A new and innovative look at anti-insulation behaviour in building energy consumption

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ABSTRACT

This paper presents the findings of a case study with building simulation using EnergyPlus dynamic thermal simulation software, in which wall insulation was varied together with cooling set-point temperature in a hot and dry climate of Botswana. Against the established norm that adding wall insulation reduces annual fuel consumption, it is shown in this paper that this is not always the case: there are instances where adding wall insulation directly increases annual fuel consumption. Initial cost of insulation aside, as the cooling set-point temperature is gradually increased, the building switches from an "insulation reduces cooling load" to an "insulation increases cooling load" behaviour. In other words, the well established knowledge that "*the lower the u-value the better*" gets overridden by "*the higher the u-value the better*". We termed this a "point of thermal inflexion". Simple graphical demonstration of the existence of this point is presented in the paper. According to the findings, design engineers and building economics related professionals who quantify investment on insulation can get disastrous results if they assume that all buildings behave pro-insulation since a building may behave anti-insulation.

Keywords:
Wall insulation
Building energy
Energy simulation
Optimization
Thermal inflexion

1. Introduction

It is world wide established knowledge that adding wall insulation in buildings reduces annual energy consumption. While this is largely correct, it is also equally important to note that this may not always be the case. During discussions of several energy audits reports [1], a hypothesis was arrived at: that there seems to be instances when building annual energy consumption increases with increased wall insulation. Extensive literature survey was then carried out on the latest research work [2–6], journals [7–19], conference papers [20–23] and other up-to-date publications like new energy codes and standards [24–27], all directly and indirectly echoed the same message: that insulating walls of building saves energy. The possibility of the opposite behaviour is not hinted in any of the publications. Previous simulation work done by the authors [28] hinted that adding wall insulation increases annual energy use, but a new and different simulation model was needed to validate this, hence this paper—thanks to today's hard working simulation software!

EnergyPlus (dynamic thermal simulation software for energy efficiency) has been used to simulate annual cooling and heating energy of a typical three-storey office building in a hot and dry climate of Botswana. The program (EnergyPlus) is a newly released tool (2001) that combines the best features of DOE-2 and BLAST programs [29], plus additional original capabilities. Logically, it is therefore better than its predecessors.

Since the findings in this paper are strange and seem not to have been reported before, preliminary discussions with several experts in the field of building energy have shown that they all suspect a software error (EnergyPlus). The next six paragraphs are meant to show that it is unlikely that the results are due to a code error since similar trends have been observed in different software.

Gratia [30], while running a TAS thermal simulation program [31], experienced increased cooling energy when changing from single skin to double skin façade. She ascribed the behaviour to direct solar gains and hot air film inside the double skin. Changing from single skin to double skin does not increase transmitted solar, so direct solar gains cannot be the reason. The hot air film being the cause of increased cooling energy does not seem enough since in either single or double skin, almost all transmitted solar ends up as cooling energy irrespective of whether it is trapped on the envelope or inside the building. A possible reason why cooling energy would increase in her set-up is: if the envelope stops heat from escaping, i.e. becomes more insulative, the air conditioning system has to work harder to remove the heat. This way the building will be anti-insulation. The cause and effect was probably

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made difficult by dealing with two variables simultaneously: variation of thermal transmittance (*u*-value) and solar transmittance. As a result anti-insulation behaviour was unnoticed.

Kalogirou [32], while running a TRNSYS transient thermal simulation program [33], repeatedly found negligible but increasing cooling energy while doing several thermal mass modifications that effectively lowered the *u*-value. He had used thermal mass instead of standard construction, and secondly he increased the gap in the wall. He dismissed the resultant increase in cooling energy as having negligible impact on the overall (i.e. cooling and heating) energy consumption and did not explain the cause of such an increase. Unnoticed to the author, some anti-insulation behaviour seems to have been in operation.

Eicker et al. [34] also used TRNSYS to test double façade. They experienced increasing cooling load during summer and they ascribed that to high gap temperature. The explanation does not seem enough because by observation of the law of conservation of energy, if on a single clear glazed façade, 'τ' amount of solar radiation is transmitted through; almost all of it will be converted into heat that contributes to cooling load. If double glazed façade is used, the outer layer will still transmit the same 'τ' amount of solar radiation which should contributes roughly the same amount of cooling load, not more! But more precisely, because the radiation is converted to heat in-between the glass panels, ΔT across the outer panel will be high, which will lead to increased heat loss by conduction back to the atmosphere, leaving *less than* 'τ' for cooling load, not more! In addition since the temperature of the outer glass is high due to trapped heat in the gap, there will be more re-radiation to the atmosphere, leaving less and less of the original 'τ' radiation for cooling load. Also, double glazing means double reflection, which reduce the transmitted radiation 'τ' even further. Once again it seems increased summer cooling in Eicker's work may have resulted from the change of *u*-value (which was lowered), and unnoticed to the author, the model seems to have behaved anti-insulation during summer. The same argument applies to Bouden [35] who experienced 60% increase in cooling energy when changing from single to double façade wall.

