Research Report for the Clay Brick Association (CBA) of South Africa

January 2010

The development of a rational basis for the selection of thermal mass and thermal insulation in external walling, and a set of deemed-to-satisfy (DTS) requirements in the SANS 204 standard for Energy Efficiency in buildings in South Africa.

Prepared by WSP Energy Africa

Authors : Prof.D.Holm, H.C.Harris

CBA Liaison : A.W. Burton

DRAFT FOR REVIEW AND COMMENT

Executive Summary

The development of national standards and regulations for energy efficiency in buildings worldwide has brought about increases in the stringency of the thermal resistance requirements of walling systems. In no country has a rational basis for the selection of the appropriate thermal capacity or thermal mass for the improvement of the energy efficiency of buildings been set out in such documents. This is despite well documented building physics being available to assist the regulators and the designers. The National Building Research Council (formally part of the Council for Scientific and Industrial Research (CSIR)) in South Africa were pioneers of the CR Method, which was one of such methods, and which was developed in the early 1980's. This work is further developed in this project. In this project modern desk-top computing is used to apply the CR methodology to develop proposed deemed-to-satisfy requirements for a combination of thermal capacity and thermal resistance, building on equations developed by Wentzel[10], and then Mathews[7].

The CR Method result is compared with the results of building Energy Simulation methods, and Life Cycle Cost evaluation, in order to provide financial justification for specifying the amount of active thermal capacity necessary to ensure comfort in buildings, in varying climatic regions of South Africa, for various types of building occupancy. This project reports on how the Active Thermal Capacity can be used as a design tool which facilitates the selection of appropriate combinations of thermal mass and thermal resistance.

Buildings in South Africa are classified according to occupancy in the SANS 10-400 series, which is the interpretation of the National Building Regulations, as per Act 103 : The National Building Standards and Regulations Act. Although these occupancy classes are referenced in SANS 204 : Energy Efficiency in Buildings, they were designed to serve the Fire Regulation requirements (as per R.Watermeyer in a presentation of the proposed amendments to the National Building Regulations for improved sustainability).

Deemed-to-satisfy external walling solutions have been proposed in the Version 2 draft of SANS 204 which have been developed out of the Building Code of Australia rules. The Clay Brick Association has tasked the authors of this report to develop a rational basis for a set of rules which building designers can apply such will ensure energy efficiency to a level which has been found acceptable to the Department of Minerals & Energy, and will assist the national effort in reaching the 2015 energy reduction targets, as have been set out in the RSA Energy Strategy.

In Section 1 of this document it is hypothesized that walling (and other elements of the shell of a building) are capable of influencing the thermal comfort and energy usage of the perimeter zone of buildings and do not have a significant influence on the thermal comfort and energy efficiency of the interior zone of buildings. Documentary support for the notion that the exterior walls are an important determinant of energy efficiency of the exterior zone is found in the literature (as is detailed in section 2), and is evidenced via the modeling of buildings, such as to confirm that this approach is scientifically correct.

Two important specification rules follow this presumption. Firstly, the specification of the walling and shell of buildings should not be influenced by the size of buildings, and the shell therefore serves the energy efficiency (of mainly) the perimeter zone. Secondly, any building which is to be entirely naturally ventilated should be comprised of perimeter zone spaces, which will generally be rooms with external windows and walling.

The determinants of the requirements of a walling system in any climate are:
The occupancy type, which dictates the occupation density, levels of activity (and heat generation), comfort requirements as in the level of comfort compliance (for example either 90% for within +/- of 1.2K about the thermal neutrality for air-conditioned buildings, or 80% for the range of +/- 3.5K for naturally ventilated buildings).

It was also shown that by grouping the above determinants that the many classifications of building in the National Building Regulations can be clustered into four main groups, such as to significantly reduce the number of different specifications of wall necessary to be tabulated in the SANS 204 tables. A further reduction of the four clusters to three, is also motivated. The three clusters of occupancy are then : Residential, Office and Institutional combined and, thirdly, the Retail cluster.

Section 2 of the project is intended to test whether the basis for a rational approach to the correct level of thermal resistance and thermal capacity could be found in the application of the CR Method.

The CR Method is a regression based formula which links the degree of modulation in amplitude of internal temperature experienced in buildings with various levels of thermal resistance and thermal capacity. The amplitude is expressed as a ratio of the internal temperature amplitude versus outside diurnal temperature fluctuation. It is shown that temperature fluctuation in a building can be reduced by improving the thermal efficiency of the shell and it follows that the building can be operated at lower energy intensity levels.

For all climatic regions an optimum indoor thermal neutrality temperature exists which is related to the mean temperatures of that local climate. For any regional climate, for a given occupancy, there exists a range of temperatures which satisfy the users of the buildings, and a daily and seasonal swing of temperature which is acceptable for minimizing heating or cooling energy and cost. The required fluctuation ranges for various South African climatic regions are provided in the report.

The CR Method provides an Active Thermal Capacity, measured in kJ/K per wall area, which indicates the minimum required combinations of thermal mass and thermal resistance which are necessary to maintain the temperature fluctuation within the comfort temperature range. For practical purposes and ease of calculation, the arithmetical product of thermal capacity and resistance (the CR Product) of walling systems is proposed to be used as a performance requirement in building design and for deemed-to-satisfy rules. The CR product is measured in time units, and is a constant property of the building shell.

This approach has been verified via a statistical correlation of the CR Product for various walling systems with the calculated energy usage of the buildings using these walling systems. The correlation is over 90% in the vast majority of cases, so it is with confidence that the CR Method can be used to construct either a Rational Design Tool using Active Thermal Capacity, or a simple deemed-to-satisfy rule for walling using CR Product, which establishes minimum thermal capacity and thermal resistance combination requirements, and which might be suitable for use in SANS 204 or the National Building Regulations.

Contents

1. Methodology

1.1 A methodology for grouping SANS 10-400 occupancy classifications

The initial phase of the project was focused on providing a rational basis for combining the 31 different occupancy classes into clusters with similar energy drivers.

The main determinants of energy usage in buildings are:

- Climate for the building location
- Timing and duration of occupancy
- Density of occupants
- Required temperature range for occupants
- Natural versus artificial ventilation
- Activities of occupants
- Size of buildings

The energy usage can be ameliorated by designing the shell of the structure with a view to optimising the above determinants, and by using energy efficient equipment (lighting, HVAC etc.).

1.1.1 Climatic variation

It is common cause that the climatic variation is to be catered for in SANS 204 by providing performance criteria which are differentiated by regional climate.

1.1.2 Timing and duration of occupancy

Buildings occupancies can be divided into those which are occupied around the clock, and those which are of pre-dominantly day-time occupancy. Those occupied on a mainly daily basis are those such as offices, shops, and clinics. The period of occupation is approximately 12 hours each day. The buildings which are occupied around the clock are those such as hospitals, and these are usually residentially based, and approximate a 24hr occupation by the majority of the occupants.

1.1.3 Density of occupants

The density of occupants can vary widely and ranges from 1 person per 10-20m^2 for some offices verses 1 person every 2.0m^2 for classrooms.

1.1.4 Required temperature range

For air-conditioned buildings the expectation is that buildings do not vary by more than 2.5K about a thermal neutrality of 22 – 24 degrees C. Thermal neutrality does vary from one climatic region to another, and for the season. The level of satisfaction of this temperature environment is recommended to be 80%[1]. For a higher level of satisfaction a tighter range applies. For naturally ventilated buildings, a wider range of temperature fluctuation of 7.0K around the thermal neutrality is acceptable, and to an 80% satisfaction level[1]. Deviation from this range will encourage either heating or cooling, or artificial ventilation, all with energy usage consequences.

1.1.5 Natural versus artificial ventilation

SANS 10-400 Part O of the National Building Regulations requires that a minimum of 7.5 litres per square meter per second of fresh air should be supplied to all buildings, whether by natural or artificial ventilation systems. The regulations assume that with sufficient openable windows, building occupants will manage the openings such as to provide this level, or an adequate level of ventilation. Smaller buildings for which the occupied area can be served by natural ventilation need not be artificially ventilated. For larger buildings the ventilation equipment has to supply the above minimum rate of ventilation.

1.1.6 Activities of occupants

The activity of occupants is an important determinant of energy usage in buildings. Sedentary occupants such as office workers are issuing approximately 100W, whereas factory workers in heavy manufacturing are issuing as much as 300W. In a building such as a shopping mall, the large number of shoppers and retail workers can give off so much heat that heating of the malls is not necessary, even in winter.

1.1.7 Building size

Smaller buildings have a proportionately larger shell or surface area to volume ratio than that of larger buildings. The influence of this effect on energy usage per square meter is that for larger buildings it is easier to meet the Energy Usage Intensity performance requirements of SANS 204, than it is for smaller buildings. (See also Section 2.6)

If this aspect is analysed in some detail it is found that the energy usage in the perimeter zone of any building is different from the interior zones. Exterior zones should be provided with separate air-conditioning ducting, air-handling, heating and cooling systems. Interior zones in larger buildings need less heating and cooling as they are not subjected to the heat losses and gains which occur through the building shell. The requirement for the interior zone of these larger buildings is often primarily for fresh air rather than heating or cooling.

The efficiency of the shell of a structure is important to the perimeter zone energy usage, and largely irrelevant to the performance of the interior zone. As result a smaller building may be considered as comprising mainly of perimeter zone, and although for a larger building the perimeter zone is still important, the relevance of this zone is reduced as the interior zone is increased in size.

1.2 Rationalisation of the above energy usage determinants

1.2.1 The size of a building

For the reasons explained above in paragraph 1.1.7, the size of buildings in any particular occupancy group is not a factor in typifying that particular occupancy group, and the efficiency of the shell is as important for large buildings as for small buildings. If economic viability and efficacy of a building shell deemed-to Satisfy solution has been demonstrated for any occupancy via a small building, then the same level of performance is applicable to the larger building of the same occupancy. This principle is tested in this document.

1.2.2 Occupant density, activity levels, temperature range and ventilation system

Larger buildings (which are deeper) need to be ventilated artificially and the temperature range at which this air is provided needs to conform to the parameters set out in 1.1.5. The air supply temperature is also designed to void the heat loads contributed by the occupants of a building, or provide them with adequate heating, and maintain the same range. The density (number of occupants per square meter) of occupants and their activity level determines the above heat loads. These factors can be combined to broadly describe the internal environment, and are either to an 80% level for naturally ventilated buildings, and 90% for artificially ventilated buildings.

1.2.3 Defining parameters for determining energy usage typical of occupancies in buildings

After combination as above, the remaining factors in determining energy usage for common building occupancies are then:

- Climatic region
- Occupancy pattern (approximately 24hr or 12hr)
- 80% or 90% performance requirement

1.2.4 Grouping of occupancies

Combinations of the above determining factors are consistent with clusters of occupancies, listed below in Table 1 :

Occupancy	24hr	12hr	80%	90%
Cluster	Occupancy	Occupancy	Requirement	Requirement
Institutional	No	Yes	Yes	Yes
(A1,A2,A3,A4,C1,C2)				
Office	No	Yes	Yes	Yes
(B1,B2,B3,G1)				
Industrial	Yes	Yes	Yes	Yes
(D1,D2,D3,D4,J1,J2)				
Residential	Yes	No	Yes	No
(E1,E2,E3,H1,H2,H3,H4,H5)				
Retail	No	Yes	Yes	Yes
(F1, F2,F3,J3)				
Health (Non-res)	No	Yes	Yes	No
(E4)				
Not classified (A5,,J4)				

Table 1 – Clustering of building occupancies

This table has informed the structuring of the Table 5.4.2.2 in SANS 204 Version 2. Further rationalization is possible if the Institutional building determining factors are compared with those of the Office clustering. It is mainly classrooms which might have different energy drivers as compared to Office buildings. Occupancy levels for classrooms are high and ventilation provisions (probably counter to actual needs) are lower than those for offices, but lighting, occupancy hours and activity levels are similar. In view of the similarities, and the above contradiction, the Office and Institutional buildings are combined for the analysis in this project. The end result of the above rationalizations is the proposed Table 2 below:

Residential	E1,E2,E3,H1,H2,H3,H4,H5
Office & Institutional	A1,A2,A3,A4,C1,C2, B1,B2,B3,G1
Retail	F1, F2,F3,J3

Table 2 – Clustered and rationalised occupancy classifications

1.3 A methodology for assessing the suitability of walling designs for energy efficiency

1.3.1 Climatic influences

An optimal indoor thermal neutrality exists for all climatic regions, and which is related to the mean temperatures of that local climate. These thermal neutralities are set out in Table 1 of Section 3, with temperature data for some South African localities in Figure 1 of that section. For any regional climate, for a given occupancy, there exists a range of temperatures which satisfies the users of the buildings for comfort. There is a daily and seasonal swing of temperature which is acceptable for minimizing heating or cooling energy and cost. The required minimum fluctuation ranges are also provided in Section 3.

