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Report for the Clay Brick Association of South Africa, after critical review

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 for external walling in the SANS 204 standard.

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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 mass, or thermal capacity, been set out. This is despite well documented building physics being available to assist the regulators and the designers. The National Building Research Council in South Africa (formally part of the Council for Scientific and Industrial Research, the CSIR), were pioneers of the CR method developed in the early 1980's. This work is developed further in this project, with modern desk-top computing used to apply the original CR method to develop requirements for a combination of thermal capacity and thermal resistance, expanding on equations developed by Wentzel10, and later, Mathews7.

The CR method result is compared with the results of building energy simulation models 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 capacity and thermal resistance, and develops deemed-to-satisfy requirements which can be applied such as to ensure optimal energy efficiency is built into external walling systems.

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, it must be noted that they were primarily designed to serve the fire regulation requirements (cf. Dr. Ron Watermeyer in a presentation of the proposed amendments to the National Building Regulations for improved sustainability).

Deemed-to-satisfy walling requirements have been proposed in the Version 2 draft of SANS 204, developed out of the Building Code of Australia. These requirements are based on surface density and R-value combinations. The Clay Brick Association has tasked the authors of this report to develop a rational basis for the specification of thermal capacity and resistance in external walls, which building designers can apply, and as such will assure energy efficiency to a level which is 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 have a primary influence on 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 usage 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 thermal modelling of buildings, confirming that this approach is scientifically correct.

Two important specification rules follow from this:

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 primarily) 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), the levels of activity (and resultant heat load), and the level of compliance with thermal comfort requirements (for example, either 90% for within +/- 1.2K about thermal neutrality for air-conditioned buildings, or 80% for the range of +/- 3.5K for naturally ventilated buildings).

It is shown that by logically grouping the above determinants, the many classifications of buildings in SANS 10400 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 clusters, is also motivated. The three clusters of occupancy type are then: Residential, office and institutional combined, and the retail cluster.

The purpose of the project was 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 formula which links the degree of modulation in fluctuation of internal temperature experienced in buildings, with various levels of thermal resistance and thermal capacity in the building envelope. The fluctuation 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 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 satisfies the users of the buildings, and a daily and seasonal swing of temperatures which are 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 a value, measured in units of time, which indicates the minimum required combinations of thermal capacity (C) and thermal resistance (R) which are necessary to maintain the temperature fluctuation within the desired comfort temperature range. For practical purposes, the arithmetical product of C and R of walling systems is proposed to be used as a performance requirement in building design, as this value combines the appropriate levels of thermal capacity and thermal resistance, and can be achieved with simple hand calculations. This approach has been verified via a correlation of the CR product, for various walling systems, with the energy usage and life cycle cost of the buildings using these walling systems. The correlation is over 90% in most cases, so it is with confidence that the CR method can be used to construct a rational design tool and a simple deemed-to-satisfy rule for walling, which establishes minimum thermal capacity and thermal resistance combination requirements, and are suitable for use in SANS 204, as referenced in the National Building Regulations via SANS 10400.

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1. Research Methodology

1.1 Energy usage determinants

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

- The main determinants of energy usage in buildings are:
- Climate for the building location
- Timing and duration of occupancy
- Density of occupation
- Required temperature range for occupants
- Natural versus artificial ventilation
- Activities of occupants
- Size of buildings

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 for lighting, HVAC etc.

1.1.1 Climatic variation

Naturally occurring climatic variation is provided for by identifying, analysing and categorising performance criteria which are differentiated by established climatic zones.

1.1.2 Timing and duration of occupancy

Buildings can broadly be divided into those which are continuously occupied, and those which are pre-dominantly day-time occupancy, such as offices, shops, and clinics. The period of occupation is approximately 12 hours each day. Continuously occupied buildings are those such as hospitals, usually residentially based, and approximating a 24hr occupation by the majority of the occupants.

1.1.3 Density of occupation

The density of occupation varies widely, ranging from 1 person per 10-20m^2 for some offices, versus 1 person every 2.0m^2 for classrooms.

1.1.4 Required temperature range

Thermal neutrality defines the temperature at which occupants are neither too hot nor cold, and varies by climatic region and season, satisfying 80% of occupants[1]. For air-conditioned buildings, the expectation is that internal air temperatures do not vary by more than 2.5K about thermal neutrality. 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 range of 7.0K around thermal neutrality is acceptable to 80% of occupants[1]. Deviation from this range will encourage either heating or cooling, often by means of artificial ventilation, with energy usage consequences.

1.1.5 Natural versus artificial ventilation

SANS 10-400 Part O of the National Building Regulations requires that for artificially ventilated structures a minimum number of air-changes are provided, depending on the occupancy type. These regulations also require that the area of opening windows is a minimum of 5% of floor area for naturally ventilated rooms. Thereafter it is assumed that occupants will manage the openings such as to provide an adequate level of ventilation. Smaller buildings for which the occupied area can be served by natural ventilation need not be artificially ventilated, if there are adequate windows in the outside walls. For larger buildings the ventilation equipment has to supply the minimum rate of ventilation, but if thermal comfort can be achieved with natural ventilation, the operating energy consumed by the building will be lower.

1.1.6 Activities of occupants

Sedentary occupants, such as office workers, issue approximately 100W/person, whereas factory workers in heavy manufacturing issue as much as 300W/person. In a shopping mall the large number of shoppers and retail workers can release so much heat that heating of the malls is not necessary, even in winter.

1.1.7 Building size

Smaller buildings have a larger ratio of shell surface area to volume, than larger buildings; therefore it is easier for larger buildings to meet the energy usage intensity performance requirements of SANS 204, as measured in kWh/m^2.a and VA/m^2.

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. Therefore, the thermal efficiency of the shell of a structure is important to perimeter zone energy usage, and largely irrelevant to the performance of the interior zone.

As a result, a smaller building comprises mainly perimeter zones. Although the perimeter zone is still important for a larger building, the relevance of this zone is reduced as the interior zone is increased in size. The efficiency of the shell is as important for large buildings as for small buildings, in terms of the effect on the perimeter zone.

1.2 Rationalisation of the energy usage determinants

A closer inspection of the determinants reveals that the list can be rationalised to a smaller group of key variables.

1.2.1 The size of a building

As explained above in 1.1.7, the size of buildings for any particular occupancy type is not a differentiating factor as regards the requirements for thermal efficiency of the shell. Therefore, if the 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 a larger building of the same occupancy type.

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

Larger buildings generally 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 occupation and the activity level of the occupants determines the heat loads. These determinants can be combined to broadly describe the internal environment, and are either to an 80% level of acceptability for buildings with natural environmental control, and 90% acceptability for buildings with artificial environmental control.

1.2.3 The key determinants of energy usage

After analysis, the key determinants of energy usage for common building occupancies are climatic region, occupancy timing and duration (approximately 24hr or 12hr), and 80% or 90% acceptability for thermal performance.

1.2.4 Grouping of occupancy types

An evaluation of the occupancy duration and ventilation possibilities for logical groupings of occupancy types found in SANS 104000 is shown in Table 1.

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

Table 1 – Grouping of building occupancies

Inspection of Table 1 reveals the similarities of the institutional and office groups.

It can be argued that school classrooms, for example, might have different energy drivers than for offices. 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, the office and institutional buildings are combined for the analysis in this project.

This results in 3 groups of occupancy types, differentiated primarily on the basis of occupancy duration and ventilation types.

Occupancy Group	SANS 10400 Occupancy Type
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 – Further grouping of occupancies

1.3 A simplified building design for thermal modelling

Considering the previous discussion regarding building sizes and the resulting perimeter zone requirements, together with the grouping of occupancies, it is possible to define two simplified variations of the CSIR 134m^2 Garsfontein house, a well know design which has been used in building research work over many years (see Annexure A). A residential and non-residential alternative is defined.

Essential features of this design are that there is no interior zone, and the building can be modelled as a single zone, all of which is within 3.5m of a perimeter wall. The standard window area is evenly distributed over the north and south facades for the residential design and for the non-residential design there are continuous window strips of equal size on both the north and south facades. Both designs include good shading. High levels of insulation, perimeter insulation/floor insulation and heavy carpeting ensure that the thermal contribution of the walls are maximised or emphasised relative to the rest of the building shell.

The floor area is maintained constant in order to meet the objective of the building being comprised entirely of a perimeter zone. For both designs, the windows are concentrated on the north side.

While developing the standard 134m^2 design for the commercial and institutional occupancy groups it transpired that the designs developed are very similar, providing further support of the combination of the institutional and commercial occupancies into one group for thermal modelling purposes.

1.4 Sequence of investigation

The initial work entailed establishing the thermal comfort ranges applicable to the occupancy groups in each of the climatic zones. These values were further used in two ways. Firstly, to determine the desired amplitude ratios for the application of the CR method equations. The application of these equations produced a set of desired active thermal capacities for the shell of a building. Secondly, the values were used as input data into the thermal modelling exercise. The models produced predicted energy consumption and life cycle cost values. The energy consumption data was correlated with CR values and desired active thermal capacities derived from the CR method, and with CR product values calculated from first principles for the wall systems. Finally, the deemed to satisfy criteria were selected through graphical means, by plotting life cycle cost against CR product values, as the latter produced the best correlation with predicted energy usage.

1.4.1 Establishing desired thermal comfort ranges

Optimal thermal neutrality exists for any location, and is related to the mean temperatures of the local climate. Thermal neutralities are set out in Tables 4 and 5, in section 3, with temperature data for some South African localities in Figure 2. For any building occupancy and ventilation type, there exists a range of temperatures around thermal neutrality which satisfies the occupants. Some minimum ranges are also provided in Section 3, for both 80% and 90% acceptability levels. The thermal comfort range values are used in solving the CR method equations and as data input into the thermal models.