Prager et al. [36] used ESP-r simulation program to vary solar emissivity of outer wall surface on two building models: one poorly insulated and the other well insulated. In each model in

Table 1
Input data to the base case model

Construction materials	
External walls	13 mm lightweight plaster/110 mm brick/110brick/13 mm lightweight plaster
Partitions	13 mm lightweight plaster/110 mm brick/13 mm lightweight plaster
Roof	2 mm IBR sheet (outermost) 2 mm silver sheet (high reflectivity) 2.5 m ceiling void (R = 0.18 m^2 K/W) 40 mm glass wool 20 mm plasterboard (innermost)
External doors	6 mm glass
Activity	
Occupancy density (offices, surveyed)	0.0538 people/m^2
Occupancy density (passages)	0 people/m^2
Occupancy schedule	Office hours
Activity	Office_typical
Heating/cooling set-point temperature	20/21 °C
Min fresh air per person	8 l/s-person
Target illuminance	500 lux
Equipment gains (surveyed)	9 W/m^2
Openings	
Type of glazing	Single clear 3 mm
Layout	1.0 × 1.5 m on steel frame
Inside shading	Drapes, close weave, medium
Lights	
Type	T8 Fluorescent, surface mounted
Lighting gains (surveyed)	8 W/m^2
HVAC	
Type	Const. air volume sys (centralised)
Heating and cooling system	Electricity
Est. cooling load	276 kW
Heating load (estimated)	252 kW
Operating hours	06:00–18:00 h
Simulation weather data	Gaborone (from Meteo-norm)
Building dimensions	
Building length × width × height	3 m × 20 m × 3.5 m
Single floor built-in area	1581 m^2
Therefore 3 floors	4743 m^2
Passages	341 m^2
South Zone (single floor)	494 m^2
North Zone (single floor)	355 m^2
Mid Zone (single floor)	385 m^2
Therefore TFA (single floor)	1234 m^2
Therefore 3 floors TFA	3702 m^2

TFA: Treated floor area; Est.: estimated.

isolation, they were concerned only with comparison of cooling demand between emissivity of 0.9 and that of 0.1. The authors were not interested in comparing similar potions of a poorly insulated building with a well insulated one, and when this is done, a clear anti-insulation behaviour is observed—which went unnoticed to the authors.

Hamza [37] used APACHE-Sim (IESVE) dynamic simulation program to compare single skin and double skin façade with various conditions like clear, tinted and reflective. Where he compares single reflective with double reflective, peak summer cooling demand was increased by 28%, which was not explained. The author explained only the overall annual picture, which showed a net reduction in cooling energy. Once again signs of anti-insulation behaviour went either unnoticed or simply ignored!

Perhaps most important of all: in the EnergyPlus Engineering Reference manual [38] (Table 12, rows 1,5,6 and 7) a simulation was run on a summer design day and transparent insulation material (TIM) varied from 0 to 25, 50 and 100 mm on top of a plastered common brick wall of a 1 zone test box. Cooling energy increased by 27%, 37% and 45% for 25, 50 and 100 mm, respectively. This was anti-insulation, but the authors concluded thus: "*The results showed that the TIM model performed reasonably well and was producing results that were within expectations*". The conclusion covers the whole 22 simulation runs (11 for design summer day and 11 for design winter day) and does not explain the quoted rows in isolation. It seems conformance of the winter and part of the summer simulations overshadowed this behaviour, which was shown clearly in only 4 simulations out of 22. Anti-insulation behaviour had once again gone unnoticed or unreported!

In conclusion, it is evident from different simulation tools and case studies around the world, that the findings of this work are unlikely to be a software error (EnergyPlus). It seems the reason why a number of researchers failed to notice anti-insulation behaviour is because it only works in summer cooling and most of them are in Europe and North America, where the figures for winter heating overshadow summer cooling.

2. Experimental Method

A detailed energy audit [39] was carried out using state-of-the-art energy auditing equipment. A complementary energy simulation work was done to explore alternative designs that are otherwise impossible under normal audit procedure. A base case model was constructed, validated and verified against measured audit and weather data.