1.3.2 Using the CR Method

The CR method is used to demonstrate that if the temperature fluctuation inside a building can be reduced by improving the thermal efficiency of the shell then it should follow that the building can be operated at lower energy intensity levels.

The CR Method is a regression formula which links the degree of fluctuation in temperature experienced in buildings with various levels of thermal resistance and thermal capacity. This fluctuation is expressed as a ratio of the internal temperature amplitude versus outside diurnal temperature fluctuation.

The CR Method provides a CR constant (arithmetical product) which is measured in hours, and which indicates, over a range, the necessary combinations of thermal mass and thermal resistance which needs to be provided in a building walling system (or other parts of the structure). The Active Thermal Capacity is calculated with cognizance of the position of thermal insulation within a high thermal mass wall, and which is necessary in order to maintain the temperature fluctuation within the comfort temperature range.

It is either the Active Thermal Capacity or the CR constant which appears to be conveniently suitable as a performance criterion for the deemed-to-satisfy rules to be proposed for in energy efficient buildings. This is to be investigated in this report.

1.3.3 Correlation with energy usage

Critical to this approach is the requirement that the CR constants for various walling systems be compared with the energy usage of the buildings using these same walling systems, and if found to be closely correlated, it then follows that the CR Method can be used to construct a rule for walling which might be suitable for use in SANS 204 or the National Building Regulations. The results of this correlation are shown in the Section 3.4.2.

The appropriate design of building for testing these correlations was developed by trying a number of building design variations. A simplified version of a 132m^2 CSIR designed building (residence) which eliminates many extraneous design elements outside of wall design was found to be suitable for this purpose. See Annexure A. The Active Thermal Capacity of walling systems and their thermal resistance are calculated for the external walls of a synthetic building design, and the required CR constants generated such as to maintain the required minimum temperature fluctuation.

In order to avoid the tedium of the many calculations, it was decided to develop software to generate the CR constants and Active Thermal Capacities for various combinations of thermal capacity and thermal resistance.

The energy usage of two building design variants are modeled for three occupancy clusters with five relevant walling combinations tested over six climate zones using Visual DOE software. This data is then evaluated against the CR constants to assess the relationship.

1.3.4 Selection of appropriate CR or active thermal capacity as performance criteria

The lowest life cycle cost of the walling intervention in the selected synthetic building is proposed as the method for selecting the appropriate deemed-to-satisfy level of performance which can be used for Regulation or Standard. The various possible criteria are tested using this technique.

The Life Cycle Cost is determined by subtracting the incremental cost of the walling intervention from the discounted value of the energy savings expected to result from using the walling material with the intervention over the life of the building. (The life of the building is assumed to be at least 20 years, and this is considered conservative. Any longer figure would serve to over-emphasise the intervention.)

The selection of the walling systems was based on a solid double brick wall with incremental levels of thermal insulation applied in the cavity of the wall, such as to yield added thermal resistances from zero to 1.0$m^{2.}$K/W, as per SANS 204. The Active Thermal Capacity and CR values are calculated using the software developed and applying the equations of Wentzel[10] and Mathews[7], and in addition a simplified alternative is developed. This is the arithmetical product of the thermal resistance and the thermal resistance of the walling system.

The application of the formulae and calculations are detailed in Section 2. It is important to understand that other and different combinations of thermal resistance and thermal mass could have been used but which would have generated the same relationships between CR or Active Thermal Capacity and Life Cycle Cost. i.e. the selection of materials has no bearing on the conclusions provided that the cost per unit thermal resistance and cost per unit thermal capacity is reasonably consistent for alternative materials.

2 *The Theory of the CR Method and further development*

2.1 Introduction

The theory of the CR method was pioneered in the 1980s by Johan D. Wentzel of the then National Building Research Institute of the Council of Scientific and Industrial Research, and was derived by correlating many field measurements of typical South African constructions with a theoretical model. At the same institution, E. Matthews later started working on a computerised electric analogue, which eventually was published as the “Building Toolbox” simulation program. The algorithm includes a calculation of the summer Sol-air temperature instead of the outside air temperature. It does not assume a blanket empirical summer dT of 2K as the old CR method does. It also introduced many refinements that were inaccessible to the original empirical CR method.

2.2 The CR Method explained

In essence the CR method (and its further developments) identifies the climatic driving forces as being the outside temperature amplitude (α_o) and the solar radiation (I). These driving forces interact with the building’s properties such as active thermal capacity (C) and its envelope resistance (R).

First, the average indoor temperature rise (dT) has been found to be proportional to $I_w R/A_{fl}$, where

I_w = solar radiation transmitted through glazing (kWh/d)
A_{fl} = floor area (m^2)
R = specific envelope resistance (m^{2}K/W)

This means that the larger the product of the unshaded sun-exposed window area multiplied with the envelope resistance, the warmer the average winter indoor temperature of a given building. This is intuitively appreciated by most building designers and the public.

However, ordinary glass has a much lower thermal resistance than typical walls. By increasing the window area the average envelope resistance is reduced counter productively. This can be compensated by either double glazing or additional insulation in the envelope (external walls, doors and roofs). In addition, there is a risk of overheating during summer.

Second, the CR-method states that the product of active thermal capacity (C) multiplied with the envelope resistance (R) is inversely proportional to the amplitude ratio: CR = constant/amplitude ratio
where amplitude ratio = indoor temperature amplitude (α_i)/outdoor temperature amplitude (α_o) and amplitude = difference between maximum and minimum temperature:

Rearranged to α_i/α_o = 48,9Rs/(CRs)^0.903

It should be noted that the definition of climatic amplitude differs from the definition used in physical sciences.
The formulae have been simplified to:

- α_{iw}/α_{ow} = 260,17/C_{actw}
- αis/$\alpha_{ossolair}$ = 150,41/C_{acts}

where
α_{iw} = indoor amplitude, winter
α_{ow} = outdoor amplitude, summer
C_{actw} = active thermal capacity, winter
α_{is} = indoor amplitude, summer
$\alpha_{ossolair}$ = solair outdoor amplitude, summer
C_{acts} = active thermal capacity, summer

2.3 Notes on the application of the CR Method

The following should also be noted:

- The simplified method expresses the amplitude ratio in terms of active capacity only, but the weighting factor is derived by the use of resistances. Therefore, the CR product is still accounted for.
- The Envelope resistance (R) can contribute positively to both the average air temperature in summer and winter as well as to the desired reduction of the indoor temperature amplitude (swing).
- R requires the “help” of both C and I.
- A given target dT can be reached by many combinations of I_w and R.
- A given target amplitude ratio can be reached by many combinations of C and R.
- The larger the CR product, the smaller the indoor amplitude (α_i).
- Dividing the target α_i by the known α_o, we obtain the target amplitude ratio, and hence the target CR (See Figures 1, 2 and 3).
- Since the indoor temperature swing is influenced by the active thermal capacity exposed to the indoor air, it would be better to express the active thermal capacity in terms of capacity per indoor air volume rather than per envelope area. (See also Baggs, in prep).

2.4 Further development of the CR Method

Closer scrutiny of the formula α_i/α_o = 48,9Rs/(CRs)^0.903 reveals that Rs (resistance per m² of envelope area) appears both in the numerator and denominator of approximately equal weight. Therefore, the thermal resistance effect is greatly reduced and the formula can therefore be refined for greater accuracy.

Secondly, the ratio of indoor to outdoor amplitudes is based on air temperatures. In fact a building “experiences” the outdoor temperature at its exterior envelope surfaces. As a result of radiative gains and losses this surface temperature deviates substantially from the air temperature. The temperature a building ‘experiences’ is called Solair temperature and it varies according to radiation, wind speed, and absorptivity. The latter is influenced by the surface colour. This effect is most pronounced during summer as a result of the higher radiation levels.

The simplified formulae can be restructured to establish a direct relationship between the required amplitude ratio and the active thermal mass:

$\alpha_{iw}/\alpha_{ow} = 260{,}17/C_{actw}$ or
$C_{actw} = 260{,}17/(\alpha_{iw}/ \alpha_{ow})$, and
$\alpha_{is}/\alpha_{ossolair} = 150{,}41/C_{acts}$ or
$C_{acts} = 150{,}41/(\alpha_{is}/\alpha_{osolair})$

Note that the summer outside temperature has been replaced by the average of the outside air and Solair amplitude.

The implications of the above are expanded upon in the results section below.

2.5 Optimal CR

2.5.1 Intuitive approach

Steve Baer, renowned inventor of Albuquerque, New Mexico, discovered that CR can be optimised. The result is that the optimal CR is achieved when the assignment to C and R is exactly equal. This holds true for all assignment criteria that may be applied to C and R, whether it be space, weight or money. It can best be visualised by the fact that the rectangle with equal sides (square) produces the largest surface area for the shortest sides. The optimal CR is achieved by investing equal amounts in C and R.

2.5.2 Typical South African construction

One of the main functions of buildings is to provide an environmental filter between the outside and in-side of the building. That is, to create a better indoor environment than outside. Few modern buildings actually achieve an acceptable indoor climate without resorting to artificial means. Since buildings generally consume about 40% of the world’s primary energy, and since this energy is predominantly derived from finite and polluting fossil fuels, there is a strong global move to reduce the dependence on artificial climate control mechanisms.

In contrast with Australian and North American building traditions, South African building construction typically is a heavy mass (high thermal capacity) construction. This is fortuitous because most of the country has a semi-arid climate at relatively high altitude with large diurnal temperature fluctuations that are best met by the use of high thermal mass combined with good insulation. Unfortunately, the fashion of oversized windows largely defeats the object of both insulation and thermal mass.

2.6 Crucial building elements

2.6.1 Envelope effects

The *building envelope* determines the degree of air leakage, which can annul the benefits of C and R.

The *building envelope* also contains the windows and their shading, which can either bring comfort or lead to overheating/overcooling. Overheating during summer must be expected to increase in South Africa with global warming aggravated by urban heat islanding. The notorious Big Californian Blackout was triggered by a summer cooling demand.

The *building envelope's* insulation determines the conductive, radiative and convective heat losses or gains of a building.

The thermal mass directly or indirectly exposed to the indoor air is called the active thermal mass.

2.6.2 Active thermal mass or Active Thermal Capacity (C)

The indoor thermal mass is active in as much it interacts with the indoor air by either heating or cooling it. Air has a thermal mass of only 1,2kJ/m^{3}K, whereas brickwork has 1360kJ/m^{3}K, and concrete 1764kJ/m^{3}K. Therefore, such materials have a strong impact on the indoor air temperature. It also explains why it takes a lot of air movement to heat or cool a heavy structure.

However, if the indoor thermal mass is insulated from the indoor air, then the effect is greatly reduced if not eliminated entirely. This happens with the usual wall panelling, cupboards, pictures, curtains, and paintings or floor carpets, rugs, wooden floors or suspended ceilings, bulkheads, acoustic treatment below concrete slabs.

In South African domestic buildings larger than about 40m^2 heavy internal walls are traditional, but from about 80m^2 upwards, carpeted floors are prominent. With commercial buildings, carpeted floors, lightweight partitions and suspended ceilings are predominant. Since the use of carpets, pictures, wall panelling etc inside of houses cannot be controlled or regulated, and since the indoor mass of floors, ceilings and partitions of many buildings cannot be relied upon with respect to legislation, it is recommended that these be ignored in calculations. This leaves the thermal mass effect of exterior walls.

The calculation of the Active Thermal Capacity (C) is achieved by weighting the thermal mass (volume x density x specific heat) of all exterior walls in terms of the ratio of the total thermal resistances of the wall to the thermal resistance from the inside surface up to the centre of the high mass element.

2.7 Surface-to-volume and perimeter ratios

When Hannibal crossed the Alps with African elephants his men suffered under cold stress. No so the elephants whose body surface to volume ratio is much smaller. The same natural law applies to buildings. When the wall thickness of the new low-income houses was reduced, this decreased the thermal mass and the thermal resistance of the exterior walls, thereby creating an additional demand for heating and cooling energy. Furthermore, when the floor plan of the standard NE 51-9 was reduced from 53m² to 30m² this caused an additional demand of 28% of energy in order to retain the same indoor conditions – assuming that the wall had remained the same. This demonstrates that the stand-alone house model is a poor choice from a thermal and energy point of view, and certainly not a sustainable model for the low-income sector. That is one of the reasons for the international use of terrace and row housing for all income sectors (see Figures 1 and 2).