1.4.2 Applying the CR Method

The CR method demonstrates that the temperature fluctuation inside a building is reduced by improving the thermal efficiency of the shell, which allows the building to be operated at lower energy intensity levels and cost. Solving the original CR method equation provides a CR value in hours, which indicates over a range the necessary combinations of thermal capacity and thermal resistance needed in a building's shell to achieve the desired amplitude ratio (inside temperature range : outside temperature range) for a specific location. A refinement of the CR method equation expresses the desired amplitude ratio in an inverse relationship with the required *active* thermal capacity of the building i.e. capacity that is complemented by resistance, with the position of the resistance layers a critical factor in determining the extent to which the capacity is active. It is measured in kJ/K of the building shell area. The active thermal capacity requirement can be expressed in terms of the volume of indoor air encompassed by the shell, or in terms of the net external wall area.

The results of applying the refined equations to the desired thermal comfort ranges, in various locations, are shown in section 3. If building shells were to comply with these active thermal capacity requirements, then thermal comfort would be achieved without any artificial means of heating, cooling and ventilating. However, bearing in mind the purpose of the project was to determine suitable deemed to satisfy requirements for external walling, it would not be sensible, practical and affordable to expect external walling to contribute all the active thermal capacity of the building shell necessary to achieve thermal comfort.

1.4.3 Thermal modelling

Thermal models produce as primary outputs the expected energy consumption and life cycle costs. The life cycle cost is determined by subtracting the incremental cost of a walling intervention from the discounted value of the energy savings expected to result from using a walling material over the life of the building.

When different walling systems are evaluated, the modelling results in a range of predicted energy consumptions and costs, for any given building design. The appropriate design of building for testing these correlations was developed by trying a number of building design variations, as described in 1.3 above. The energy usage of two building design variants was modelled for three occupancy groups (see table 2), with five walling systems, and tested over six climate zones using Visual DOE software.

The walling systems were based on a solid double brick wall with incremental levels of thermal insulation applied in the cavity or to the wall, yielding added thermal resistances from zero to 1.0m^{2}K/W, as per SANS 204. The required active thermal capacities of the occupancy groups in each location, and of the wall systems, were calculated using software developed during the project which applies the equations of Wentzel[10] and Mathews[7]. In addition, a simplified alternative was proposed to describe the modelled wall systems. This is the arithmetical “CR product”, calculated from first principles, of the thermal capacity and the thermal resistance values of each walling system, expressed in hours. It is important to understand that walling systems with different combinations of thermal resistance and thermal capacity, would have generated similar correlations between CR values, active thermal capacity and life cycle cost i.e. the selection of materials have 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.

1.4.4 Correlating life cycle cost and CR

If the correlation between energy consumption, life cycle cost and the CR product values of the walling systems is high, it follows that the CR product values could be suitable for use in SANS 204 or the National Building Regulations. The output data from the models was evaluated against the CR values of the walling systems to determine the correlation.

1.4.5 Deemed to satisfy requirements for external walls

The walling intervention that produces the lowest life cycle cost during thermal modelling is proposed as the criterion for selecting the deemed-to-satisfy levels of thermal capacity and resistance, which can be used for regulations and standards.

In other words, if the external walls in such buildings meet these minimum criteria, then a reasonable level of energy efficiency will be achieved. If buildings are designed using compliance with deemed to satisfy criteria, the external walls must contain such minimum levels of thermal capacity and resistance for compliance to be achieved.

2 The CR Method and its Further Development

2.1 Introduction

The CR method was pioneered in the 1980's by Johan D. Wentzel of the 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 worked 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 original CR method does. It also introduced many refinements that were inaccessible to the original empirical CR method.

2.2 The CR Method

In essence the CR method (and its further development) identifies the climatic driving forces of building thermal performance to be the outside temperature amplitude (α_o) and solar radiation (I). These climatic variables interact with the building's thermal properties, such as its active thermal capacity (C_{act}) and envelope resistance (R).

Firstly, the average indoor temperature rise (dT) is proportional to I_wR/A_{fl}, where

I_w = solar radiation transmitted through glazing (kWh/d)

A_{fl} = floor area (m²)

R = specific envelope resistance (m²K/W)

The larger the product of the unshaded sun-exposed window area and the envelope resistance is, the higher the average indoor temperature for a given floor area. This is intuitively appreciated by most building designers and the public.

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 clearly a risk of overheating the interior during summer.

Secondly, the CR-method states that the product of active thermal capacity (C_{act}) and envelope resistance (R) is inversely proportional to the amplitude ratio.

$$C_{act} \times R = \text{constant/amplitude ratio},$$

Where the amplitude ratio = indoor temp. amplitude (α_i)/outdoor temp. amplitude (α_o), and amplitude = the difference between maximum and minimum temperatures.

The equation is $\alpha_i/\alpha_o = (48{,}9 \times R)/(\sum C_{act}R)^{0.903}$

Closer scrutiny of the equation reveals that R (resistance per m² of envelope area) appears both in the numerator and denominator of approximately equal weight. The simplified method expresses the amplitude ratio in terms of active thermal capacity only, but the weighting factor used to calculate C_{act}, is derived from the use of thermal resistances in the envelope. Therefore, the envelope resistance (R) is still accounted for. The formulae have been simplified to

$\alpha_{iw}/\alpha_{ow} = 260{,}17/C_{actw}$ and $\alpha_{is}/\alpha_{ossol\text{-}air} = 150{,}41/C_{acts}$

α_{iw} = indoor amplitude, winter

α_{ow} = outdoor amplitude, winter

C_{actw} = active thermal capacity, winter

α_{is} = indoor amplitude, summer

$\alpha_{ossol\text{-}air}$ = Sol-Air outdoor amplitude, summer

C_{acts} = active thermal capacity, summer

A building "experiences" the outdoor temperature at its exterior envelope surface. 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 absorption. The latter is influenced by the surface colour. This effect is most pronounced during summer, as a result of the higher radiation levels.

2.3 Application of the CR Method

The following should be noted:

- 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.
- R requires the "help" of both C and I to achieve its purpose.
- A target dT can be reached by many combinations of I_w and R.
- A target amplitude ratio can be reached by many combinations of C_{act} 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 C_{act} (See Figures 4, 5 and 6).
- Since the indoor temperature amplitude 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[5], in prep).

2.4 Optimal CR

2.4.1 Intuitive approach

Steve Baer, renowned inventor of Albuquerque, New Mexico, discovered that CR can be optimised. The somewhat counterintuitive 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. See Annexure E.

2.4.2 Typical South African construction

Buildings provide a filter between the outside and inside environments. Few modern buildings achieve an acceptable indoor climate without resorting to artificial means of climate control. Buildings 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 global move to reduce the dependence on artificial climate control mechanisms.

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

2.5 Crucial building elements

2.5.1 Envelope effects

Air leakage through the building envelope can annul the benefits of C and R. The envelope also contains the windows and their associated 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 building envelope's level of insulation determines the conductive, radiative and convective heat losses or gains of a building.

2.5.2 Active thermal capacity (C_{act})

The thermal capacity directly, or indirectly, exposed to the indoor air, is active in as much as it interacts with the indoor air by either heating or cooling it. Air has a thermal capacity of only 1.2 kJ/m^{3}K, whereas brickwork is typically 1360 kJ/m^{3}K, and concrete 1764 kJ/m^{3}K.
Therefore, such materials have a strong impact on the indoor air temperature by absorbing and releasing heat energy. It also explains why a lot of air movement is needed to heat or cool a heavy structure. However, if the indoor thermal capacity is insulated from the indoor air, then the effect is greatly reduced, if not eliminated entirely. This happens with wall panelling, cupboards, pictures, curtains, and paintings, or floor carpets, rugs, wooden floors or suspended ceilings, bulkheads, and acoustic treatment below concrete slabs.

In South African domestic buildings larger than about 40m², heavy internal walls are traditional, and from about 80m² upwards, carpeted floors are prominent. With commercial buildings, carpeted floors, lightweight partitions and suspended ceilings are predominant. The use of carpets, pictures, wall panelling etc. inside of houses cannot be controlled or regulated, and since the indoor capacity of floors, ceilings and partitions of many buildings cannot be legislated, these are ignored in calculations. This leaves the thermal capacity effect of exterior walls to be carefully considered.

The calculation of active thermal capacity (C_{act}) is achieved by weighting the thermal capacity (volume x density x specific heat) of all exterior walls, by the ratio of the total thermal resistance of the wall to the thermal resistance from the outside surface up to the centre of the high capacity element.

2.6 Surface-to-volume and perimeter ratios

When Hannibal crossed the Alps with African elephants his men suffered under cold stress. Not so the elephants, whose body surface to volume ratio is much smaller than humans. The same natural law applies to buildings. When the wall thickness of the low-income subsidised houses was reduced for cost reasons, this decreased the thermal capacity 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 house was reduced from 53m² to 30m² this caused an additional energy demand of 28% in order to retain the same indoor conditions – assuming that the walls were unchanged.

This demonstrates that the stand-alone house model is a poor choice from a thermal efficiency and energy point of view, and certainly is not a sustainable model for the low-income sector. That is one of the reasons for the international use of terraced and row housing, across all income sectors.

With artificially controlled environments it is possible to construct large buildings with indoor climates 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 daylight, heating, cooling, natural ventilation, sound and view.

2.7 Notional perimeter zone

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%) of typical activities were accommodated in a room size of 18,5m², and 14m² housed 61% of the activities (See figure 1 below).