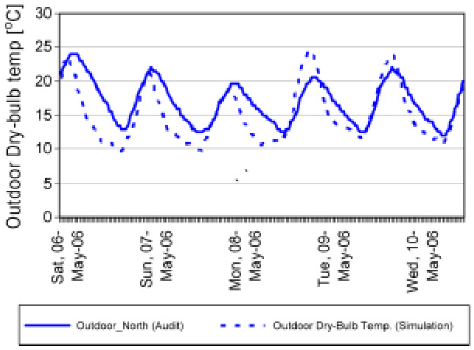


Fig. 1. Measurement and verification window identified from 06th-May to 11th-May ($r = 0.79$).

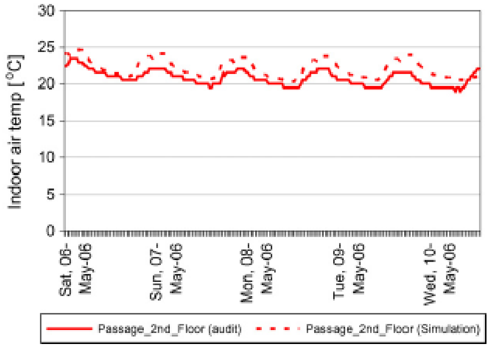


Fig. 2. M&V of a non-air conditioned space—2nd floor passage ($r = 0.86$).

2.1. The simulation process

The physical model was constructed using measurements from as-built drawings, complemented by site measurements and observations. Heat gains from equipment were calculated by dividing installed equipment load by office floor area. Diversity factors were applied to equipment that are used for only brief

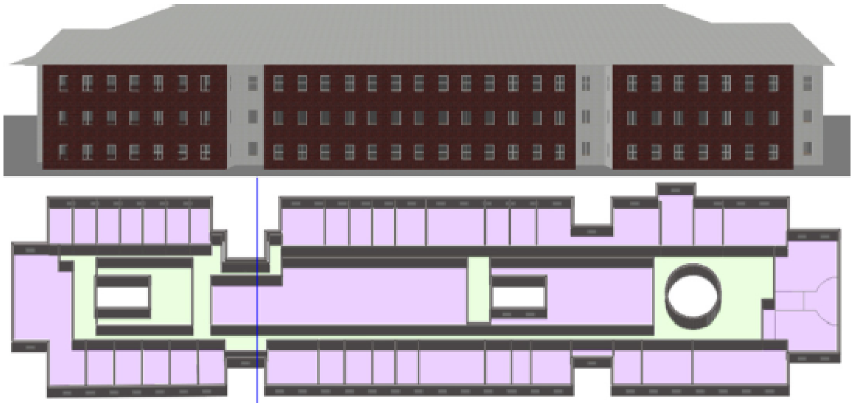
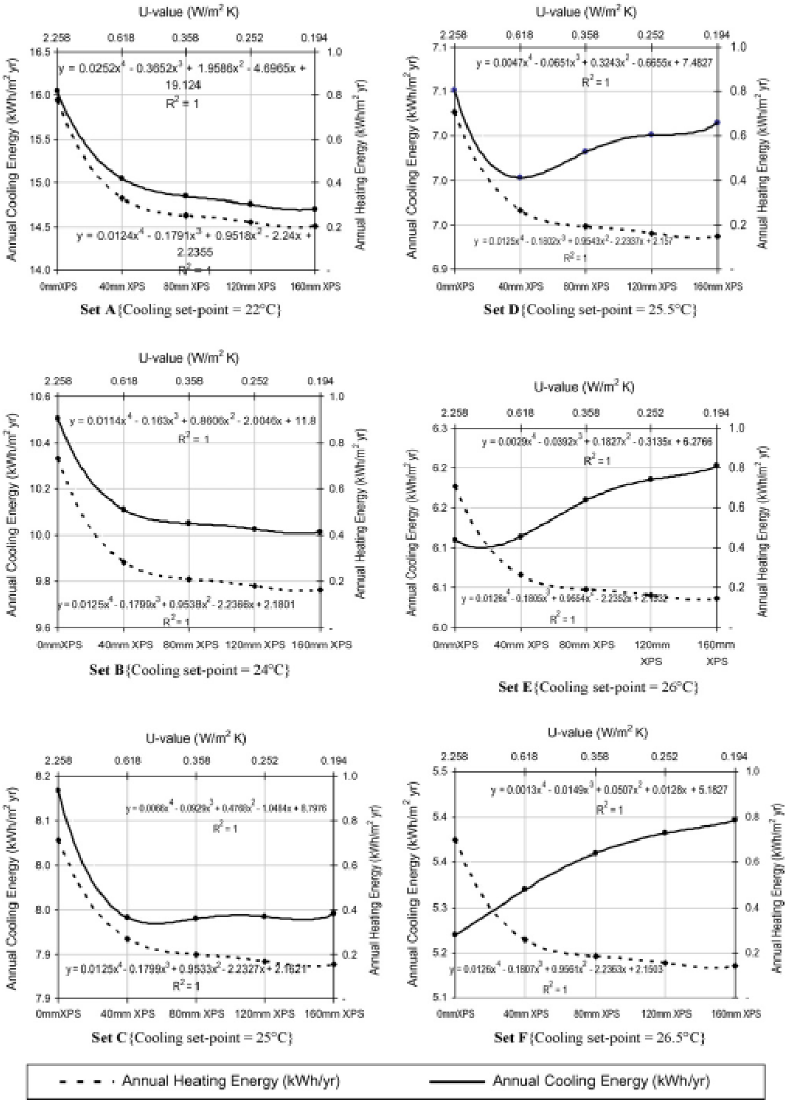