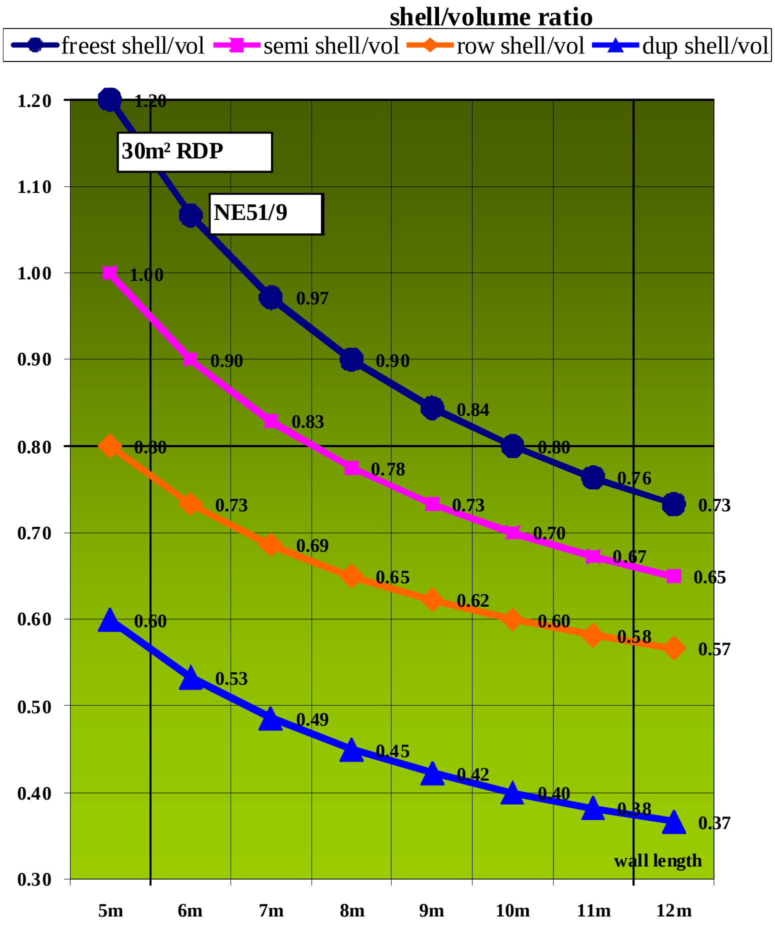


Figure 1 – Building shell (envelope)-to-volume ratio.

The size reduction of the low-income house increased the surface-to-volume ratio. To retain the same indoor climate would require an additional 28% of envelope insulation and commensurate thermal mass. The figure also graphically shows the poor thermal performance of the stand-alone (freestanding) housing model as compared to duplexes.

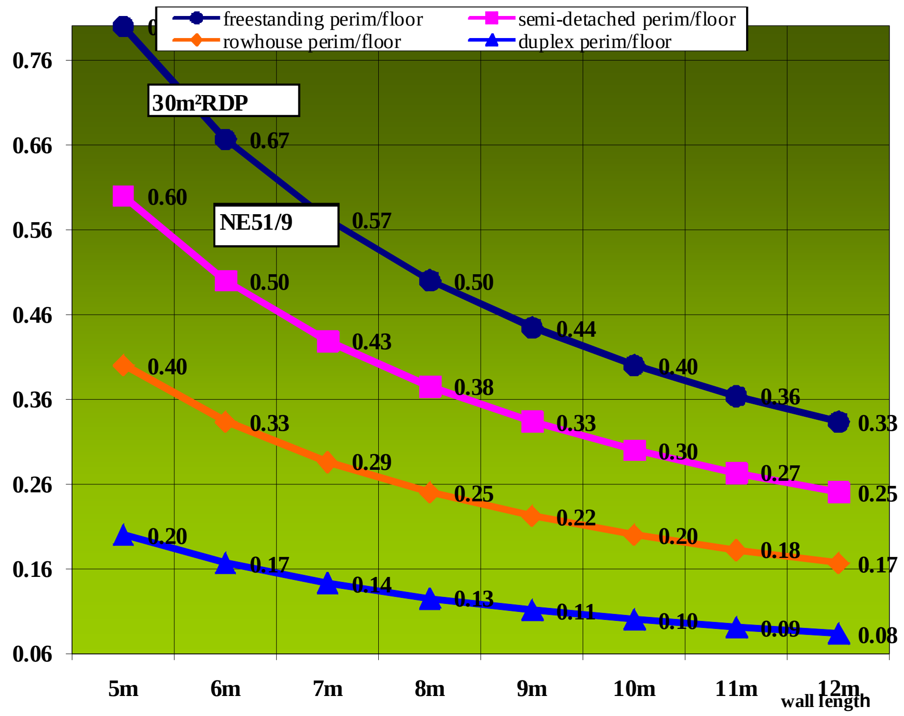


Figure 2 – Perimeter to floor area ratio.

The reduction of floor area has increased the perimeter to floor area ratio. Therefore, the unwanted heat gains/losses are increased and the thermal mass effect is reduced. The figure also graphically shows the poor thermal performance of the stand-alone (freestanding) housing model as compared to duplexes.

With the advent of artificially controlled environments it became possible to construct buildings whose indoor climate is only very tenuously linked to the outside environment. These buildings have a small surface to volume ratio and are characterized by a cooling demand even in midwinter because the heat (of lighting, appliances, people) generated by the large interior of the building cannot be cooled by the relatively small perimeter zone.

The perimeter zone is that area of a building that is directly influenced by the exterior environment with respect to potential daylighting, heating, cooling, natural ventilation, sound and view. In deep plan buildings the perimeter zone is the preferred area for senior staff.

2.8 Notional perimeter zone

Obviously, the physical dimensions of the perimeter zone is influenced by the many factors listed above, plus practical considerations of room sizes as well as limitations of building construction and costs.

Cowan (1964) reported that the majority (67%) typical activities were accommodated in a room size of 18,5m²; and 14m² housed 61% of the activities (See figure 3 below).

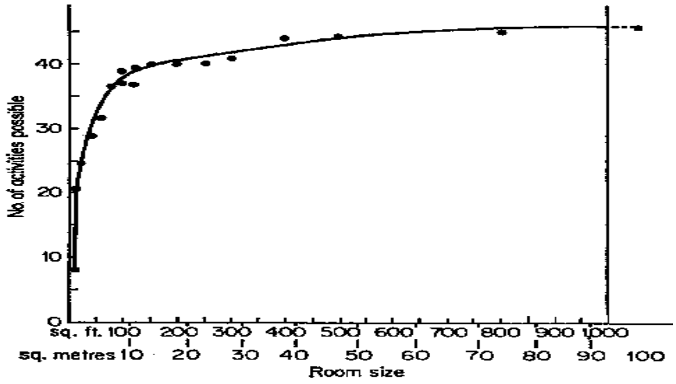


Figure 3 – Room sizes to accommodate activities (Cowan P. 1964)

For daylighting in South Africa the National Building Regulations prescribe a minimum glazed area equivalent to 10% of the served floor area, while the NBRI CSIR publication K61 1982 (p72) recommends a room depth of 1,5-3,5 (average 2,5) times the vertical difference between lintel and work surface (850mm) height. With standard lintel heights of 2100mm in most residential buildings this yields a room depth of 3000mm. The standard office used by DEO (2590 high x 3050 wide x 4570 deep) produces a room depth of 2,6 times the lintel-sill level.

The room depths of the comparable notional South African buildings are tabled below.

	Room depth (mm)	**Window height depth ratio**
53m² low-income house	3 000	2,4
153m²middle-income house	3 500	2,4
School	3 600	2,4
Clinic	4 500	3,2
Office	3 500 - 5 500	3,2

Table 3 – Room depths

The New Architects Journal Metric Handbook recommends similar room depths for the residential sector (including old age homes and hotels) but significantly shallower depths for both clinics (3000) and offices (4000-4800). Hausladen (2004) recommends an office depth from 3500 to 5500 with a preponderance of 4000.

SABS 0400-1950 prescribes a minimum ceiling height of 2100 in certain areas, but the largest area of habitable rooms must be at least 2400 high. This is reflected in the notional buildings.

2.9 Conclusion on the perimeter zone

The following conclusions can be reached regarding notional perimeter zones and how these can be used in developing the design requirements for the shell of a structure.

- With the exception of a few underground buildings the majority of naturally ventilated and artificially conditioned buildings has a perimeter zone in contact with the outdoor environment.
- This outdoor environment has the strongest impact on the perimeter zone of all buildings
- While deep plan buildings have perimeter zones and inner zones, naturally ventilated have perimeter zones only.
- In case of power failures or emergencies it should be possible to open perimeter zone windows of deep offices.
- The notional perimeter zone of 2500 height and 3500 depth can be assumed to capture the majority of the population with a view to energy use, peak demand and GHG emissions.
- The shell of the structure, and more specifically the wall can be designed to serve the perimeter zone as conceptualised.

2.10 Development of simplified design for analysis purposes

The combination the above perimeter zone requirements into simplified designs, which would cover the variations between building occupancies; residential, commercial, institutional and retail – following the clustering of occupancies, as per Section 1, culminated in two simplified variations on the CSIR ‘134m2 Garsfontein house’; a well know design which has been used in building research work over many years. (See Annexure A)

The essentials of the design are that there is no interior zone, and the building can be modelled as a single zone, all of which is within 3.500m of a perimeter wall. The standard window area is evenly distributed over the North & South facades, for the non-residential design which has continuous window strips of equal size on both the North and South facades, and are well shaded. High levels of insulation, perimeter insulation/floor insulation and heavy carpeting ensure that the thermal contribution of the walls are maximised or emphasised.

Variants of this design are developed to cater for the proposed classification. The floor area is maintained constant in order to meet the objective of the building being of entirely perimeter zone. For the residential and retail design the windows are concentrated on the north side.

While developing the standard 130m2 design for the required commercial and institutional occupancies it transpired that the designs developed are very similar providing further support of the combination of Institutional and Commercial occupancies.

3 Analysis and Results

3.1 Target Temperatures

This section aims to establish target temperatures for indoor conditions in South African buildings. The scientific base is explained eventually leading to differentiated and practically implementable target temperatures.

3.1.1 Function of buildings

One of at least five generic functions of buildings is to serve as an environmental filter, that is to keep out unwanted elements such as heat, cold, rain, pollution, vermin, mosquitoes and criminals. In the past little attention had been paid to this environmental filter because of the exceptionally benign climate, conducive to outdoor living and even sleeping with open windows and doors during summer nights. Malaria mosquitoes and the criminal element were perceived to be under control. Cheap and reliable electricity was available artificially improve the indoor climate. An adequate supply of qualified engineers and maintenance staff kept the HVAC systems going. Hence buildings with piteously poor thermal performance could be built with impunity.

But buildings are long-term investments, outlasting the useful life cycle of their designers, owners and the power stations at least a factor of four.

3.1.2 Energy in buildings

Energy is imported into buildings for two reasons. The one is to power indoor processes. This is normally independent of the building's thermal design. The other driver of energy use in buildings is the absence of desirable indoor conditions, which may be insufficient daylight, undesirable temperatures, humidity, indoor quality and noise intrusion. This significant part of energy use is influenced by the building design.

The energy invested in erecting and dismantling buildings is not included here.

3.1.3 Desirable indoor conditions

Productivity is influenced by indoor conditions. It has been shown (Romm et al, 2004) that the money value of productivity increases through desirable natural lighting and temperatures outweighs the money value of concomitant energy savings by a large factor. Other studies revealed higher manual process productivity (e.g. typing) at slightly elevated temperature while intellectual productivity (e.g. arithmetic) increased at lower temperatures. In addition racial and gender productivity trends were documented.

Comfort is a much more popular theme, both in literature and practice. Air temperature dominates other factors. The comfort temperature is defined as that temperature at which a person feels neither to hot nor too cold. Initially it was believed that there must be a single static comfort temperature for all humans in all climates. When this concept conflicted with observed reality, the single static comfort temperature was extended to a *comfort range,* thus adding a certain fuzziness.

The fact that people can be comfortable in a sauna led to the thought that expectations, culture and adaptation may be a consideration. It was also observed that the perception of comfort in winter is different from that in summer.
De Dear et al () made a comprehensives analysis of available data. His findings are that there is a definite drift in indoor comfort temperatures dependent on the seasonal and annual outdoor mean temperatures. However, this is only valid within certain minimum and maximum mean outdoor temperatures. They also found boundaries for 80% and 90% acceptability, meaning that 80% or 90% of a climatically adapted population would find a given indoor temperature range acceptably comfortable. Their findings essentially substantiated earlier findings of Auliciems and Szokolay (1997), adding more weight and precision.

The implications for energy efficient building design cannot be overestimated. As a result of adaptation the perceived indoor comfort of a given population is a variable that, within limits, is dependent on mean environmental conditions. It follows that people living in air conditioned spaces will also tend to adapt to the conditioned environment. This would then make the comfort range of air conditioned spaces a self-fulfilling prophecy.
The following formulae have been derived.

Table 4 – Comfort temperatures after de Dear (1997)

Building type	Acceptability	Formulae	Range
Air conditioned	80%	$Tn_{AC80\%}$=22,6°C+0,04ET^*_{outd}	±2K
Air conditioned	90%	$Tn_{AC90\%}$=22,6°C+0,04ET^*_{outd}	±1,2K
Naturally ventilated	80%	$Tn_{NV80\%}$=18,9°C+0,225ET^*_{outd}	±3,5K
Naturally ventilated	90%	$Tn_{NV90\%}$=18,9°C+0,225ET^*_{outd}	±2,5K

The validity limits are 17,8°C < Tn < 29,5°C where Tn is the neutrality temperature, and ET* is the New Effective Temperature and is calculated in a rather complicated manner.

