster, 220 mm brick normal fire clay and 15 mm cement plaster. U_{value} = 2.72 W/m^2.K, thermal lag = 6.05 hours
Internal walls	9 mm fibre cement sheet, 0.2 mm vapour membrane, 30 mm OSB board, 102 mm glass wool insulation in combination with 0.8 mm steel studs and 15 mm gypsum board. U_{value} = 0.5402 W/m^2.K, thermal lag = 2.6 hours	15 mm cement plaster, 110 mm brick normal fire clay and 15 mm cement plaster. U_{value} = 3.54 W/m^2.K, thermal lag = 3.24 hours
Ceiling	6.4 mm gypsum board. U_{value} = 5.58 W/m^2.K. Thermal lag = 0.06 hours	6.4 mm gypsum board. U_{value} = 5.58 W/m^2.K, thermal lag = 0.06 hours
Floor	75 mm concrete 1:2:4 mix and 10 mm cement screed. U_{value} = 3.51 W/m^2.K, thermal lag = 2.15 hours	75 mm concrete 1:2:4 mix and 10 mm cement screed. U_{value} = 3.51 W/m^2.K, thermal lag = 2.15 hours

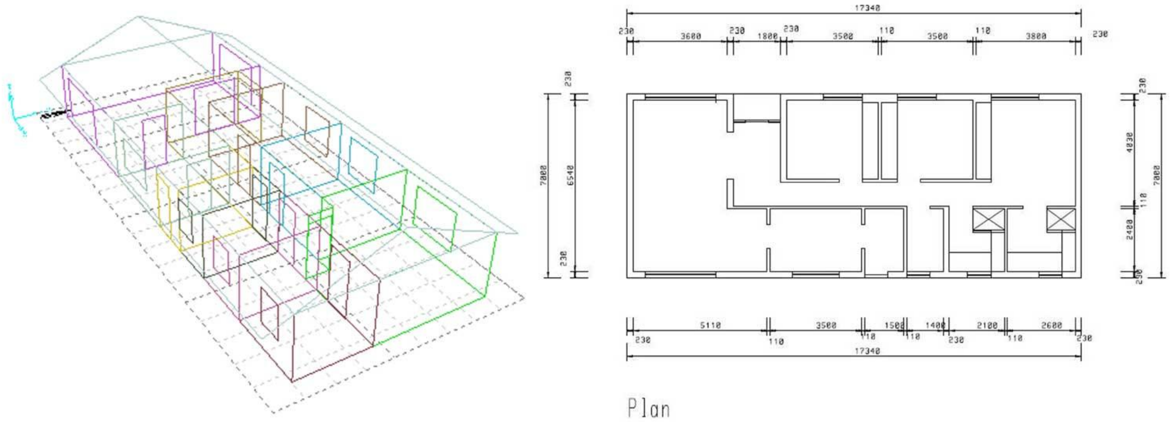

Figure 4 3D thermal model (left) and building plan (right) used in thermal analyses (authors)

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[1] Order of material layers is from outside to inside.

Table 5 Description of high thermal mass and light-weight alternative building envelope materials for energy evaluation. (The colour codes match the bar graphs colours in Figure 5) (authors)

Case	Roof	External wall	Internal wall	Ceiling	Floor
C	Table 4	Table 4 (low thermal-mass house)	Table 4 (low thermal-mass house)	140 mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, thermal lag = 0.44 hours	Table 4
D	30 mm concrete tiles, 0.2 mm polyethylene (high density) and 40 mm isotherm insulation. U_{value} = 0.93 W/m^2.K, thermal lag = 0.96 hours	Table 4 (low thermal-mass house)	Table 4 (low thermal-mass house)	140 mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, thermal lag = 0.44 hours	Table 4
E	Table 4	15 mm plaster, 220 mm dense concrete and 15 mm plaster. U_{value} = 3.05 W/m^2.K, thermal lag = 6.3 hours	Table 4 (high thermal-mass house)	140 mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, thermal lag = 0.44 hours	Table 4
F	Table 4	15 mm cement plaster, 110 mm brick normal fire clay, 50 mm mineral wool insulation, 110 mm brick normal fire and 15 mm cement plaster. U_{value} = 0.59 W/m^2.K, thermal lag = 9.08 hours	Table 4 (high thermal-mass house)	140 mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, thermal lag = 0.44 hours	Table 4
G	Table 4	15 mm cement plaster, 50 mm mineral wool insulation, 220 mm brick normal fire clay, 50 mm mineral wool insulation and 15 mm cement plaster. U_{value} = 0.33 W/m^2.K, thermal lag = 10.16 hours	Table 4 (high thermal-mass house)	140 mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, thermal lag = 0.44 hours	Table 4
H	Table 4	15 mm plaster, 220 mm dense concrete and 15 mm plaster. U_{value} = 3.05 W/m^2.K, thermal lag = 6.3 hours	Table 4 (high thermal-mass house)	Table 4	Table 4
I	Table 4	15 mm cement plaster, 110 mm brick normal fire clay, 50 mm mineral wool insulation, 110 mm brick normal fire and 15 mm cement plaster. U_{value} = 0.59 W/m^2.K, thermal lag = 9.08 hours	Table 4 (high thermal-mass house)	Table 4	Table 4