Fig. 3. Case study office building showing outside view and typical floor plan.

periods of time like tea urns and paper shredders. 9 W/m^2 was used in the base case model, which was slightly more than the surveyed load of 7.9 W/m^2 from equipment inventory. Similar calculations were done for lighting heat gains. Inputs into the Designbuilder software were as shown in Table 1. The sizing of HVAC equipment and operation schedules were done with the assistance of the building's mechanical contractor and maintenance engineers.

2.2. Measurement and verification

The model was validated and it's response to weather verified against actual energy audit records, in line with the international performance measurement and verification protocol (IPMVP) [40] and comparable work [41]. A measurement and verification (M&V) window was identified from 06th-May to 11th-May where outdoor temperatures as measured during the energy audit corresponded closed with the simulation weather file (Fig. 1). The same window was used in M&V to test simulated room temperatures with recorded ones. Fig. 2 shows a Pearson correlation coefficient (r) of 0.86 in a non-air conditioned room, which is fairly high correlation given that the M&V window was 0.79. A coefficient of 0.67 was recorded for the ceiling void. Air conditioned rooms showed varying correlation (0.77 and 0.40) because practically air conditioning does not match cooling requirements as it does in the simulation.



Set A {Cooling set-point = 22°C}

Set D {Cooling set-point = 25.5°C}

Set B {Cooling set-point = 24°C}

Set E {Cooling set-point = 26°C}

Set C {Cooling set-point = 25°C}

Set F {Cooling set-point = 26.5°C}

Fig. 4. Graphical demonstration of the point of thermal inflexion at 15 W internal gains and variable cooling set-point temperature.

3. Case study

A three-storey office building was used as a case study (Fig. 3 and ref. [39]). The physical model finds its origin from a building housing Botswana's Ministry of Local Government in Gaborone (capital city). After constructing the base case model, the model was then significantly modified in search for its point of thermal inflexion.

3.1. Parameter variation

All model parameters were fixed as shown in Table 1, except equipment gains which were lifted from 9 to 15 W/m^2, to fulfil a previously established hypothesis [1] that high internal loads may contribute to anti-insulation behaviour in buildings.

Six sets of simulations were done: Set A(22 °C), Set B(24 °C), Set C(25 °C), Set D(25.5 °C), Set E(26 °C) and Set F(26.5 °C). In a single set, like Set A, the temperature was fixed at 22 °C and only one parameter of wall insulation varied from 0 mm extruded polystyrene (XPS) to 160 mm XPS, in each step annual energy consumption (both heating and cooling) were simulated and plotted (Fig. 4). This procedure was repeated in all sets.

4. Results and discussions

The aim of this paper was to point out that there exists a point where a building switches from pro-insulation to anti-insulation for walls. In Fig. 5, going down the left column (Set A–Set C), then the right column (Set D–Set F), it should be clear that such behaviour exists. This behaviour happens only to annual cooling energy and excludes the heating energy curve (dotted). What causes it, how it behaves, what type of buildings it is confined to, are all matters of further research. Optimization of insulation thickness is well understood, but that is not the objective of the paper.