Holm and Engelbrecht have shown (2005) that the practical difference between ET* and dry bulb temperatures was practically negligible for South African historic data. This is not valid for the combined effects of urban heat islanding and climate change.
As the South African population generally does not live in air conditioned spaces and seem climatically adapted HVAC engineer, Dr A. Johannsen suggests that the single comfort temperature of Tn_{NV} be used for purposes of building fabric design (email: 2009-09-16).
Since the amplitude of ±2K ($Tn_{AC80\%}$) and ±2,5K ($Tn_{NV90\%}$) is very close, it is proposed to group these into the 2,5K category.
This results in the following target temperatures, ranked in decreasing stringency.

Building type	Acceptability	Formulae	Range
Air conditioned	90%	$Tn=18{,}9+0{,}225ET^*_{outd}$	±1,2K
Air conditioned &	80%	$Tn=18{,}9+0{,}225ET^*_{outd}$	±2,5K
Naturally ventilated	90%		
Naturally ventilated	80%	$Tn=18{,}9+0{,}225ET^*_{outd}$	±3,5K

Table 5 – Target indoor comfort temperatures for AC and NV buildings

The adaptive indoor comfort target temperatures for 15 South African locations are presented in Figure 4. The required amplitudes are taken from Table 5.

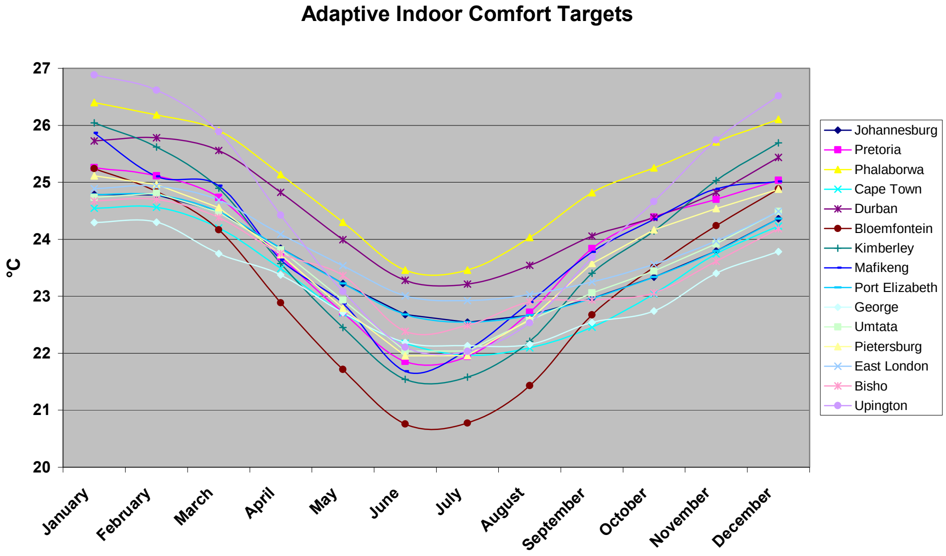


Figure 4 – Adaptive indoor comfort targets.

Bloemfontein has the lowest winter comfort temperature while Upington has the highest. The annual drift of the monthly comfort temperature is clearly visible.

3.1.4 Amplitudes and amplitude ratios

Our body's thermoregulatory mechanism is adapted to varying temperatures. That is why temperature changes are invigorating, while a steady temperature - often achieved at great cost – is soporific. Soporific conditions may be comfortable but are hardly helpful with productivity. However, the extent of acceptable change is limited. During a diurnal cycle the outdoor temperature normally moves from a minimum to a maximum. In climatology the difference is called the outdoor temperature amplitude. The indoor temperature has a similar amplitude, normally smaller. This has to be limited for comfort.

A maximum acceptable (target) amplitude of 7K is expressed as Tn±3,5K. The target indoor amplitude divided by the average outdoor amplitude produces the target *amplitude ratio.* The amplitude ratio is a constant and measurable property of any building.

If boundaries for required amplitude ratios are mapped to achieve 2,4K indoor amplitudes, then the same boundaries will be valid for say a 7K target indoor amplitude.

3.1.5 Summary and conclusion with regard to target temperatures

When buildings are designed for target indoor conditions, comfort is the predominant target and not productivity. However, it is possible to achieve both. Within limits, the indoor comfort mean temperature has been found to be dependent on the outdoor mean temperature.

Having reduced the indoor comfort temperature to a single, albeit complicated, formula for both air conditioned and naturally ventilated buildings, it was possible to reduce the aspect of indoor amplitudes to only three acceptability ranges.

Although 90% acceptability is not an unusual design target, it is proposed that the much less stringent 80% be selected as the prescribed minimum for the building fabric design.

The result is $\mathbf{Tn_{AC} = 18{,}9°C + 0{,}255ET^*_{outd} \pm 2{,}5K}$

and $\mathbf{Tn_{NV} = 18{,}9°C + 0{,}255ET^*_{outd} \pm 3{,}5K}$

Where Tn_{AC} = minimum comfort design temperature for building fabric of air conditioned buildings,

And Tn_{NV} = minimum comfort design temperature for building fabric of naturally ventilated buildings.

3.2 Raising/lowering monthly average indoor temperatures

3.2.1 Heating and cooling differences

The difference between Tn and the monthly mean outdoor temperature (To_{mean}) is called δT_{reqd} and this is an indication of the average monthly heating (+) or cooling (-) required. The area under curve represent Kelvin-days. Multiplying Kelvin-days with the specific thermal transmittance of a building (W/K) yields the monthly heating/cooling required.

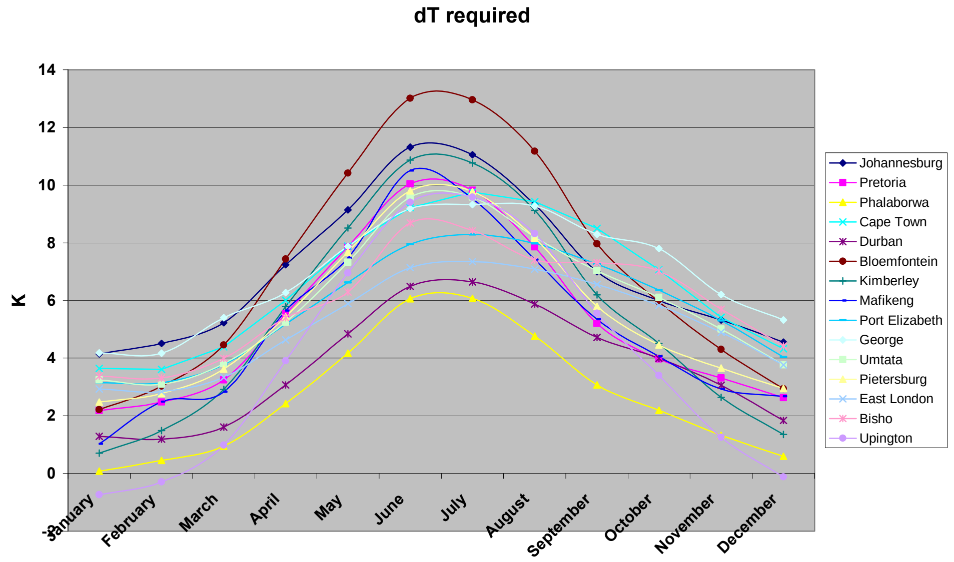


Figure 5 – Relative temperature rise/lowering required.

Bloemfontein requires most winter heating and Upington most summer cooling. Note: indoor loads and sol-air temperature reduce the heating and increase the cooling required.

3.2.2 Passive heating and cooling

For passive winter heating the product of the winter sun penetrating north facing windows and the heat resistance of the envelope is proportional to the actual indoor temperature rise (δT_{act}) above To_{mean}. *For passive summer cooling* window shading and envelope insulation plus night air cooling are effective. This requires sufficient active thermal mass (capacity) on the inside of the envelope insulation. Night cooling may be implemented by natural wind or by the chimney effect, which is weaker. Alternatively, the air is moved by a fan. Night air cooling is very effective in air conditioned buildings.

3.2.3 Achieving the target amplitude ratio

The target indoor amplitude (α_i) is constant while the monthly average outdoor amplitude (α_o) varies. It follows that the amplitude ratio (Ar) also varies during the course of the year. However, the amplitude ratio of a given building is a constant. This implies that the largest α_o becomes the criterion, called Ar_{regd}. The required CR can now be calculated.

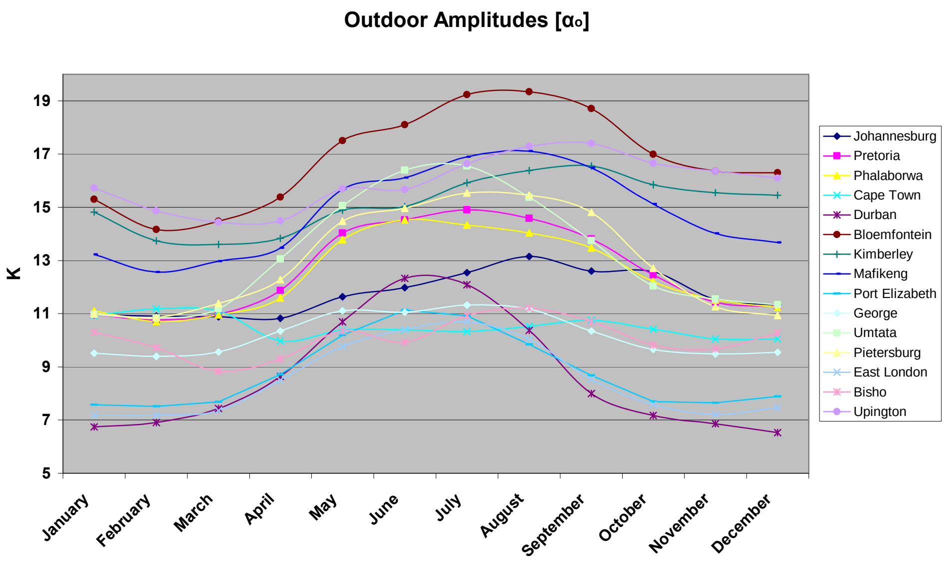


Figure 6 – Outdoor amplitudes.

Inland summer rainfall areas have the highest amplitude during winter, while coastal winter rainfall areas have theirs in late summer.

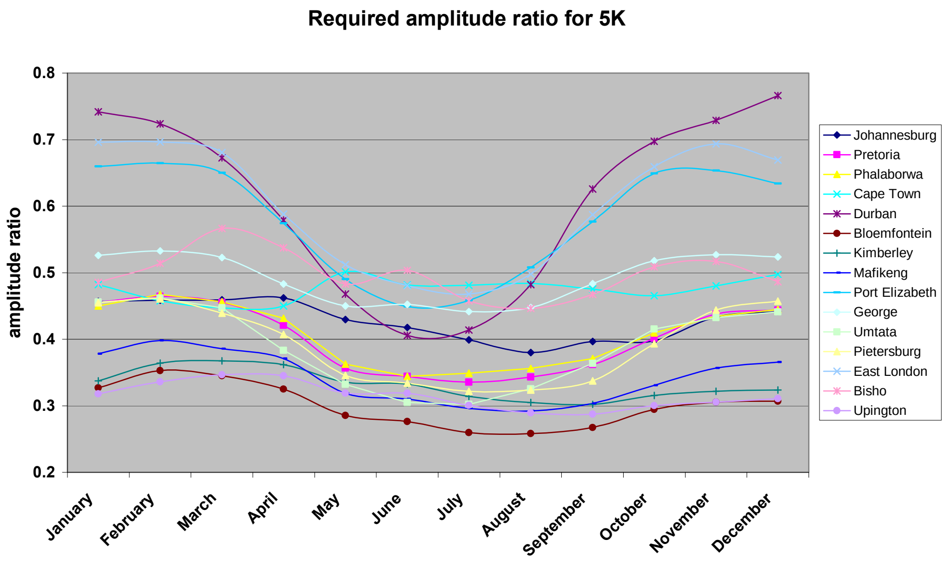


Figure 7 - Amplitude ratios required for 5K indoor amplitude.

Durban requires the least stringent amplitude ratio, while Bloemfontein requires the most stringent.