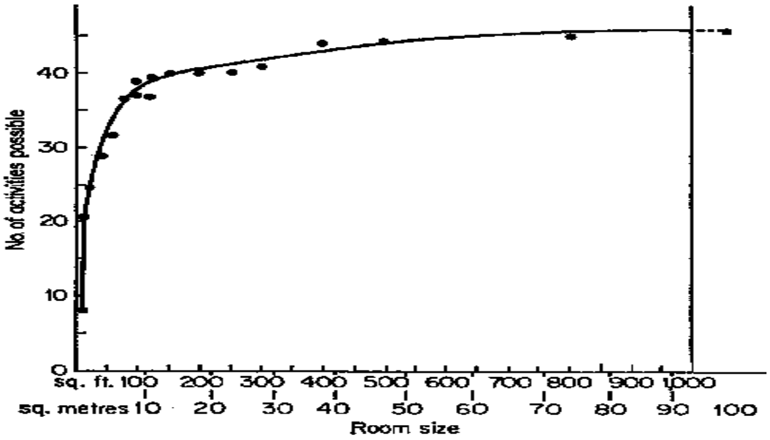


Figure 1 – Room sizes to accommodate activities (Cowan P. 1964)

For daylight 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 2100 mm in most residential buildings this yields a room depth of 3000 mm. The standard office used by DEO (2590 mm high x 3050 mm wide x 4570 mm deep) produces a room depth of 2,6 times the lintel-sill level.

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

Occupancy type	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 mm) and offices (4000 mm-4800 mm). Hausladen (2004) recommends an office depth from 3500 mm to 5500 mm with a preponderance of 4000 mm.

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

The following conclusions are reached regarding notional perimeter zones and how they are used to develop the design requirements for the building envelope.

- With the exception of a few underground buildings the majority of naturally ventilated and artificially conditioned buildings have a perimeter zone in direct contact with the outdoor environment.
- For all buildings, the outdoor environment has the strongest impact on the perimeter zone.
- While deep plan buildings have perimeter zones and inner zones, naturally ventilated ones have perimeter zones only.
- In the case of power failures or emergencies it should be possible to open the perimeter zone windows of deep offices.

- The notional perimeter zone of 2500 mm height and 3500 mm depth can be assumed to capture the majority of occupants, with a view to determining 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.

3 Analysis and Results

3.1 Thermal comfort ranges

This section describes how desired indoor thermal comfort temperatures for South African buildings are established. Some scientific background is included, leading to practically implementable temperature ranges.

Productivity is influenced by indoor conditions. It has been shown (Romm[4] et al, 2004) that the monetary value of productivity improvements through desirable natural lighting and temperatures, outweigh the monetary value of concomitant energy savings, by a large factor. Other studies revealed higher manual process productivity (e.g. typing) at slightly elevated temperatures, while intellectual productivity (e.g. arithmetic) increased at lower temperatures. In addition, racial and gender productivity trends were documented.

Comfort is a more popular theme, both in literature and practice. Air temperature dominates other factors. The comfort temperature (thermal neutrality) is defined as that temperature at which a person feels neither too 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 conflicted with observed reality, the concept of a comfort range was accepted. 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[2]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. He 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. His findings essentially substantiated earlier findings of Auliciems and Szokolay[1] (1997), but added more weight and precision.

The implications of this 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. The following formulae have been derived.

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

Table 4 – Comfort temperature ranges, after de Dear (1997)

The validity limits are 17,8°C < Tn < 29,5°C where Tn is the neutrality temperature, and ET* is the New Effective Temperature. Holm and Engelbrecht[3] (2005) have shown that the difference between ET and dry bulb temperatures is practically negligible for South African historic data. This is not valid though 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. 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 and ranges, 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

For illustration, some adaptive indoor comfort target temperatures (thermal neutrality) for 15 South African locations are presented in Figure 2.

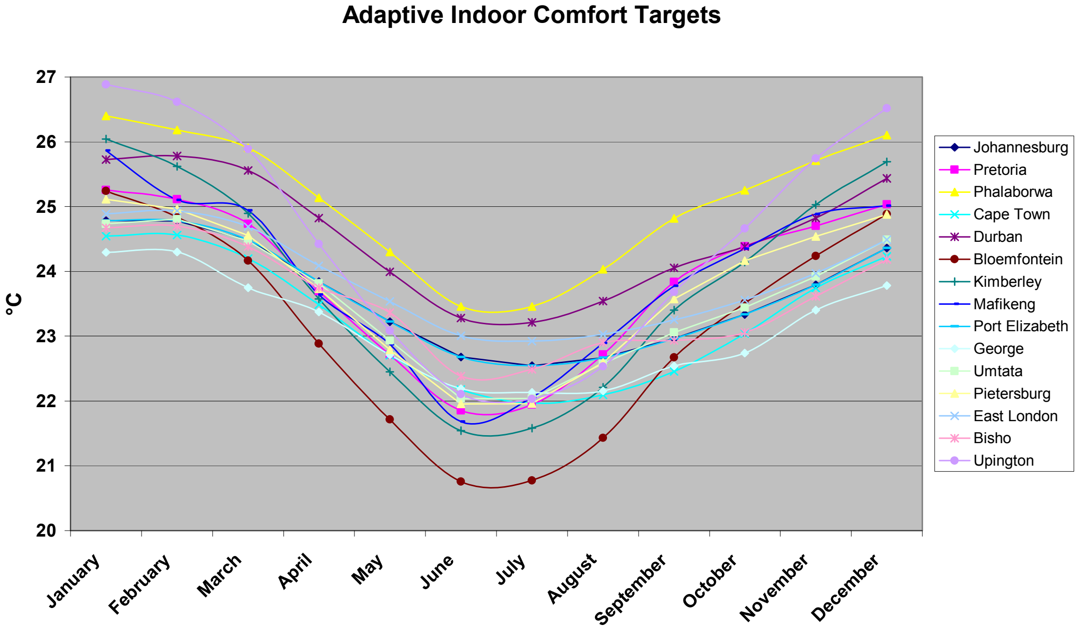


Figure 2 – Adaptive indoor comfort targets.

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

3.1.1 Temperature amplitudes and amplitude ratios

During a diurnal cycle the outdoor temperature moves from a minimum to a maximum, called the outdoor temperature amplitude. Indoor temperatures have a similar, but normally smaller, amplitude which has to be limited to achieve comfort.

A desired amplitude of 7K is expressed as Tn±3,5K. The desired indoor amplitude divided by the actual average outdoor amplitude produces the desired amplitude ratio. The amplitude ratio is a constant and measurable property of any building.

3.1.2 Thermal comfort ranges for modelling

Given the purpose of the research project was to propose deemed-to-satisfy requirements for walling alone, the less stringent 80% acceptability criterion was adopted for thermal modelling and calculation purposes.

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} = comfort design temperature range for building fabric of air conditioned buildings, and
Tn_{NV} = comfort design temperature range for building fabric of naturally ventilated buildings.

3.2 Raising/lowering monthly average indoor temperatures

3.2.1 Heating and cooling

The difference between Tn and the monthly mean outdoor temperature (To_{mean}) is called δT_{reqd}. This is an indication of the average monthly heating (+) or cooling (-) required. The area under the curves in Figure 3 represents Kelvin-days. Multiplying Kelvin-days with the specific thermal transmittance of a building (W/K) yields the monthly heating/cooling required.

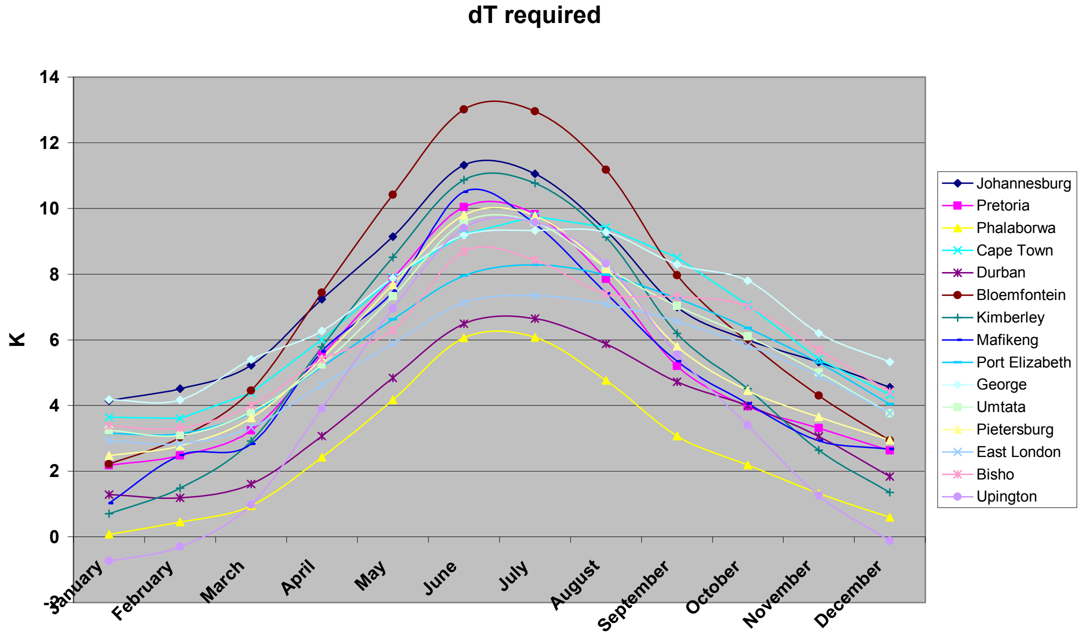


Figure 3 – Relative temperature rise/lowering required.