Taking cognisance of the fact that in cold climates heating energy is the most dominant (making cooling energy issues ignorable) and vice versa for hot climates, one may then think that since this inflexionery behaviour is seen only in the cooling energy curve, it is a problem to hot climates where cooling energy is dominant. There are reasons why people in both the hot and the cold climates should worry about this cooling curve behaviour on insulation. It should be remembered that even in cold climate (heating dominated climates), mid zones in large buildings often need cooling throughout the year. Combine this with the ever increasing use of office equipment (which generates heat), increased use of insulation (which stops the heat from escaping), modern construction practices that eliminate thermal bridges (thus stopping heat from escaping), high quality air tightness (stops heat from escaping), increased use of glass façades (which lets more of direct solar gains into the building), urban heat islands [14] (which result in city centres being hotter than surrounding climates) and global warming (which increases the need to cool). All these examples point in the same direction: that there is likely to be more heat trapped in buildings and cooling system needed to exhaust the heat. This means that even countries that are concerned with heating should not rule out the crisis of them needing cooling and consequently facing the problem of insulating a building that is anti-insulation.

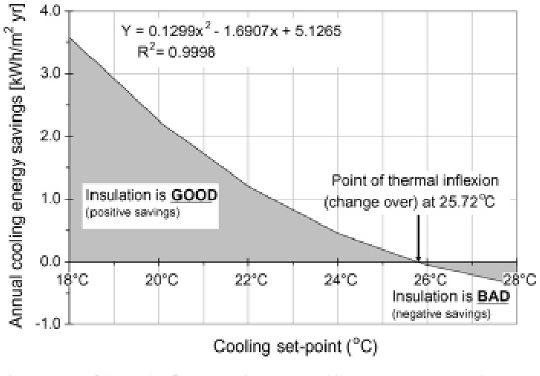


Fig. 5. Point of thermal inflexion as demonstrated by energy savings with 80 mm XPS insulation.

Fig. 5 shows the point of thermal inflexion by way of savings that change from positive to negative. This occurs at 25.72 °C for 80 mm XPS. Below this temperature, insulation brings positive savings and after the temperature insulation brings negative savings, i.e. insulation is bad.

5. Conclusions

It is a well-established knowledge that the lower the *u*-value of a wall the lower the annual energy consumption of the heating and cooling systems. This is not always the case. There is a point where due to a combination of the cooling set-point temperature and internal gains, the building switches from "*the lower the u-value the better*" to "*the higher the u-value the better*". This is a point we have named "*point of thermal inflexion*". Exact characterisation of this point is a matter of ongoing research.

References

[1] J. Vauvert, Chief Technical advisor to project: energy efficiency and conservation in the building sector, Botswana, Danish Energy Management A/S (verbal discussions of energy audits results), 2007.
[2] F. Pedersen, A method for optimizing the performance of buildings, Ph.D. Thesis, Technical University of Denmark, October 2006, pp. 12, 13, 27, 35, 55.
[3] T.R. Nielsen, Optimization of buildings with respect to energy and indoor environment, Ph.D. Thesis, Technical University of Denmark, September 2002, pp. 23, 32, 57, 90–95, 108, ISBN: 87-7877-094-7.
[4] S. Citherlet, Towards the holistic assessment of building performance based on an integrated simulation approach, Ph.D. Thesis, Swiss Federal Institute of Technology, 2001, pp. 7.
[5] C.A. Morbitzer, Towards the integration of simulation into the building design process, Ph.D. Thesis, University of Strathclyde, January 2003, pp. 14, 36, 66, 117, 187, 195.
[6] J.F. Busch Jr., From comfort to kilowatts: an integrated assessment of electricity conservation in Thailand's commercial sector, Ph.D. Thesis, Lawrence Berkeley Laboratory, University of California, 1990, pp. 41, 65, 71.
[7] K. Comakli, B. Yuksel, Optimum insulation thickness of external walls for energy saving, Applied Thermal Engineering 23 (2003) 473–479.
[8] A. Dombayci, M. Golcu, Y. Pancar, Optimization of insulation thickness for external walls using different energy sources, Applied Energy 83 (2006) 921–928.
[9] O. Arslan, R. Kose, Thermo-economic optimization of insulation thickness considering condensed vapour in buildings, Energy and Buildings 38 (2006) 1400–1408.
[10] J. Pfafferott, S. Herkel, J. Wapler, Thermal building behaviour in summer: long-term data evaluation using simplified models, Energy and Buildings 37 (2005) 844–852.
[11] A. Bolatturk, Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey, Applied Thermal Engineering 26 (2006) 1301–1309.
[12] L.J. French, M.J. Camilleri, N.P. Isaacs, A.R. Pollard, Temperatures and heating energy in New Zealand houses from a nationally representative study—HEEP, Energy and Buildings 39 (2007) 770–782.
[13] G. Verbeeck, H. Hens, Energy savings in retrofitted dwellings: economically viable? Energy and Buildings 37 (2005) 747–754.
[14] M. Kolokotroni, Y. Zhang, R. Watkins, The London heat island and building cooling design, Solar Energy 81 (2007) 102–110.
[15] M.R. Gaterell, M.E. McEvoy, The impact of energy externalities on the cost effectiveness of energy efficiency measures applied to dwellings, Energy and Buildings 37 (2005) 1017–1027.
[16] P.F.A.F. Tavares, A.M.O.G. Martins, Energy efficient building design using sensitivity analysis—a case study, Energy and Buildings 39 (2007) 23–31.