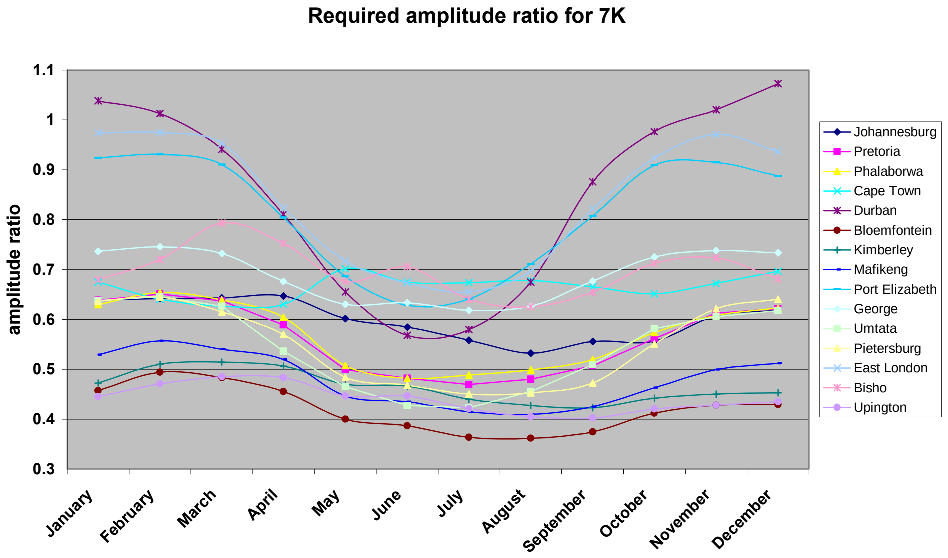


Figure 8 – Amplitude ratios required for 7K indoor amplitude.

The pattern is the same as in Figure 7 but the values differ.

3.3 Achieving target amplitude ratios with added thermal capacity

3.3.1 Application of the CR methodology

In Section 2 the simplified formulae for determining the active thermal capacity required to achieve the target amplitude ratios for summer and winter conditions were indicated i.e.:

$\alpha_{iw}/\alpha_{ow} = 260{,}17/C_{actw}$ or

$C_{actw} = 260{,}17/(\alpha_{iw}/\ \alpha_{ow})$, and

$\alpha_{is}/\alpha_{ossolair} = 150{,}41/C_{acts}$ or

$C_{acts} = 150{,}41/(\alpha_{is}/\alpha_{osolair})$

These formulae are applied to South African locations and climate zones in the following tables 6 to 9.

It is shown that the more stringent amplitude ratios require higher figures of active thermal mass. As expected, Upington (Zone 6) requires the highest active thermal mass, while Durban requires the least. Cape Town has large winter temperature fluctuations as a result of cold fronts coming in from the sea alternated with sunny days.

Comparing the summer and winter active thermal mass requirements, it appears that winter conditions dominate the requirements for active thermal mass. The summer results are therefore ignored. It should be noted that the thermal mass is defined in terms of kJ/K per m² of external envelope area.

Table 6 : Required Amplitudes & Thermal Mass for winter

	winter outdoor amplitude [K]	**indoor amplitude required for 90% acceptability AC [K]**	**winter amplitude ratio required for 90% acceptability AC**	**winter active thermal capacity required for 90% acceptability AC [kJ/K per m^2 of envelope]**	**indoor amplitude required for 80% acceptability AC & 90% acceptability NV [K]**	**winter amplitude ratio required for 80% acceptability AC & 90% acceptability NV**	**winter active thermal capacity required for 80% acceptability AC & 90% NV [kJ/K per m^2 envelope]**	**indoor amplitude required for 80% acceptability NV [K]**	**amplitude ratio required for 80% acceptability NV**	**winter active thermal capacity required for 80% acceptability NV [kJ/K per m^2 envelope]**
Z1 Johannesburg	16	2.4	0.15	**1 734**	4	0.25	**1 041**	7	0.44	**595**
Z1 Bloemfontein	14.4	2.4	0.17	**1 561**	4	0.28	**937**	7	0.49	**535**
Z2 Pretoria	15.1	2.4	0.16	**1 637**	4	0.26	**982**	7	0.46	**561**
Z3 Phalaborwa	12.3	2.4	0.20	**1 333**	4	0.33	**800**	7	0.57	**457**
Z4 Cape Town	17.9	2.4	0.13	**1 940**	4	0.22	**1 164**	7	0.39	**665**
Z4 Port Elizabeth	13.4	2.4	0.18	**1 453**	4	0.30	**872**	7	0.52	**498**
Z4 George	10.2	2.4	0.24	**1 106**	4	0.39	**663**	7	0.69	**379**
Z5 Durban	10.1	2.4	0.24	**1 095**	4	0.40	**657**	7	0.69	**375**
Z5 East London	19.2	2.4	0.13	**2 081**	4	0.21	**1 249**	7	0.36	**714**
Z6 Upington	18.7	2.4	0.13	**2 027**	4	0.21	**1 216**	7	0.37	**695**

Table 7: Required Amplitudes & Thermal Mass for summer

	summer outdoor amplitude forcing function [K]	summer outdoor amplitude [K]	indoor amplitude required for 90% acceptability AC [K]	summer amplitude ratio required for 90% acceptability AC	summer active thermal capacity required for 90% acceptability AC [kJ/K per m² envelope]	indoor amplitude required for 80% acceptability AC & 90% acceptability NV [K]	summer amplitude ratio required for 80% acceptability AC & 90% acceptability NV	summer active thermal capacity required for 80% acceptability AC & 90% NV [kJ/K per m² envelope]	indoor amplitude required for 80% acceptability NV [K]	amplitude ratio required for 80% acceptability NV	summer active thermal capacity required for 80% acceptability NV [kJ/K per m² envelope]
Z1 Johannesburg	22.5	12.4	2.4	0.14	1 094	4	0.23	656	7	0.40	375
Z1 Bloemfontein	25.9	15.2	2.4	0.12	1 288	4	0.19	773	7	0.34	442
Z2 Pretoria	23.8	14.5	2.4	0.13	1 200	4	0.21	720	7	0.37	411
Z3 Phalaborwa	23.4	15.0	2.4	0.13	1 203	4	0.21	722	7	0.36	413
Z4 Cape Town	25.2	13.3	2.4	0.12	1 206	4	0.21	724	7	0.36	414
Z4 Port Elizabeth	23.4	12.1	2.4	0.14	1 112	4	0.23	667	7	0.39	381
Z4 George	22.5	11.3	2.4	0.14	1 059	4	0.24	635	7	0.41	363
Z5 Durban	18.0	8.8	2.4	0.18	840	4	0.30	504	7	0.52	288
Z5 East London	21.1	9.6	2.4	0.16	962	4	0.26	577	7	0.46	330
Z6 Upington	26.3	16.4	2.4	0.11	1 338	4	0.19	803	7	0.33	459

Formatted: Top: 1.5 cm, Bottom: 1.75 cm, Header distance from edge: 1.25 cm, Footer distance from edge: 1.25 cm

Since it is the indoor air volume that is influenced by the effects of the thermal mass exposed to it, the required active thermal mass has been redefined as kJ/m^3 of indoor air:

Table 8: Required active thermal mass within envelope insulation - winter [kJ/m^{3}K]

	for 2.4 K indoor amplitude	for 4K indoor amplitude	for 7K indoor amplitude
Z1 Johannesburg	1 542	925	529
Z1 Bloemfontein	1 388	833	476
Z2 Pretoria	1 456	873	499
Z3 Phalaborwa	1 186	711	407
Z4 Cape Town	1 725	1 035	592
Z4 Port Elizabeth	1 292	775	443
Z4 George	983	590	337
Z5 Durban	974	584	334
Z5 East London	1 851	1 110	635
Z6 Upington	1 803	1 082	618

Alternatively, the thermal mass required can also be expressed in terms of thermal mass per square metre of **net** external wall area [kJ/m²K]. This is better than "surface density" which apart from being scientifically dubious, bears no relationship to the indoor air. These requirements are set out in Table 9 below.

Table 9: Required active thermal mass exterior wall - winter [kJ/m²K]

	for 2.4 K indoor amplitude	for 4K indoor amplitude	for 7K indoor amplitude
Z1 Johannesburg	1 919	1 151	658
Z1 Bloemfontein	1 727	1 036	592
Z2 Pretoria	1 811	1 087	621
Z3 Phalaborwa	1 475	885	506
Z4 Cape Town	2 147	1 288	736
Z4 Port Elizabeth	1 607	964	551
Z4 George	1 223	734	419
Z5 Durban	1 211	727	415
Z5 East London	2 303	1 382	790
Z6 Upington	2 243	1 346	769

3.3.2 Relative contribution of building elements to active thermal capacity

Figure 9 below illustrates the relative percentage contribution to the total active thermal mass (capacity) of non-residential buildings whose exterior envelope resistances are SANS 204 compliant.

- The left-hand values illustrate a single storey building with a heavy power float finished concrete floor resting on compacted soil. Partitions and ceiling finishes are of typical light-weight construction, while the exterior walls consist of insulation sandwiched between two 106mm standard brick skins plastered on the inside.
- The centre values show the same construction as above, but a with a suspended concrete floor construction.
- The right-hand values depict the same construction as the centre values but the suspended concrete floor is covered with typical carpeting, effectively isolating the thermal mass from the indoor air.

The following conclusions are evident:

(a) The active thermal capacity of the lightweight ceiling is negligible.
(b) As the percentage contribution of the floor decreases, the sum of the others increases.
(c) The growth of the exterior wall percentage contribution by far outweighs all other elements.
(d) Significantly, it is difficult to regulate, and impossible to control the interior finishes of buildings: interior walls are covered with pictures, panelling, shelves, cupboards and other furniture. Floors may be covered with carpets, rugs and furniture. These considerations lead to the conclusion that the active thermal mass of the building interior should be regarded as a bonus if available, but should not be relied upon in legislation.

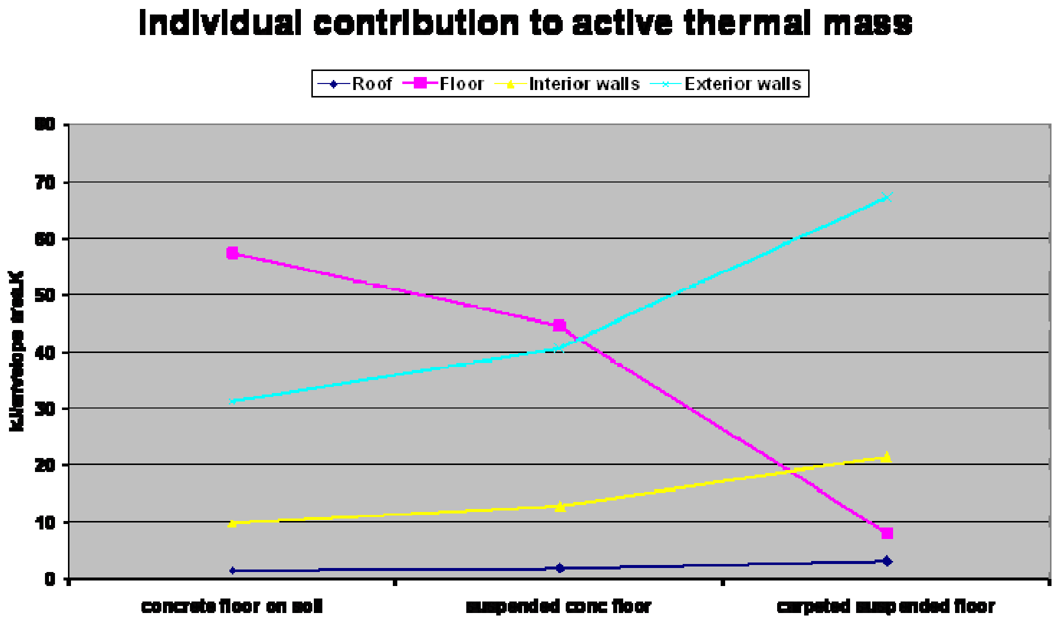


Figure 9: Contribution of building elements to active thermal capacity

The contribution of the floor is progressively reducing from left to right, thereby reducing the total active mass (and CR) while increasing the relative share of the exterior walls.

As the indoor thermal masses are often isolated from the indoor air by furniture and refurbishment, they cannot be considered to be a permanent building property and should therefore be disregarded in regulation

3.4 Check on the affordability of recommended thermal performance

3.4.1 Energy Usage and Life Cycle Cost modelling

The impact of the thermal efficiency of any proposed building design intervention can be modelled using energy modelling software. In this project Visual DOE software has been used to model the effects on the Life Cycle Cost (LCC) of three simplified building designs/occupancies over six climatic regions for five alternative wall material combinations, of thermal mass and thermal resistance.

Life Cycle Cost is the sum of all energy savings (discounted for time weighting) and the initial premium of a proposed energy improving intervention.

Important in the Life Cycle Costing is the selection of discount rate and the period over which the costing is calculated, and the energy cost escalation estimates over this period.

Discount Rate:
As all monetary figures are real (not considering the erosion of value of money by inflation) the discount rate of 8.5% is close to a 15% nominal interest rate.
The rate of 8.5% was selected as being the current long term borrowing rate as indicated by the R157 as trading at the time of writing.

Period of analysis:
The period of 20 Years is selected from the maximum life of equipment, glazing, and building components such as thermal insulation, although the expected life of masonry buildings probably nearer 50 years.

Cost escalation:
A synthetic electricity cost was derived with an energy charge of R0.72 per kilowatt-hour.
This rate is some 35% above current rates, in anticipation of the tariff 2010 increase, and is then escalated at five percent. This is to show a tripling of energy prices in real terms over the twenty year evaluation period.