Bloemfontein requires most winter heating and Upington most summer cooling. Note: indoor loads and solar radiation 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 envelope insulation and night air cooling are effective. This requires sufficient active thermal capacity on the inside of the envelope insulation. Night cooling may be implemented by natural wind or by the chimney effect. Alternatively, the air is moved by a fan. Night air cooling is very effective in air conditioned buildings.

3.2.3 Achieving the desired amplitude ratio

The target indoor amplitude (α_i) is constant, while the monthly average outdoor amplitude (α_o) varies. It follows, therefore, 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 determines the criterion, called Ar_{regd}. The required CR can now be calculated.

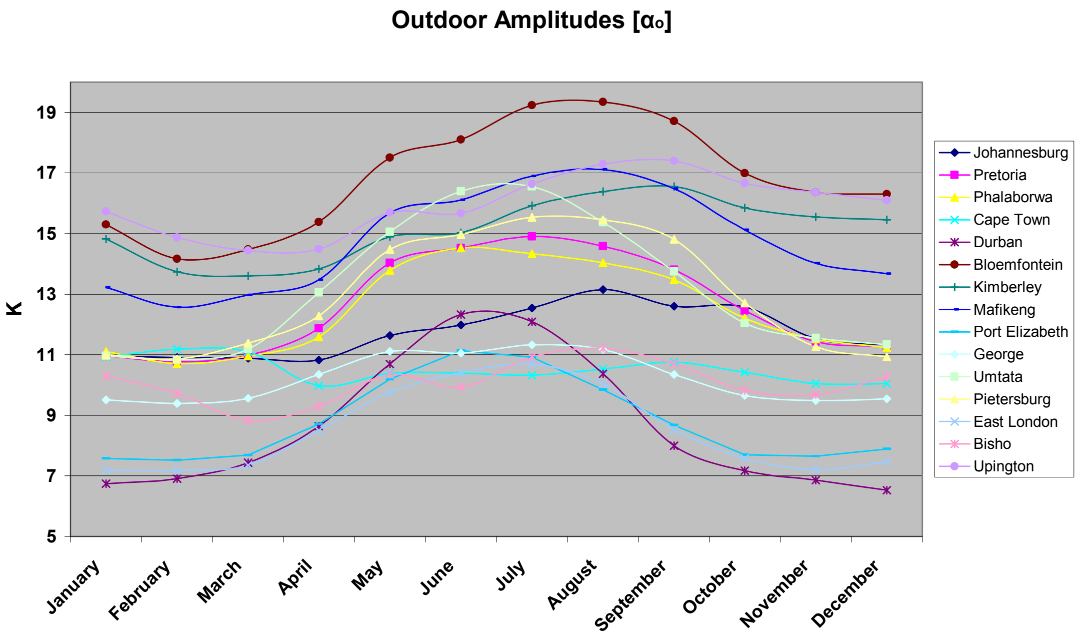


Figure 4 – Outdoor amplitudes.

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

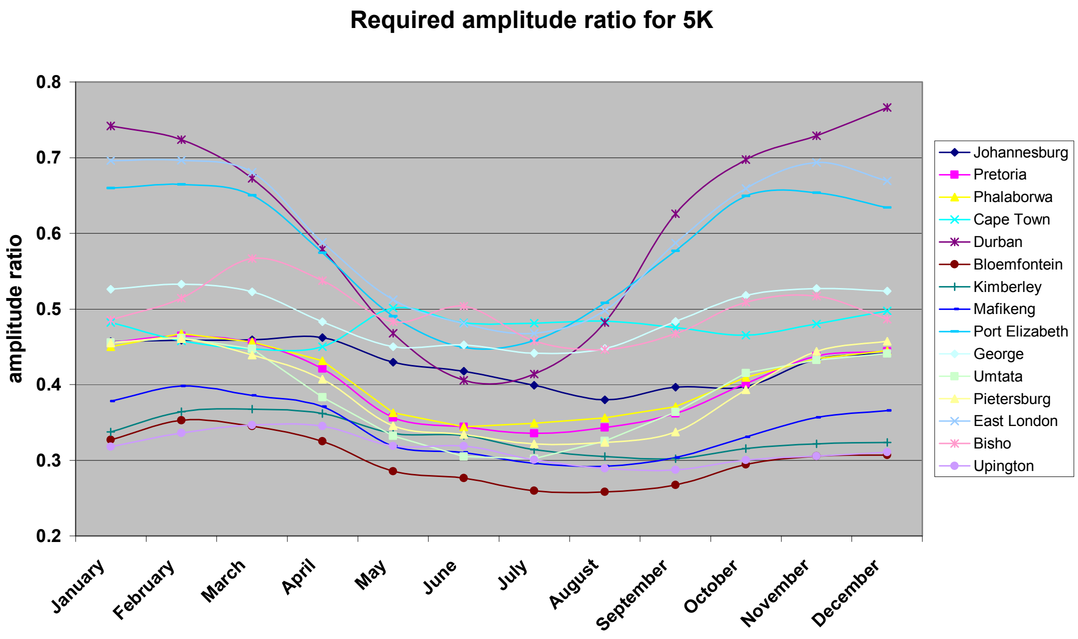


Figure 5 - Amplitude ratios required for 5K indoor amplitude.

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

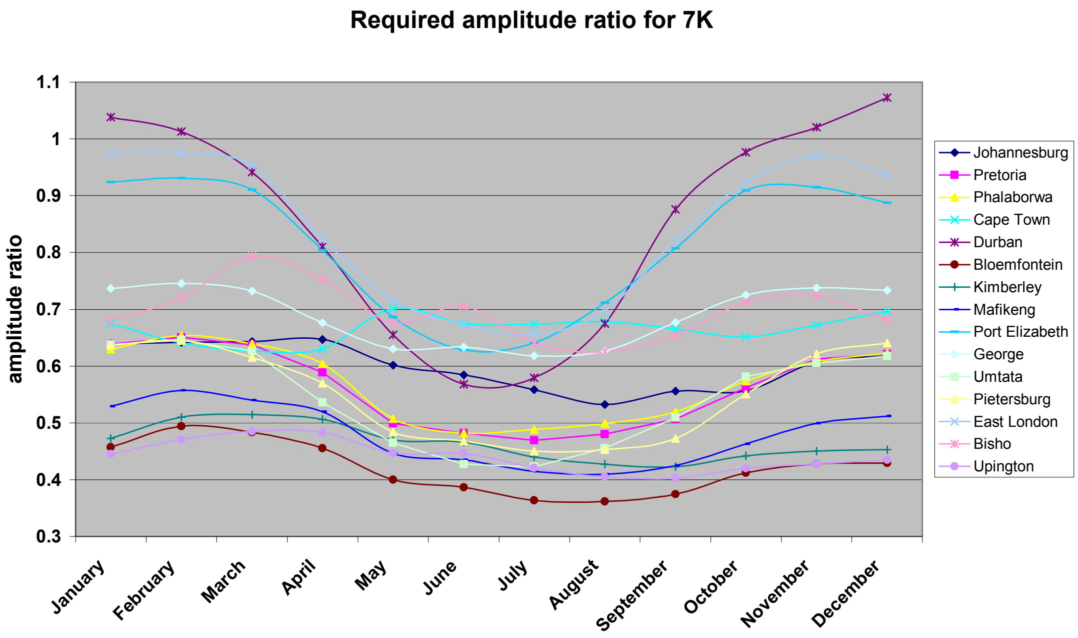


Figure 6 – Amplitude ratios required for 7K indoor amplitude.

The pattern is the same as in Figure 5, but the values differ.

3.3 Achieving desired amplitude ratios with active thermal capacity

3.3.1 Application of the CR method

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 as:

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

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

These formulae are applied to South African locations and climate zones, with the results shown in the following tables 6 to 9. It is clear that the more stringent amplitude ratios require higher values of active thermal capacity. As expected, Upington (Zone 6) requires the highest active thermal capacity, 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 capacity requirements, it appears that winter conditions dominate the requirements for active thermal capacity. The summer results are therefore ignored in the further analysis. It should be noted that the thermal capacity is defined in terms of kJ/K per m² of external envelope area.

Table 6 : Required Amplitudes & Thermal Capacity 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 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 Capacity 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

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

Table 8 : Required active thermal capacity 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 capacity required can also be expressed in terms of thermal capacity per square metre of **net** external wall area [kJ/m²K]. This is better than "surface density" as currently used in SANS 204, 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 capacity 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 7 below illustrates the relative percentage contribution of some building components to the total active thermal capacity (capacity) of non-residential buildings, whose exterior envelope resistances are SANS 204 compliant.

The first values ("concrete floor on soil") are for 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 second data set ("suspended concrete floor") is for the same construction, but with a suspended concrete floor construction. The third data set ("carpeted suspended floor") of values is for the same construction as the second one, but with the suspended concrete floor covered with typical carpeting, effectively isolating the thermal capacity from the indoor air.

The following is evident from this analysis:

- The active thermal capacity of the lightweight ceiling is negligible.
- As the percentage contribution of the floor to total active thermal capacity decreases, the sum of the others increases and the total active thermal capacity decreases.
- The growth of the exterior wall percentage contribution by far outweighs all other elements as the contribution of the floor decreases.

- It is difficult to regulate, and impossible to control the interior finishes of buildings as they 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 capacity of the building interior should be regarded as a bonus if available, but should not be relied upon through legislation.