Tracer gas tests were used to measure the infiltration rate for an LSF house built on the CSIR building performance laboratory test site. Carbon dioxide was injected into the house with external windows and doors closed during the tests. In this analysis an infiltration value of 0.57 ACH for all the thermal zones of the light and heavy-weight houses was assumed. Zero occupancy was assumed in each case to simplify the analysis. Weather files for Pretoria, Bloemfontein, Cape Town, Durban, Musina and Kimberley were used. Some new material composites were introduced in the materials database to represent typical building materials used in the construction of heavy and light-weight buildings in South Africa. The thermal characteristics were calculated. *Ecotect*™ does not address the calculation of thermal lag. To address this shortcoming, *Ecomat*™ v1.0 software was used.

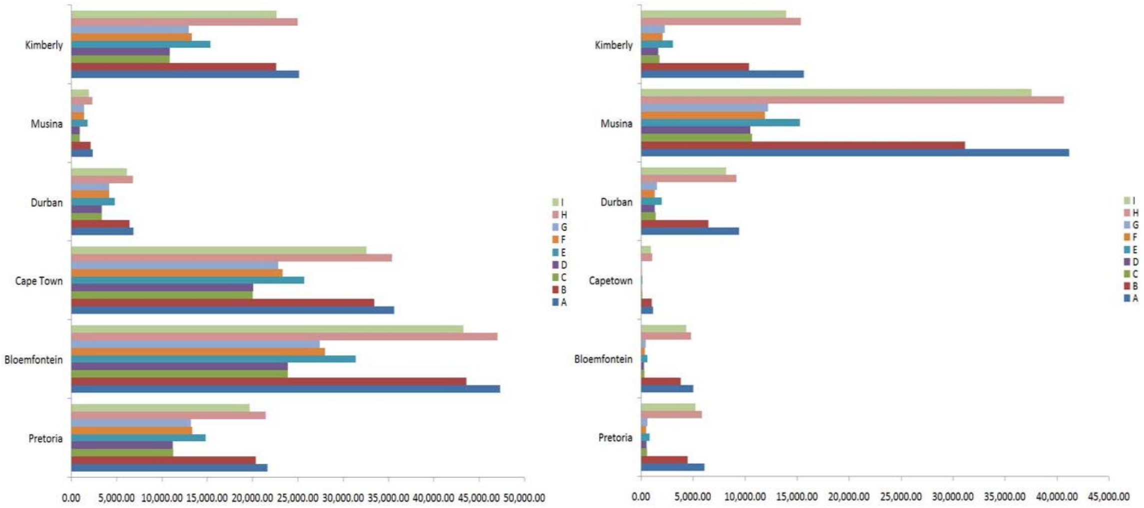

Figure 5 Annual space-heating demand (KWh) (left) and cooling demand (KWh) (right) in six regions (authors)

Figure 5 indicates that some cities require much more space heating and space cooling than others. In cases C and D, the lengths of bar graphs for both heating and cooling are similar for both cases (C and D) in the six regions. The fact that the heating and cooling loads remain similar even after adding roof insulation on top of ceiling insulation, indicates that this intervention does not change the heating and cooling loads in all six regions. The bar graphs for cases C and D are the shortest for both space heating and space cooling in all six regions, when compared to lengths of bar graphs for the masonry buildings. Cases C and D are constructed from high R-value and low thermal-mass building envelope materials. Therefore high R-value and low thermal-mass building envelope materials are far more energy efficient when compared to low R-value and high thermal-mass building envelope materials in the six regions.

5. Conclusions

Advanced computational building performance (CBP) software products make it easier to qualify and quantify the effect of a particular building design, before construction. A good understanding of the basic principles will lead to far better “climate aware” and environmentally conscious energy-efficient architecture. This assumes the availability of enough weather files to support the process. The creation of a new South African Köppen-Geiger map and the subsequent research enabled the team to largely overcome the restricted availability of specific weather files. The research indicated that 0.2% of the country’s area is equatorial, 70.89% arid and 28.91% has a warm temperate climate. The study indicated that a strong relationship exists between a particular Köppen region and the expected building performance. This was investigated by means of extensive CBP simulations in different climatic regions. Based on this, a relationship could be established between a particular Köppen region, climatic characteristics and appropriate passive design strategies. When adopting this finding for the prediction of thermal comfort across regions, the impact of regional humidity variations should be factored in separately. Neither the Köppen data nor the *Ecotect*™ simulations consider humidity directly and the correlation could not be extrapolated to include this factor.

From other studies and publications it is clear that, depending on the climatic region, designers can go much further in better use of thermal mass, insulation, ventilation and solar penetration. Holm (1996) provides a detailed discussion of the possible measures that should be taken when designing for the different climatic zones in South Africa.

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