Sensitivity studies:
Sensitivity analysis run on the Residential design for Region 1 shows that had a discount rate of 15% been applied to the above energy cost scenario, the ranking of the options would have been unchanged.

Note on the choice of materials used in modeling:
The model is neutral to the selection of walling types, and artificial or synthetic walling combinations of thermal mass and thermal resistance could have been selected.
For convenience known walling of 106mm thickness brick and SANS 204 levels for thermal insulation have been used to construct the data points.

Note on the selection of set points used:
In order to differentiate between air-conditioned and naturally ventilated buildings the set-points for heating and cooling have been adjusted to reflect a four degree K range or a seven degree K range, about the thermal neutrality temperature for the climatic region selected.

Residential (Naturally Ventilated)			Non-residential (Artificially Ventilated)		
Units: Degrees Celsius					
Region	Heating	Cooling	Region	Heating	Cooling
1	20	27	1	21	25
2	20	27	2	22	26
3	22	29	3	23	27
4	20	27	4	21	25
5	21	28	5	23	27
6	21	28	6	23	27

Table 10: Set points used in modeling for each climatic region:

3.4.2 Relationship between CR constants, Annual Energy Usage and Life Cycle Cost

The relationship between Annual Energy Usage and the CR value of three building designs (for the residential, commercial (inc. Institutional), and retail buildings), has been assessed, and has been found to have very strong correlations.

Summary of calculations and modelling results					
Occupancy	**Residential**				
Region	**1 Highveld**				
Walling type	**Solid double leaf**	**Double leaf with 50mm Air cavity**	**Double leaf with R=0.5 insulation in cavity**	**Double leaf with R=1.0 insulation in cavity**	**Double leaf with R=1.0 external insulation**
Annual heating energy	6250	4637	2974	2378	2530
Annual cooling energy	549	469	396	445	410
Combined energy Including fans	9152	7204	5330	4835	4920
CR_{Summer}	16	23	44	77	114
CR_{winter}	21	33	66	122	179
Energy to CR Correlation	0.99				
Life Cycle Cost – R	160623	143546	132488	132752	133529
LCC /100	1606	1435	1324	1328	1335
Inverse CR_{ave}*10^5	2703	1786	909	503	341

Table 11 : Example of typical results of calculations and energy modelling of walling alternatives

It can be seen from the above calculation sheet that the relationship between CR constant and Energy usage is an inverse one, with energy usage decreasing as CR values increase.

3.4.3 Optimisation of CR values for occupancies and regional climates

An analysis of the variation of Life Cycle Cost with CR values yields some interesting possibilities for an optimization of the CR. The graph of this relationship is illustrated below in the residential building for the Highveld region.

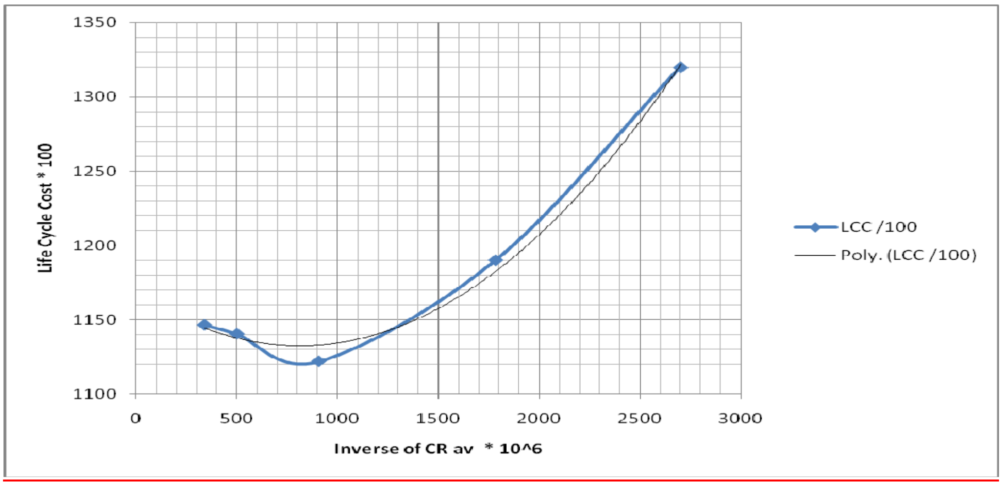


Figure 10 : relationship of Life Cycle Cost to CR Value

The correlation of Energy Usage to CR value is shown to be very strong, with 78% of cases showing over 90% correlation.

As the equations for Active Thermal Capacity (ATC) are developed from the CR Method equations (as was described in Sections 2 and 3 of the Report) and because the ATC is conceptually simpler and easily calculated, a possibility is then to develop the Deemed-to-satisfy rules using the ATC.

Calculations of the Active Thermal Capacity are reproduced and compared to the Life Cycle Cost for every climatic region, for the Residential, Offices & Institutional buildings and Retail occupancies, in the following section.

3.4.4 Optimal Active Thermal Capacity

The optimal Life Cycle Cost for the walling Active Thermal Capacity for each building occupancy and climatic region, has been selected via a graphical technique and as is presented by way of example in Figure 11 below.

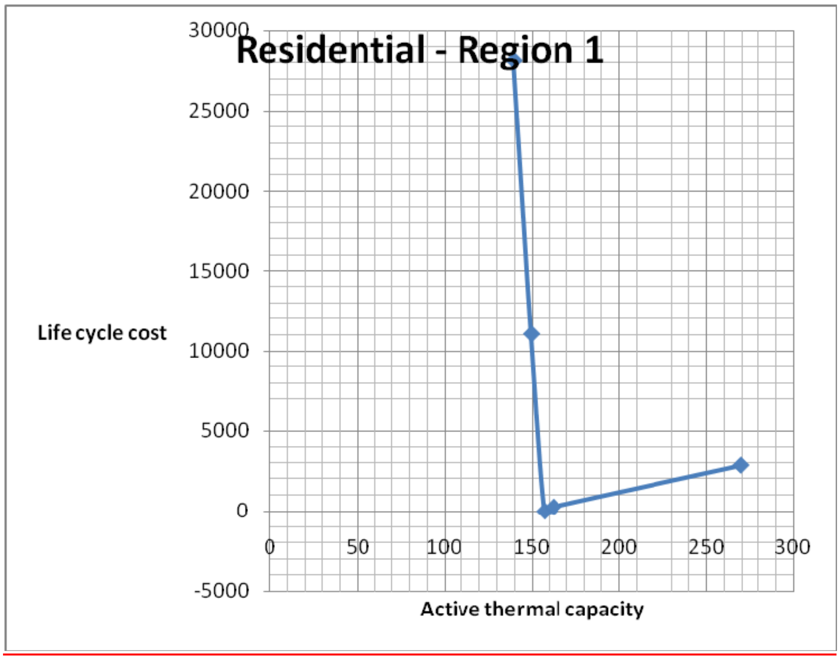


Figure 11 : Graph of Life Cycle Cost shown against Active Thermal Capacity

The ATC is correlated with the Energy Usage modeled for the three buildings in six climatic regions, and the correlation is not as good, with only 72% of cases with an over 60% correlation. The algorithms used in the modeling software and the formulae for calculating ATC are not necessarily the same.

The possibilities that a simpler performance criteria might show a good correlation with energy usage is therefore investigated in the next section.

3.4.5 The C*R Product as a suitable performance criteria

As shown in prior sections the correlation between the CR co-efficient as developed by Wentzel shows a strong correlation for the synthetic building. The possibility that the product of the thermal resistance and thermal capacity of the walling systems used in the synthetic design would have a good correlation with the energy usage of the buildings is therefore investigated.

Two alternative methods of calculating the CR Product present:
Firstly, C * R
Where $C = C_{calculated}$
Secondly ATC * R
Where ATC= Active Thermal Capacity
and R= Thermal resistance

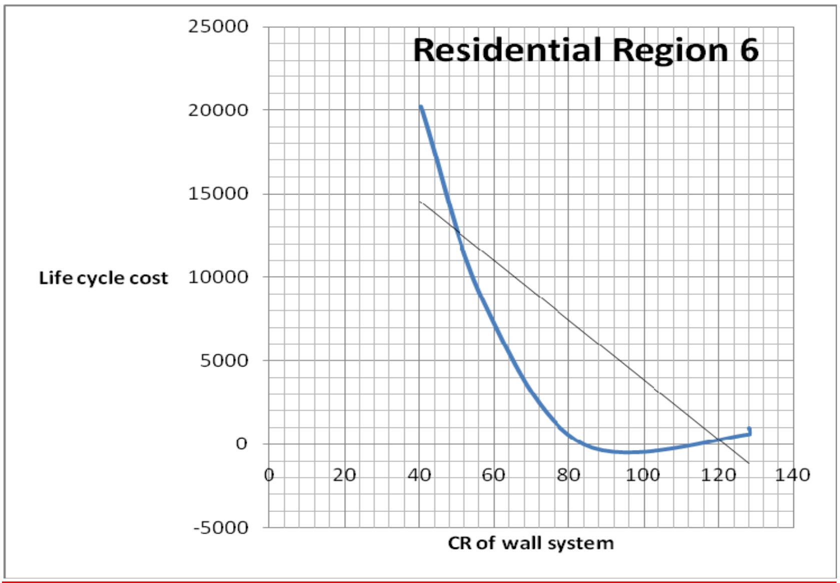
The correlations of the CR Products as above, and other variants were calculated and the results are all in the range of 91-92%.

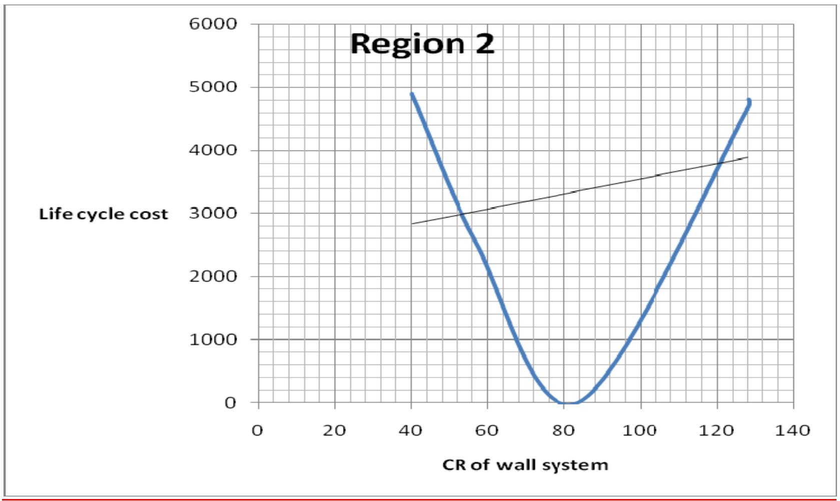
As the CR Product would be more universally useful if the correlation between the CR is calculable from the physical properties of the walling material and configuration (sequence in the structure) and was independent of summer and winter climate detail or design considerations the simple $C_{Calculated}$ * R is selected. The detailed correlation results are set out below:

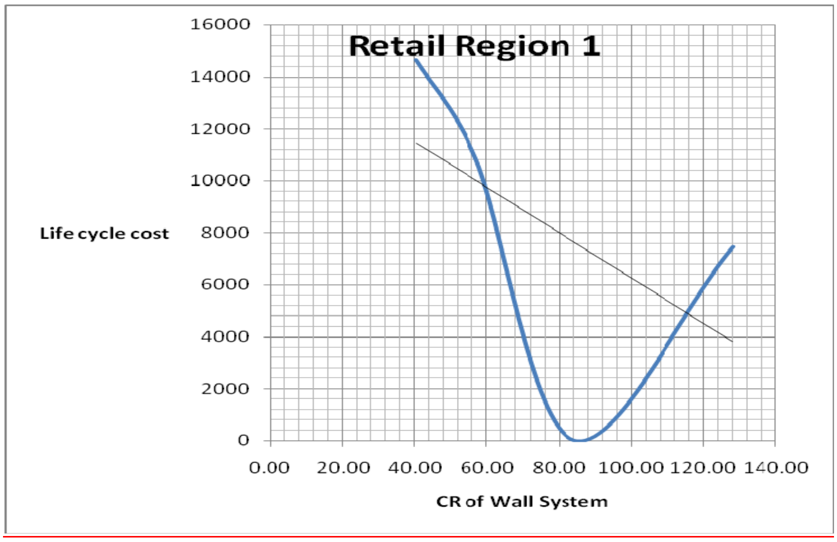
Table of energy usage versus CR product for building per walling type							
Energy for CR product values	**Wall Type**	**Solid Double brick**	**As before with 50mm air-space**	**Same & R=0.5 insulation in cavity**	**Same & R=1.0 insulation in cavity**	**R=1.0 external insulation**	**Correlation**
C*R	**Pure**	40	57	84	128	128	
C*R	**Modified**	6457	4299	2304	1325	938	Inverse
Energy usage for Retail occupancies	**Region1**	18,706	18,198	16,323	16,642	16,282	0.95
	2	18,029	16,146	13,344	12,330	12,458	0.99
	3	17,984	16,933	14,691	14,498	14,573	0.98
	4	19,029	18,589	16,454	16,690	16,522	0.94
	5	12,080	11,899	10,781	11,041	11,053	0.89
	6	26,216	24,043	20,469	19,198	19,119	0.99
Energy usage for Residential occupancies	**Region1**	9,152	7,204	5,300	4,835	4,920	0.99
	2	7,518	6,188	4,860	4,698	4,679	0.99
	3	11,822	10,971	9,507	9,551	9,414	0.97
	4	9,546	7,625	5,706	5,202	5,281	0.99
	5	4,906	4,169	3,394	3,489	3,453	0.97
	6	12,338	10,515	8,310	7,735	7,790	0.99
Energy usage for Office and Institutional occupancies	**Region1**	7,139	6,389	5,331	5,083	5,102	0.99
	2	7,503	7,071	6,000	6,192	6,210	0.94
	3	11,259	11,125	8,755	10,526	10,490	0.51
	4	7,133	6,385	5,293	5,033	5,029	0.99
	5	7,009	6,891	5,417	6,567	6,577	0.47
	6	10,658	10,052	8,536	8,649	8,721	0.95
					Average correlation		0.92

Table 12 : Correlation of Thermal capacity & resistance products to energy usage by occupancy and climatic region

The optimization of the C*R product is done graphically for each permutation, as indicated in the graphs below, for each occupancy. The C*R product is in hours.