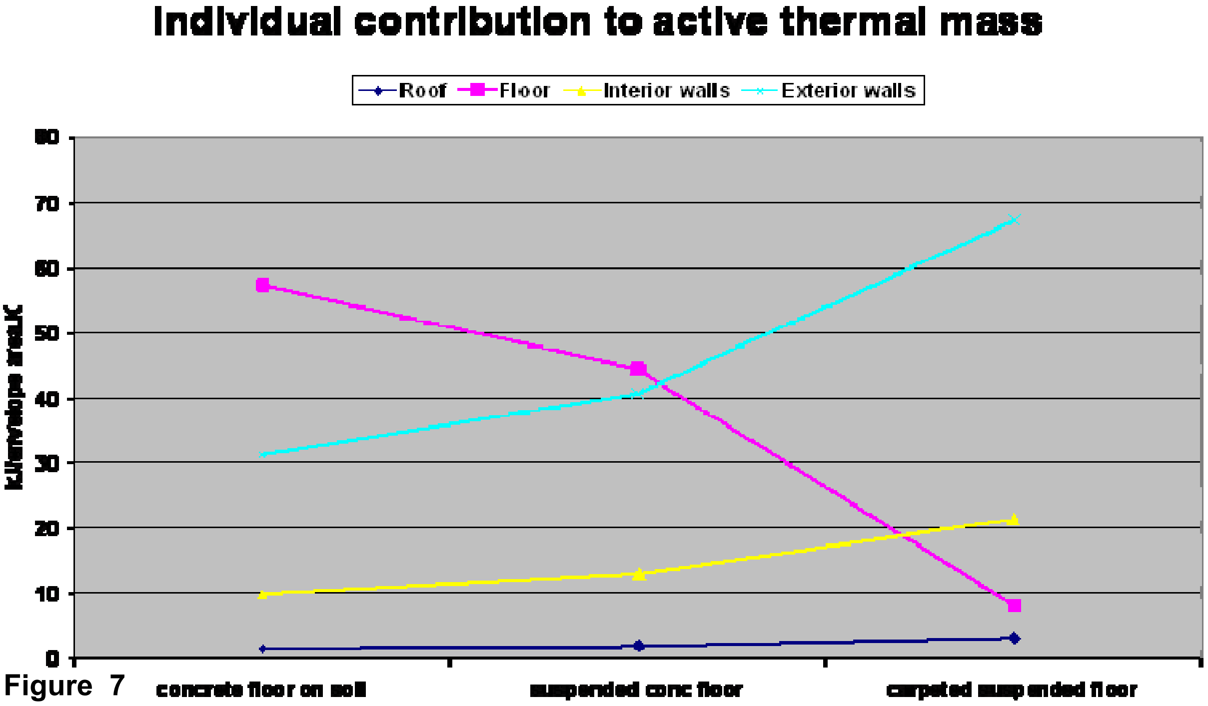


Figure 7 : Contribution of building elements to active thermal capacity

3.4 Thermal Modelling

3.4.1 Energy Usage and Life Cycle Cost modelling

In this project Visual DOE thermal modelling software was used to model the effects on the energy usage and life cycle cost (LCC) of two simplified building designs, for 3 occupancy type groups, in six climatic zones, for five wall systems of differing thermal capacity and thermal resistance combinations. LCC is the sum of all energy savings (discounted for time weighting) and the initial premium of a wall system energy improvement intervention.

All monetary values in the discounted cash flow analysis are absolute with a discount rate of 8.5% selected, being the current long term borrowing rate as indicated by the R157 trading at the time of computation. A sensitivity analysis for the residential design for Region 1 shows that had a discount rate of 15% been applied, the ranking of the results would be unchanged.

An analysis period of 20 years was chosen after consideration of the maximum life of equipment, glazing, and building components such as thermal insulation, although the expected life of masonry buildings is more than 50 years.

A synthetic electricity cost was derived from known data, 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 p.a. This is to show a tripling of energy prices in real terms over the twenty year evaluation period.

The models are neutral to the selection of walling types, and artificial or synthetic walling combinations of thermal capacity and thermal resistance could have been selected. For convenience and practical relevance, known walling of 106 mm thickness brick and SANS 204 levels for thermal insulation have been used to construct the data points.

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 Kelvin range or a seven degree Kelvin range, about the thermal neutrality temperature for the climatic region selected.

Residential (Naturally Ventilated)	Non-residential (Artificially Ventilated)
Units: Degrees Celsius	Units: Degrees Celsius

Region	Heating	Cooling	Region	Heating	Cooling
1	20	27	1	21	25
2	20	27	2	22	26
3	20	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 modelling for each climatic region:

3.4.2 Energy Usage and Life Cycle Cost modelling

As the equations for active thermal capacity are developed from the CR method equations (as was described in Section 2), and because active thermal capacity is conceptually simple and relatively easy to calculate, further investigation into the possibility of using active thermal capacity for deemed-to-satisfy requirements was done. Calculations of the active thermal capacity are reproduced and compared to the life cycle cost for every climatic region, for the occupancy groups, in the following section.

3.4.3 Optimal active thermal capacity

The optimal active thermal capacity for each occupancy group and climatic region, can be selected via a graphical technique, and is presented by way of an example in Figure 8 below.

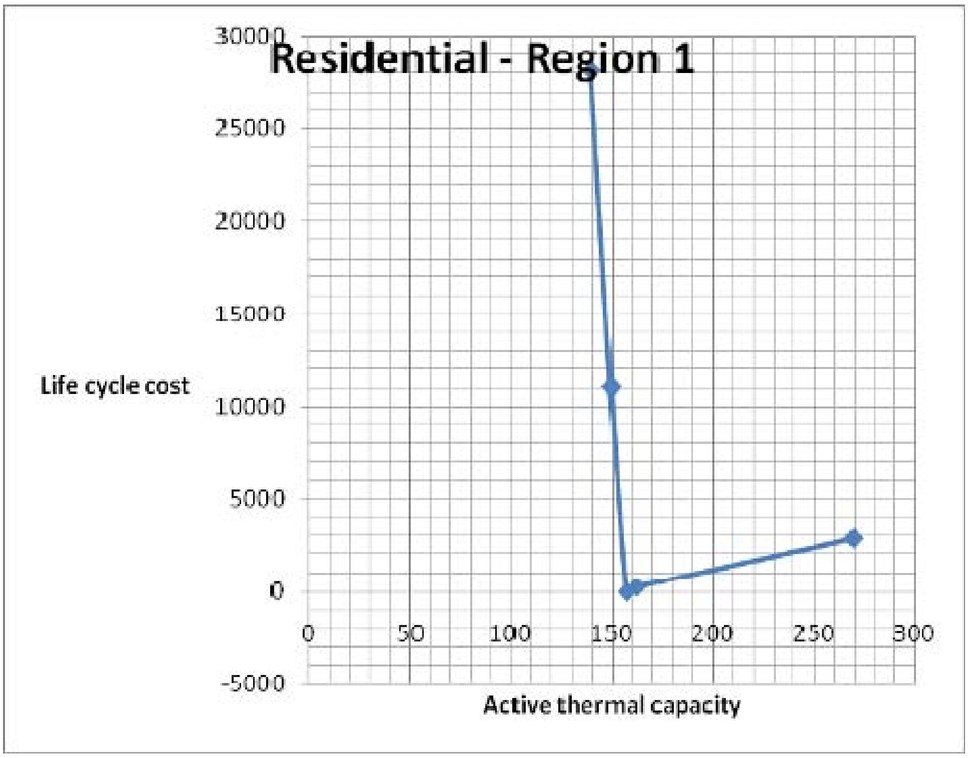


Figure 8: Relationship of Life Cycle Cost to Active Thermal Capacity

However, active thermal capacity was correlated with energy usage modelled, and in only 72% of cases, was a correlation over 60% achieved. The most likely cause of this is that the algorithms developed in the project to calculate active thermal capacity, differ from the underlying algorithms in the Visual DOE software. The possibility that a simpler performance criterion could show a better correlation with energy usage was, therefore, investigated.

3.4.4 The CR product as a suitable performance criterion

As shown in prior sections, there is a direct correlation between the CR co-efficient (developed by Wentzel) and the amplitude ratio for the synthetic building. The possibility that the arithmetical product of the thermal resistance and thermal capacity of the walling systems would have a good correlation with energy usage was, therefore, investigated.

The CR product of a walling system is calculated from first principles:

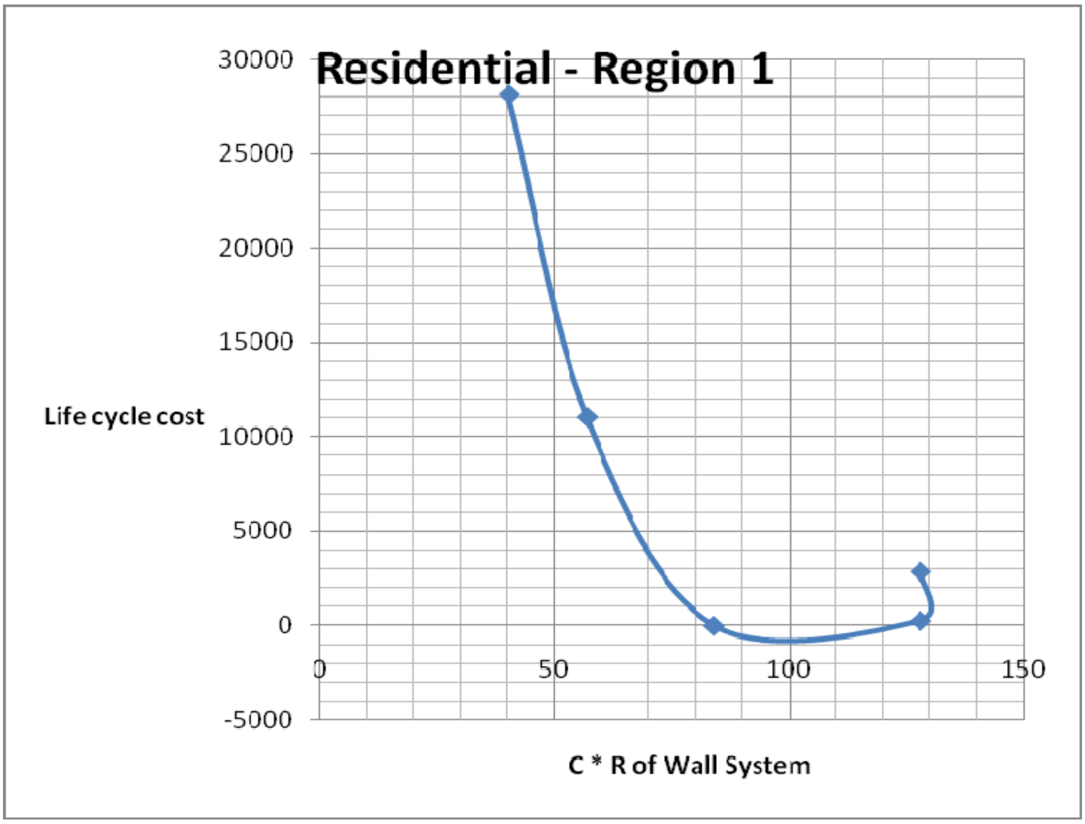
C (thermal capacity) = total of all layers in the wall system, with each layer's capacity calculated as : Specific heat (kJ/kg.K) x thickness (m) x density (kg/m^3) = C (kJ/m^2.K)

R (thermal resistance) = total of all layers in the wall system, with each layer's resistance calculated as : thickness (m) / thermal conductivity (W/m.K) = R (m^2.K/W)

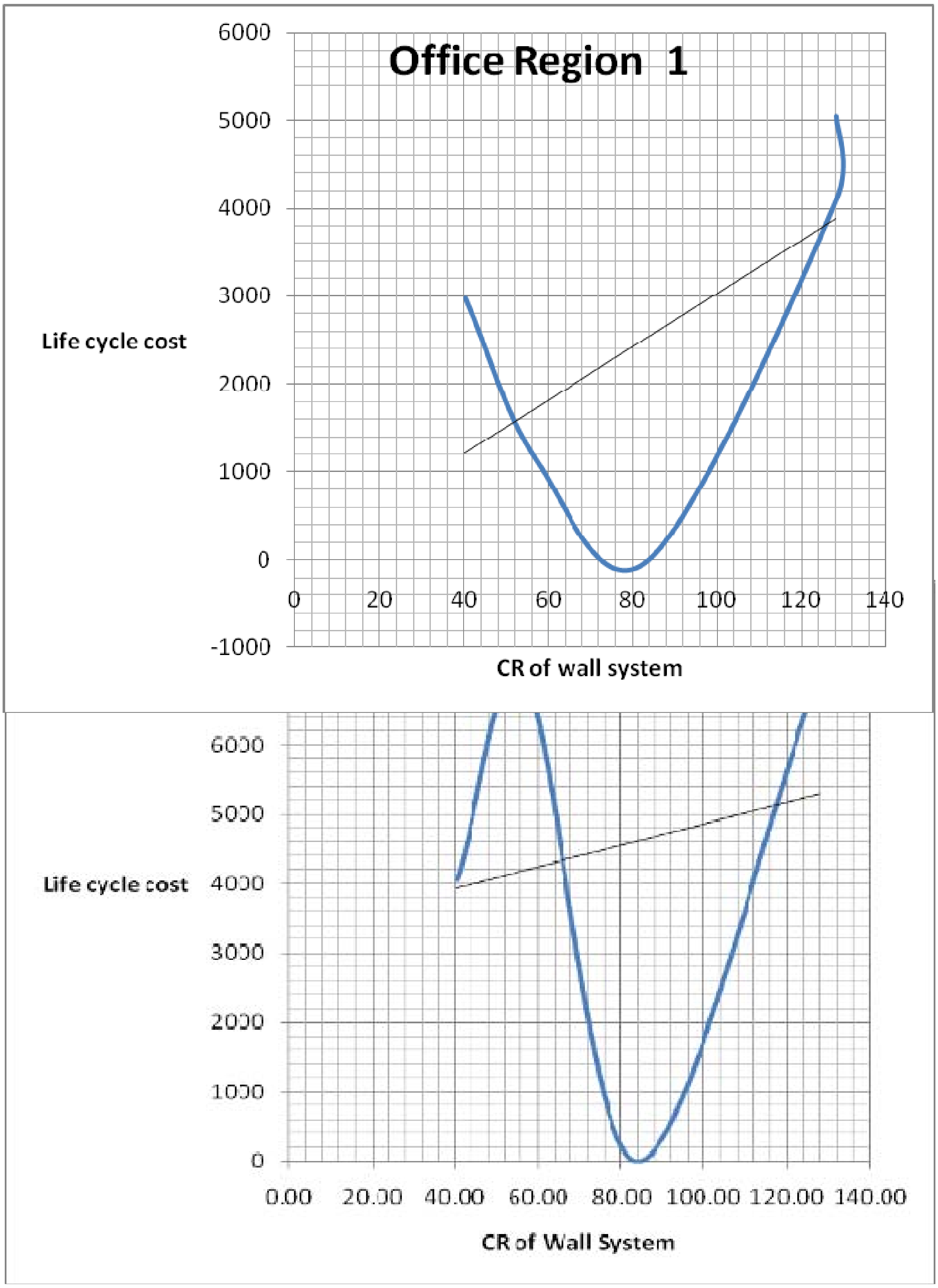
C x R = kJ/m^2.K x m^2.K/W = kJ/W = kiloseconds.

Multiplying by 1000/3600 provides a CR product value in hours.

The correlations of the CR products with energy usage predicted by the thermal models are very high, with an average of 86% (see Table 12 below). Continuing with the graphical technique addressed above, the optimal CR product value can be determined, at the lowest life cycle cost, for each combination of occupancy group and climate zone. This is illustrated in figures 10, 11 and 12 below for Region 1.



Figures 9: Lowest life Cycle Cost for C*R combinations



Figures 10 & 11: Lowest life Cycle Cost for C*R combinations

Table of energy usage versus CR product for building per walling type

	Wall Type	**Solid double brick (DB)**	**DB with 50mm air-space**	**DB with R=0.5 insulation in cavity**	**DB with R=1.0 insulation in cavity**	**DB with R=1.0 external insulation**	**Correlation of CR product with energy**
	C*R	40	57	84	128	128	
	Climate	kWh	kWh	kWh	kWh	kWh	Inverse

	Zone						
Energy usage for Retail occupancies (kWh)	**1**	17,420	17,645	16,193	16,472	16,193	0.81
	2	14,365	13,952	12,754	12,741	12,719	0.97
	3	17,783	17,414	15,603	15,447	15,507	0.95
	4	11,263	11,601	10,864	10,993	12,307	0.61
	5	12,080	11,899	10,781	11,041	11,053	0.90
	6	24,492	23,131	19,887	19,012	18,559	0.98
Energy usage for Residential occupancies (kWh)	**1**	7,719	6,460	4,950	4,606	4,687	0.99
	2	6,470	5,795	4,730	4,612	4,616	0.98
	3	10,936	10,590	9,299	9,490	9,365	0.92
	4	8,291	7,903	5,498	5,109	5,195	0.94
	5	4,162	3,976	3,406	3,467	3,435	0.93
	6	11,025	9,882	8,018	7,610	7,691	0.98
Energy usage for Office and Institutional occupancies (kWh)	**1**	6,432	6,077	5,211	5,316	5,061	0.96
	2	6,936	6,860	5,934	6,382	6,182	0.79
	3	10,900	11,017	8,742	10,360	10,465	0.57
	4	6,488	6,152	5,224	5,034	5,037	0.98
	5	6,643	6,784	5,448	6,778	6,570	0.30
	6	9,986	9,767	8,352	8,702	8,675	0.90
						Average correlation	0.86

Table 11: Correlation of thermal capacity & resistance products to energy usage by occupancy and climatic region

The correlation is developed with the inverse of the C * R product to the power of 0.903, and multiplied by a factor of 10^5. This modification is derived from the Wentzel regression equation for the CR function.

3.4.5 Comment

The C * R product requirements which are proposed for incorporation into regulations and standards are developed from the minimum life cycle cost options, as in figures 9, 10 and 11 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 be optimal for the range of a solid double brick wall up to the same wall with an added thermal resistance of R=1.0, in ten types of building, across six climatic regions.

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

The tendency toward lightweight industrial building systems, using a range of technologies and materials, has incorporated thermal resistance aspects, but not thermal capacity. Much has been made of the thermal efficiency of such systems, but it is shown in this research that when thermal capacity is combined with thermal resistance, the most economical results are achieved. An extension of this research is published in a separate document, and shows the significant energy cost premium of using walls that do not comply with the minimum CR values proposed for SANS204.

Most thermal insulation materials are light in capacity and most brickwork high in thermal conductivity, and 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 106 mm double brick 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/m^3	w/mK	kJ/kgK
Brickwork	1820	0.82	0.8
Insulation	30	0.03	1.2

Table 12: Material Properties of 106mm double brick wall

The costs of all walling systems have been calculated using Buildcost, and by discussion with building contractors with experience of constructing cavity walls. An example of a cost sheet is attached as Annexure D.