Figures 12,13,14 : Lowest life Cycle Cost for C*R combinations

3.4.5 Commentary

The C * R Product requirements which are to be proposed for incorporation into regulation and standard are developed from the minimum Life Cycle Cost options, as in Figures 12,13,14 above. This can be achieved in practice with a standard double clay brick construction and some varying level of thermal insulation in the cavity.

This finding is similar to that of earlier research by Holm, Johannsen and Harris for the Department of Minerals & Energy in support of SANS 204, which showed that the Life Cycle cost of additional thermal resistance to typical brick walls, would have optimal levels between the range of an solid wall through to an added thermal resistance of R=1.0, in ten types of building across six climatic regions.

For lighter wall constructions the thermal insulation requirement would increase, and vice-versa for heavier wall constructions. The area of windows relative to high mass walling is similarly important, and should this figure be above 20% of wall area for the residential or retail buildings or above 25% for office and institutional buildings, the benefits of thermal capacity will reduce, and the Rational Design requirements should be invoked.

The tendency toward lightweight industrial building systems, using a range of technologies and materials, has been able to incorporate the thermal resistance aspects, but not the thermal mass. Much has been made of the thermal efficiency of such systems, but it is shown in this research that when thermal mass is combined with thermal resistance, the most economical results are achieved.

The assumption that the thermal resistance of the walling is primarily supplied by the thermal insulation and that there is proportionality between the thickness of the materials and the cost, is implicit. The similar presumption that the thermal capacity is primarily provided by the brickwork, and that proportionality exists between the mass and the cost, is also made.
Most thermal insulation material are light in mass and most brickwork high in thermal conductivity, but it can be envisaged that for some materials the cost effectiveness is better than others, and for these materials and combinations the Rational Design compliance route should be applied.

The properties of the 106mm double leaf wall have been assumed to have the properties and thermal performance as per the norms of the CSIR publication X-Bou 2-8 and the NBRI publication K61, of 1982.

Material	**Density**	**Thermal Conductivity**	**Specific Heat**
Units	**kg/m3**	**W/mK**	**kJ/kgK**
Brickwork	1820	0.82	0.8
Insulation	30	0.03	1.2

The costs of all walling systems have been built up using Buildcost, and by discussion with Building contractors with experience of constructing cavity walls. The cost sheets are attached as Annexure D.

4 Deemed-to-satisfy requirements and conclusions

By selecting the walling option which has a C * R Product which provides the lowest Life Cycle Cost as the Deemed-to-satisfy proposal, it can be assured that the economic viability of the proposal is not in doubt, for that climatic region and for the occupancy cluster.

The following table of C * R Products is developed as a proposed replacement for the present SANS 204 external walling requirements:

Optimal Thermal Capacity & Resistance Product by Region and Occupancy (hours)

Region	1	2	3	4	5	6
Residential	100	80	80	100	60	100
Office & Institutional	80	80	90	80	80	80
Retail	80	120	120	90	80	120

Table 13 : Minimum Thermal Capacity & Resistance Products by Region and Occupancy

The results above correspond to the 106mm double brick construction, face brick externally and plastered internally, with a minimum thermal insulation as provided by a 50mm air-cavity, through to a similar wall with 30mm of extruded polystyrene.

Typical constructions will have the following Thermal Capacity and Resistance Product.

Wall Type	Solid double 106mm brick and12 mm plastered internally	Same with 50mm air-space in cavity	Same with R=0.5 insulation in cavity	Same with R=1 insulation in cavity	Same with R=1 insulation Fixed externally
Thermal Resistance, R. (m^2K/W)	0.45	0.64	0.95	1.45	1.45
Thermal Capacity, C. (kJ/m^2K)	326	326	326	326	326
C * R Product (hours)	41	58	86	131	131
Active Thermal Capacity (kJ/m2.K)	139	149	157	162	270

Table 14 : Various CR values for typical constructions

Note 1: If the insulation were to be positioned internally the weakest result would register, which would be approximately that of a solid wall.

References

1.Auliciems A. & Szokolay S.V. 1997. **Thermal comfort.** Passive and Low Energy Architecture International. Design Tools and Techniques. PLEA Notes. Note 3.

2.De Dear R., Gail Brager & Donna Cooper 1997. **Developing an Adaptive Model of Thermal Comfort and Preference.** Final Report, ASHRAE RP-884. Macquarie University, Sydney, Australia.

3.Holm D. and Engelbrecht F. A. 2005. Practical choice of thermal comfort scale and range in naturally ventilated buildings in South Africa. **Journal of the South African Institution of Civil Engineering.** Volume 47 Number 2, pp 9-14. Halfway House.

4.Romm J.J. & Browning W.D. 2004. **Greening the Building and the Bottom Line. Increasing Productivity through Energy-Efficient Design.** Rocky Mountain Institute, Snowmass, Colorado.

5.Baggs, D.W. in prep. **Thermal Mass & its Role in Building Comfort and Energy Efficiency.**

6.Johannsen, A. 2009. **BSIMAC, version 0.8.** Pretoria.

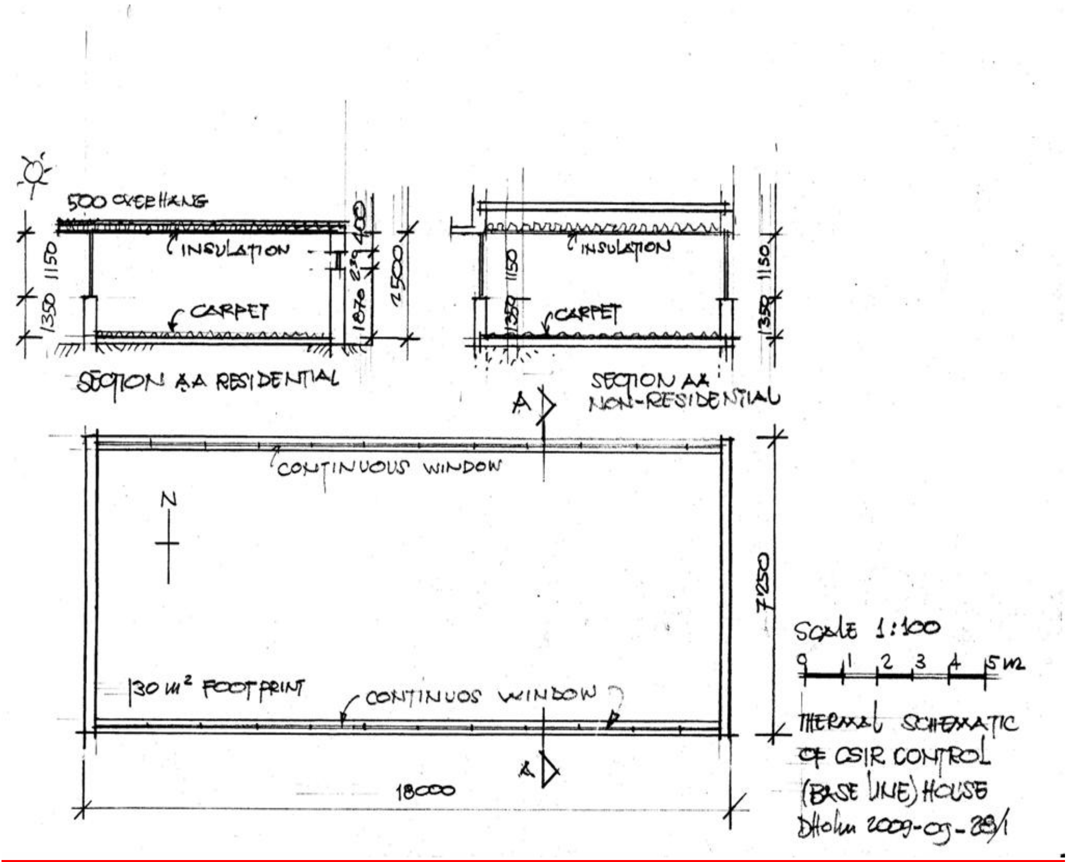
7.Mathews, E. H. 1998. **New Quick, version 1.01.** Pretoria.

8.Holm,D. Johannsen,A. & Harris,H.C. 2007. Reports OR-13554 and MR-490 for the Department of Minerals and Energy in support of SANS 204.

9.Steenkamp, I. 2009. **TERMO, version 2009.** Port Elizabeth.

10. Wentzel,J.D., Page-Shipp, R.J. & Venter, R. J. 1981. **The Prediction of the Thermal Performance of Buildings by the CR-Method.** BRR 396. National Building Research Institute, Council for Scientific and Industrial Research. Pretoria.

Annexure A


500 OVERHANG
INSULATION
CARPET
1150
1350
400
230
1870
2500
SECTION AA RESIDENTIAL
INSULATION
CARPET
1150
1350
1150
1350
SECTION AA NON-RESIDENTIAL
A
CONTINUOUS WINDOW
N
7250
130 m² FOOTPRINT
CONTINUOS WINDOW
A
18000
SCALE 1:100
0 1 2 3 4 5 m
THERMAL SCHEMATIC OF CSIR CONTROL (BASE LINE) HOUSE
DHolm 2009-09-28/1

Annexure B

Modelling results sheet example

Name: Naturally ventilated residence
Address: Johannesburg
Description: 130.5 m2 design
Analysis done by: Howard Harris @ Structatherm Projects
Weather File: Johannesburg
Project File: c:\program files\gdt4\wsp\cba\residential\130.5m2 region 1.gph
Calculation Engine: DOE-2.1E-119

Electrical Use Summary

Alternative	Lights	Equipment	Heating	Cooling	Fans	Ext. Lights	Total
Electrical End-use Totals (kWh)							
Double brick with 50mm air cavity	3,430	4,287	4,637	469	2,098	657	15,578
Double brick insulation added to R=1.0	3,430	4,287	2,378	445	2,012	657	13,209
Double brick solid	3,430	4,287	6,250	549	2,353	657	17,526
Double brick solid internally insulated	3,430	4,287	3,956	715	2,180	657	15,225
Double brick external insulate	3,430	4,287	2,530	410	1,980	657	13,294
Double brick insulation added to R=0.5	3,430	4,287	2,974	396	1,930	657	13,674

Energy Cost Summary (R/y)

Alternative	Total Electric	Total Utility	Incremental First Cost	PV Life Cycle Cost*
Total Energy Cost (R/y)				
Double brick with 50mm air cavity	R11,216	R11,216	R782	R143,546
Double brick insulation added to	R9,510	R9,510	R11,703	R132,752
Double brick solid	R12,619	R12,619	R0	R160,623
Double brick solid internally insulated	R10,962	R10,962	R11,703	R151,234
Double brick external insulate	R9,571	R9,571	R11,703	R133,529
Double brick insulation added to	R9,845	R9,845	R7,175	R132,488

* 20 year life cycle w/ 8.5% discount rate.