4. Deemed-to-satisfy requirements and conclusions

By selecting the walling option with a C * R Product that provides the lowest life cycle cost, as the deemed-to-satisfy value, economic viability for each combination of climate region and occupancy group is provided.

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

Minimum Thermal Capacity & Resistance CR Products (hours) by Region and Occupancy						
Occupancy **Region**	**1**	**2**	**3**	**4**	**5**	**6**
Residential E1-3, H1-5	100	80	80	100	60	90
Office & Institutional A1-4,C1-2,B1-3,G1	80	80	100	100	80	80
Retail F1-3,J3	80	80	120	80	60	100

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

The results above correspond to masonry walling ranging from a 106mm double brick construction (face brick externally and stock brick plastered internally), with a minimum thermal insulation provided by a 50mm air-cavity, through to a similar wall with 30mm of extruded polystyrene in the cavity. Typical constructions will have the following indicative thermal capacity and resistance product.

Wall Type *Thermal Metric*	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 (m^2K/W)	0.45	0.64	0.95	1.45	1.45
Thermal Capacity (kJ/m^2K)	326	326	326	326	326
*C * R Product (hours)*	41	58	86	131	131
Active Thermal Capacity (kJ/m^2K)	139	149	157	162	270

Table 14: Various Thermal Metrics for typical constructions

*If the insulation layer was to be positioned internally, the weakest energy consumption result would occur, similar to that of a solid double wall without a cavity.

References

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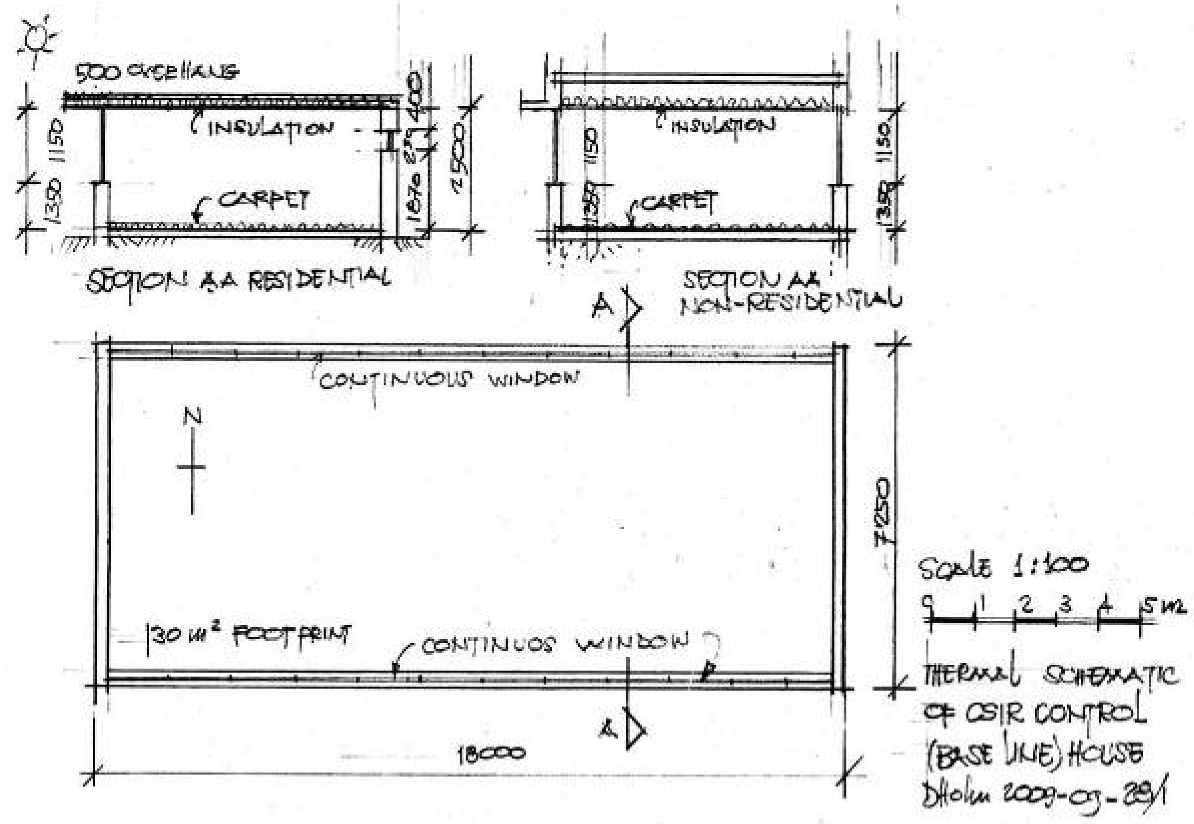
Annexure A


500 OVERHANG
INSULATION
CARPET
1150
1350
400
570
1870
2500
SECTION AA RESIDENTIAL
INSULATION
CARPET
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	Equipme	Heating	Cooling	Fans	Ext.	Total
Electrical End-use Totals (kWh)							
Double brick with 50mm air cavity	3,430	4,287	4,025	433	2,002	657	14,834
Double brick insulation added to R=1.0	3,430	4,287	2,176	438	2,992	657	12,980
Double brick solid	3,430	4,287	5,082	446	2,180	657	16,902
Double brick solid internally insulated	3,430	4,287	3,510	661	2,143	657	14.688
Double brick external insulate	3,430	4,287	2,313	406	1,968	657	13,061
Double brick insulation added to R=0.5	3,430	4,287	2,619	400	1,932	657	13,324

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	R10.681	R0.681	R782	R136,737
Double brick insulation added to R=1.0	R9,345	R9,345	R11,703	R130,652
Double brick solid	R11,585	R11.585	R0	R147461
Double brick solid internally insulated	R10,575	R10,575	R11,703	R146,308
Double brick external insulate	R9,404	R9,404	R11,703	R131,403
Double brick insulation added to R=0.5	R9,593	R9,593	R7,175	R129,281

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

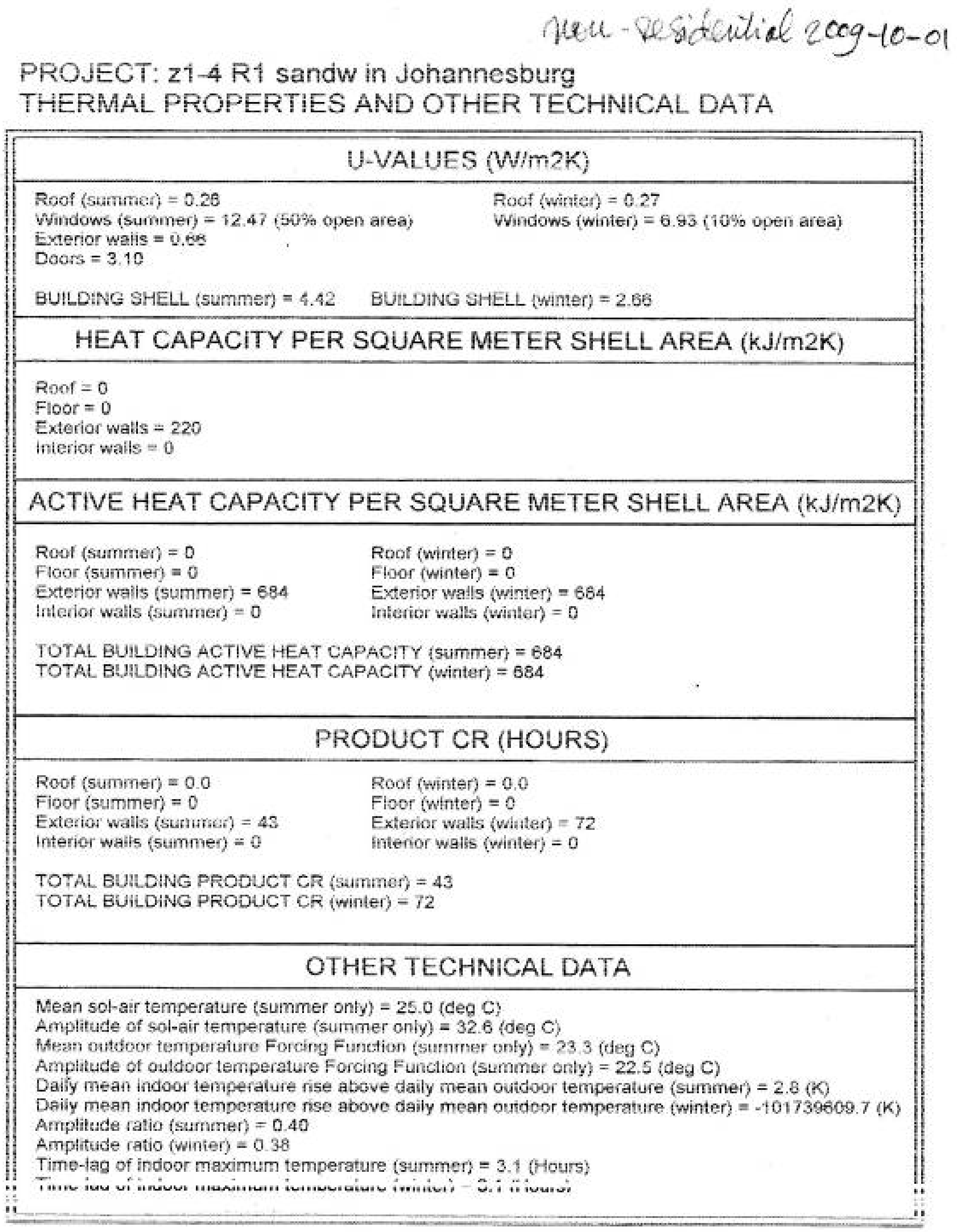
Monthly Electrical Usage (kWh)

Alternative	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Double brick with 50mm air cavity	970	859	943	1104	1422	1858	1819	1564	1262	1067	1021	945
Double brick insulation added to R=1.0	965	839	920	962	1172	1449	1427	1276	1101	983	956	929
Double brick solid	996	891	982	1199	1578	2097	2062	1739	1369	1133	1075	971
Double brick solid internally insulated	1032	891	970	1085	1388	1751	1736	1515	1247	1076	1014	982
Double brick external insulate	954	833	916	965	1187	1489	1465	1293	1102	987	949	922
Double brick insulation added to R=0.5	951	833	916	988	1223	1550	1519	1337	1128	996	960	924

Monthly Electrical Power Demand (kW)

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

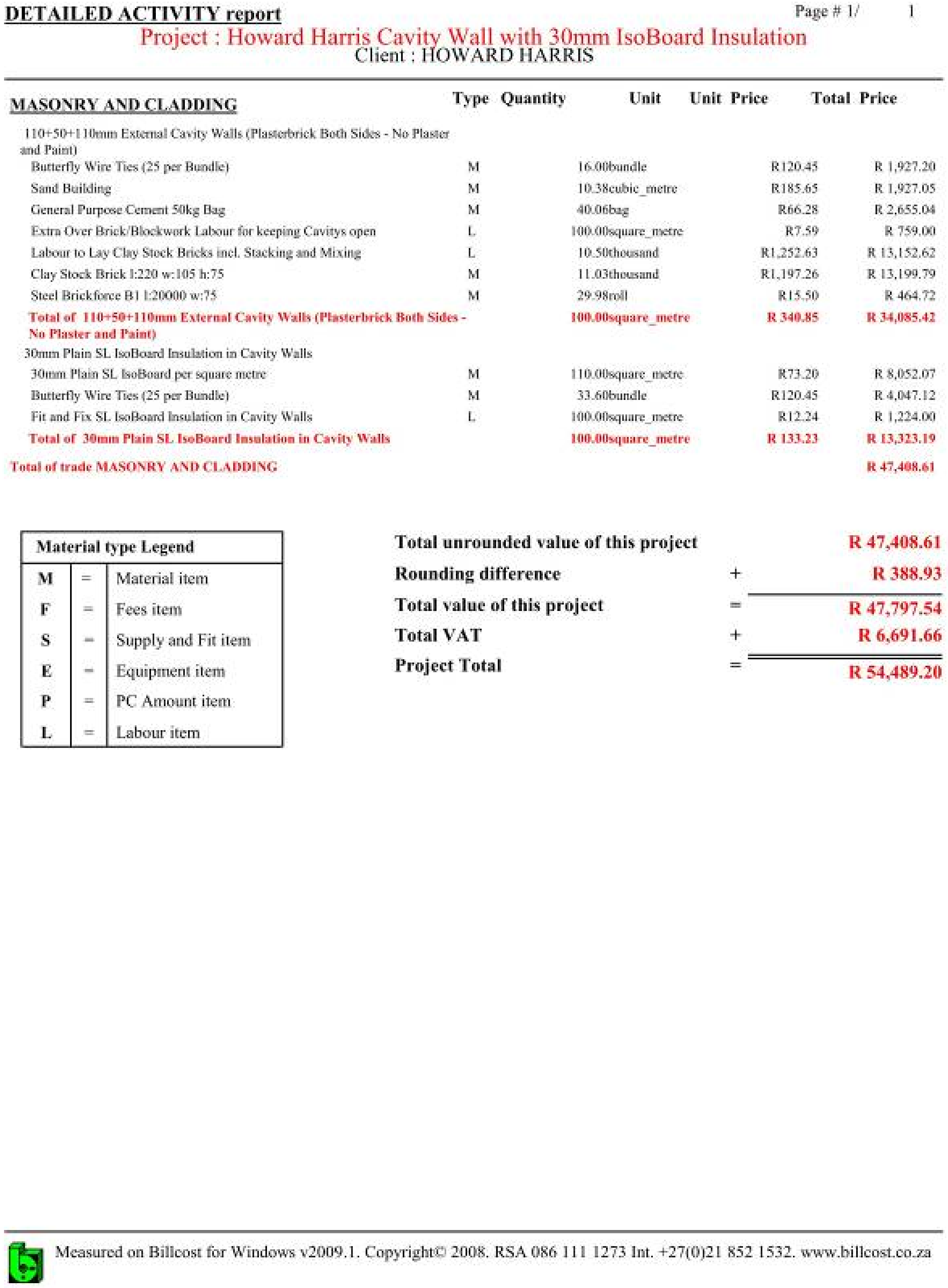
Roof (summer) = 0.0
Roof (winter) = 0.0
Floor (summer) = 0
Floor (winter) = 0
Exterior walls (summer) = 43
Exterior walls (winter) = 72
Interior walls (summer) = 0
Interior walls (winter) = 0

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

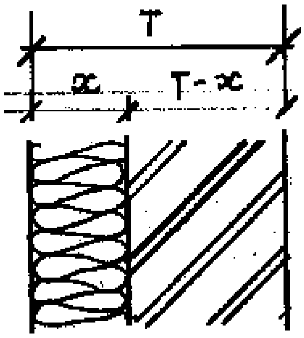
Measured on Billcost for Windows v2009.1. Copyright© 2008. RSA 086 111 1273 Int. +27(0)21 852 1532. www.billcost.co.za

ANNEXURE E

How to build a wall
By Steve Baer, September 1988

The time constant measures how sluggishly an object changes temperature. It is defined as the thermal capacity divided by the rate of the heat loss. A long time constant is a worthy goal for a house builder; the building can then coast through long periods of heat or cold without becoming uncomfortable.

It was a great surprise to me to discover that if a wall is assigned a certain thickness the wall will have the longest time constant if exactly half of its width is insulation and the other half is thermal capacity. You would think that the proportions would depend on the kind of insulation and the kind of thermal capacity. It does not make any difference. Urethane insulation or crumbled newspaper; they have different R-values, but each fills exactly half the width of the wall for the best results.



The time constant A for a section of wall is:

$$A = C(T-x)/(1/xk) = CTxk-Cx^2k$$

Where k is the resistance to heat loss per unit thickness and C the thermal capacity per thickness

$$dA/dx = CTk-2xCk$$

At A’s maximum value

$$dA/dx = 0 = \cancel{C}T\cancel{k}-2x\cancel{Ck}$$

$$x = T/2$$

The values of k and C have nothing to do with the problem. We only need to be sure that our insulation has negligible thermal capacity and our thermal capacity negligible insulating value.

If there is no limit on the thickness, rather a limit on how much we spend, the same rule for splitting things down the middle crops up again. Spend one half the money on insulation, one half on thermal capacity.

We have T dollars per unit area to spend on insulation and thermal capacity together. Assume that each unit of thermal resistance costs $k/unit area and each unit of thermal capacity costs $C/unit area.

We spend x dollars on insulation and (T-x) on thermal capacity. The time constant

$$A = CTxk-Cx^2k$$

It is the same equation as before – only now x represents dollars instead of inches.

Spend half your money on thermal capacity and half on insulation even if your thermal capacity is gold sheet while your insulation is rock wool.

Weight could also be the limiting quantity. Then 1" of water would nestle inside 30" of Styrofoam. This division splits the weight in half since water is 30 times as heavy as Styrofoam.

For me these equations prove everything but explain nothing. How can this rule be true? I have come closest to an intuitive understanding this way: I don't think of the time constant by its definitions – thermal capacity divided by conductivity. I think of it as thermal capacity multiplied by the conductivity's reciprocal – the resistance. The product is like the area of a rectangle with one side resistance and the other thermal capacity. It is plain to me, who has fenced things in, that a square gets the most area of all rectangles out of a fixed perimeter. Here we confirm our rule, for the square divides the perimeter equally.

This is a good first step, but the problem is more complicated. If the wall's composition is limited by money, not space, how is the lesson of the square with its equal sides going to help us? The wall is unlikely to have equal thicknesses of insulation and thermal capacity. A geometrical equivalent of maximising the time constant where money is our constraint again uses a fence around the rectangle, only now we deal with all kinds of fences. Sometimes the sides that run east west require three strands of wire (cheap fence) while those that run north south require 10 strands. How do we divide the wire to enclose the maximum area? Half of our spool of wire, just as half of our money, goes to the long east west fence, which has only three strands; the other half goes to the short north south fence. This gives the greatest area of all such enclosures. Whether it is wire, space or money that is limited, you must divide it up equally to the partners regardless of how they use it, for them to give you their biggest product. Why is this so? We think the factor that gets a lot for its money (or its wire) should take more than its half, but the factors trying to produce a big product have faith in team work. Each side knows that as it lengthens the rectangle's area swells at the rate of its partner's length not its own. The 50-50 split of space, weight, wire or money is the perfect compromise of two things each trying to make sure the other gets its share.

I realise I still have explained nothing about this mystery but I can close my discussion and avoid further questions by tainting my arguments with a moral. "The struggling performer" such as the fence that uses 10 strands of wire badly needs every bit of space, or raw material it can get. It deserves its one half share, while the other member of the pair which had it easy, has already grown so large it wouldn't know how to appreciate more space or raw material anyway.

After showing you Baer's wall law I wish to disavow it. Walls are never built with only one goal – a long time constraint – or one restraint – such as limited space or money. We are always short on several things and reaching towards several goals, but I have learned something about walls and they no longer look the same to me. Did you spend about as much on the thermal capacity as the insulation? That's the question I'll ask in our New Mexico climate.