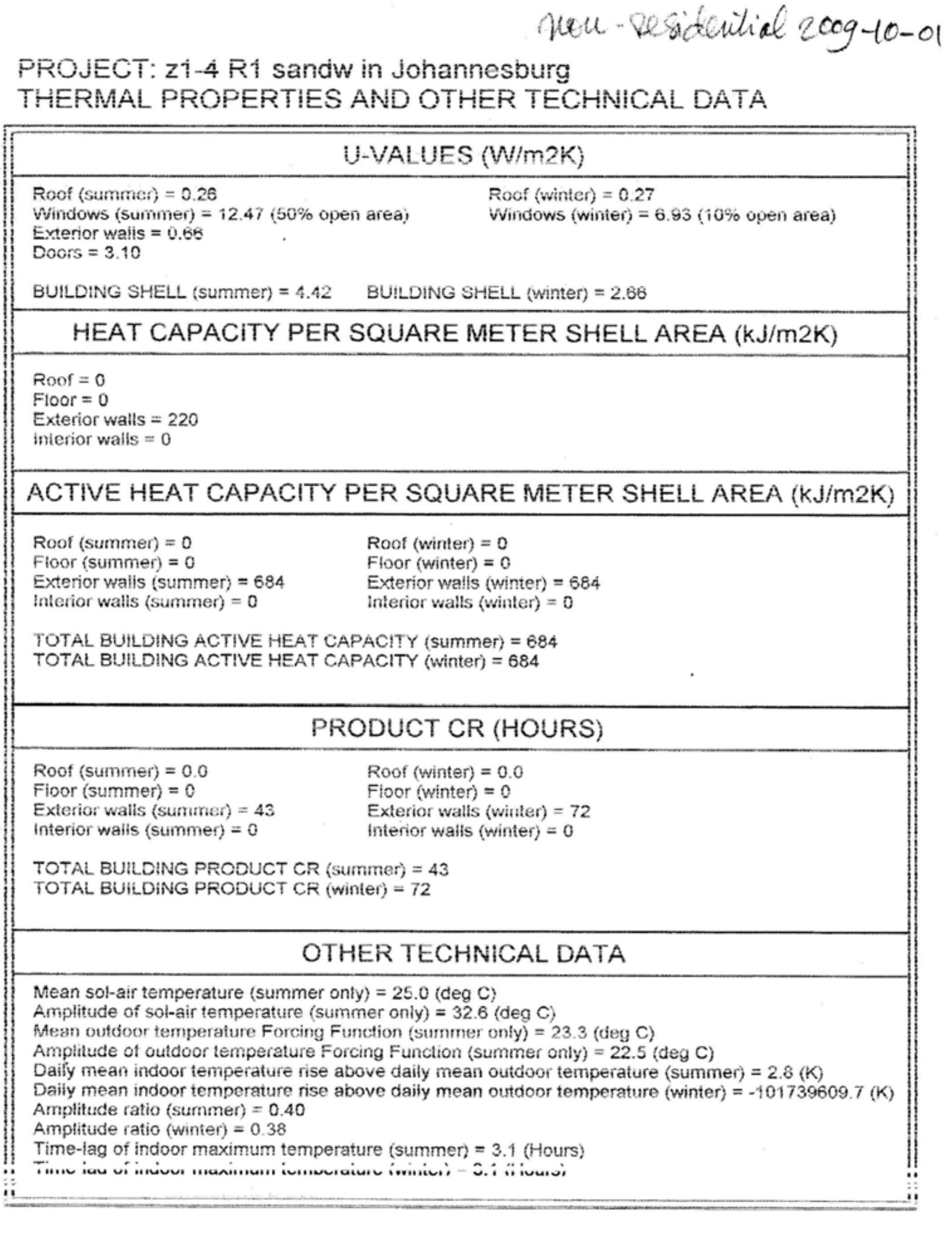
Monthly Electrical Usage (kWh)

Alternative	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Double brick with 50mm air cavity	991	879	966	1,163	1,515	1,986	1,948	1,667	1,331	1,111	1,057	964
Double brick insulation added to R=1.0	967	845	923	980	1,201	1,498	1,470	1,307	1,122	997	964	932
Double brick solid	1,046	938	1,043	1,313	1,749	2,317	2,284	1,928	1,502	1,234	1,154	1,018
Double brick solid internally insulated	1,048	908	984	1,132	1,454	1,836	1,820	1,592	1,297	1,110	1,045	1,000
Double brick external insulate	957	834	921	982	1,218	1,536	1,514	1,327	1,122	996	961	925
Double brick insulation added to R=0.5	952	839	918	1,015	1,268	1,627	1,593	1,390	1,159	1,011	972	927

Monthly Electrical Power Demand (kW)

Alternative	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Double brick with 50mm air cavity	4	4	3	6	7	8	8	7	7	5	5	3
Double brick insulation added to R=1.0	4	3	3	4	6	6	6	5	6	4	4	3
Double brick solid	4	4	4	6	8	9	9	7	8	6	6	4
Double brick solid internally insulated	4	4	3	5	6	7	7	6	7	5	5	3
Double brick external insulate	4	3	3	4	5	6	6	5	6	4	4	3
Double brick insulation added to R=0.5	4	3	3	5	6	7	6	5	6	4	5	3

ANNEXURE C



non-residential 2009-10-01

PROJECT: z1-4 R1 sandw in Johannesburg
THERMAL PROPERTIES AND OTHER TECHNICAL DATA

U-VALUES (W/m2K)

Roof (summer) = 0.26
Roof (winter) = 0.27
Windows (summer) = 12.47 (50% open area)
Windows (winter) = 6.93 (10% open area)
Exterior walls = 0.66
Doors = 3.10

BUILDING SHELL (summer) = 4.42
BUILDING SHELL (winter) = 2.66

HEAT CAPACITY PER SQUARE METER SHELL AREA (kJ/m2K)

Roof = 0
Floor = 0
Exterior walls = 220
Interior walls = 0

ACTIVE HEAT CAPACITY PER SQUARE METER SHELL AREA (kJ/m2K)

Roof (summer) = 0
Roof (winter) = 0
Floor (summer) = 0
Floor (winter) = 0
Exterior walls (summer) = 684
Exterior walls (winter) = 684
Interior walls (summer) = 0
Interior walls (winter) = 0

TOTAL BUILDING ACTIVE HEAT CAPACITY (summer) = 684
TOTAL BUILDING ACTIVE HEAT CAPACITY (winter) = 684

PRODUCT CR (HOURS)

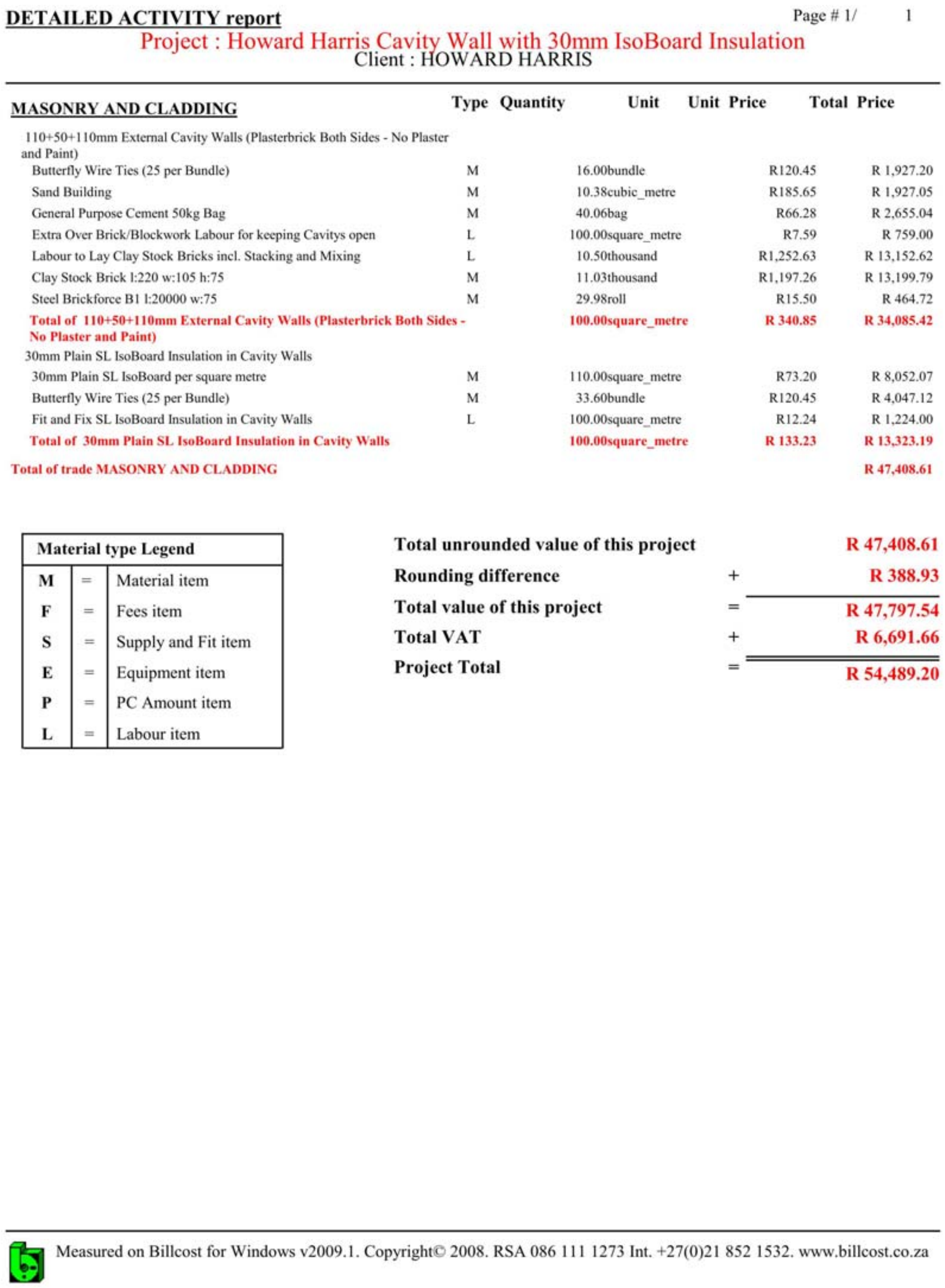
Roof (summer) = 0.0
Roof (winter) = 0.0
Floor (summer) = 0
Floor (winter) = 0
Exterior walls (summer) = 43
Exterior walls (winter) = 72
Interior walls (summer) = 0
Interior walls (winter) = 0

TOTAL BUILDING PRODUCT CR (summer) = 43
TOTAL BUILDING PRODUCT CR (winter) = 72

OTHER TECHNICAL DATA

Mean sol-air temperature (summer only) = 25.0 (deg C)
Amplitude of sol-air temperature (summer only) = 32.6 (deg C)
Mean outdoor temperature Forcing Function (summer only) = 23.3 (deg C)
Amplitude of outdoor temperature Forcing Function (summer only) = 22.5 (deg C)
Daily mean indoor temperature rise above daily mean outdoor temperature (summer) = 2.8 (K)
Daily mean indoor temperature rise above daily mean outdoor temperature (winter) = -101739609.7 (K)
Amplitude ratio (summer) = 0.40
Amplitude ratio (winter) = 0.38
Time-lag of indoor maximum temperature (summer) = 3.1 (Hours)
Time-lag of indoor maximum temperature (winter) = 3.1 (Hours)

Annexure D



DETAILED ACTIVITY report Page # 1/ 1

Project : Howard Harris Cavity Wall with 30mm IsoBoard Insulation

Client : HOWARD HARRIS

MASONRY AND CLADDING	**Type**	**Quantity**	**Unit**	**Unit Price**	**Total Price**
110+50+110mm External Cavity Walls (Plasterbrick Both Sides - No Plaster and Paint)					
Butterfly Wire Ties (25 per Bundle)	M	16.00bundle		R120.45	R 1,927.20
Sand Building	M	10.38cubic_metre		R185.65	R 1,927.05
General Purpose Cement 50kg Bag	M	40.06bag		R66.28	R 2,655.04
Extra Over Brick/Blockwork Labour for keeping Cavitys open	L	100.00square_metre		R7.59	R 759.00
Labour to Lay Clay Stock Bricks incl. Stacking and Mixing	L	10.50thousand		R1,252.63	R 13,152.62
Clay Stock Brick l:220 w:105 h:75	M	11.03thousand		R1,197.26	R 13,199.79
Steel Brickforce B1 l:20000 w:75	M	29.98roll		R15.50	R 464.72
Total of 110+50+110mm External Cavity Walls (Plasterbrick Both Sides - No Plaster and Paint)		**100.00square_metre**		**R 340.85**	**R 34,085.42**
30mm Plain SL IsoBoard Insulation in Cavity Walls					
30mm Plain SL IsoBoard per square metre	M	110.00square_metre		R73.20	R 8,052.07
Butterfly Wire Ties (25 per Bundle)	M	33.60bundle		R120.45	R 4,047.12
Fit and Fix SL IsoBoard Insulation in Cavity Walls	L	100.00square_metre		R12.24	R 1,224.00
Total of 30mm Plain SL IsoBoard Insulation in Cavity Walls		**100.00square_metre**		**R 133.23**	**R 13,323.19**
Total of trade MASONRY AND CLADDING					**R 47,408.61**

Material type Legend		
M	=	Material item
F	=	Fees item
S	=	Supply and Fit item
E	=	Equipment item
P	=	PC Amount item
L	=	Labour item

Total unrounded value of this project		**R 47,408.61**
Rounding difference	+	**R 388.93**
Total value of this project	=	**R 47,797.54**
Total VAT	+	**R 6,691.66**
Project Total	=	**R 54,489.20**