[17] M.S. Hatamipour, H. Mahiyar, M. Taheri, Evaluation of existing cooling systems for reducing cooling power consumption, Energy and Buildings 39 (2007) 105–112.

[18] T. Frank, Climate change impacts on building heating and cooling energy demand in Switzerland, Energy and Buildings 37 (2005) 1175–1185.

[19] R. Lollini, et al., Optimisation of opaque components of the building envelope. Energy, economic and environmental issues, Building and Environment 41 (2006) 1001–1013.

[20] Y. Zhun, X. Yingbai, Y. Xianliang, Optimization for thermal insulation in energy saving construction, in: Proceedings of The 2005 Sustainable Building Conference (SB05Tokyo), Tokyo, Japan, 27–29 September, 2005, § 01–157.

[21] V. Novakovic, J.N. Holst, M. Kostic, Optimizing the building envelope and HVAC system for an impatient room using simulation and optimization tools, in: Proceedings of The 2005 Sustainable Building Conference (SB05Tokyo), Tokyo, Japan, 27–29 September, 2005, § 01-069.

[22] C. Ketlogetswe, J.K. Fiszdon, Sustainable houses for Botswana, in: Proceedings of the IASTED International Conference on Power, Energy and Applications, Gaborone, Botswana, September, 2006.

[23] R. Bozovic, Passive architecture as "Green Design" strategy, at Botec building, Gaborone, in: Proceedings of the IASTED International Conference on Power, Energy and Applications, Gaborone, Botswana, September, 2006.

[24] International Code Council Inc., 2006, International Energy Conservation Code, http://www.iccsafe.org, 2007.

[25] Building Research Establishment (BRE), Building Regulation 2000: Approved Document L—Conservation of Fuel and Power, 1995 ed., amended 2000, BRE, 2000.

[26] The Council of The South African Bureau of Standards (SABS), Code of practice for the application of the national building regulations, SABS 0400–1990, SABS, 1990.

[27] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings.

[28] O.T. Masoso, Energy audit of the Physics block at the University of Botswana (Report for Department of Energy, Ministry of Minerals, Energy and Water Resources), Gaborone, Botswana, February 2007.

[29] D.B. Crawley, F.C. Winkelmann, L.K. Lawrie, C.O. Pedersen, EnergyPlus: new capabilities in a whole-building energy simulation program, in: Proceedings of Building Simulation, Seventh International IBPSA conference '01, Rio de Janeiro, Brazil, August, (2001), pp. 51–58.

[30] E. Gratia, A. De Herde, Are energy consumptions decreased with the addition of a double-skin? Energy and Buildings 39 (2007) 605–619.

[31] A.M. Jones, EDSI Ltd., TAS, Software Package for the Thermal Analysis of Buildings, 13/14 Cofferidge Close, Stony Stratford, Milton Keynes, UK.

[32] S.A. Kalogirou, G. Florides, S. Tassou, Energy analysis of buildings employing thermal mass in Cyprus, Renewable Energy 27 (2002) 353–368.

[33] S.A. Klein, W.A. Beckman, J.W. Mitchel, J.A. Duffie, N.A. Duffie, T.L. Freeman, et al., TRNSYS Manual, University of Wisconsin, 1998.

[34] U. Eicker, V. Fux, U. Bauer, L. Mei, D. Infield, Façades and summer performance of buildings, Energy and Buildings 40 (2008) 600–611.

[35] C. Bouden, Influence of glass curtain walls on the building thermal energy consumption under Tunisian climatic conditions: the case of administrative buildings, Renewable Energy 32 (2007) 141–156.

[36] C. Prager, M. Kôhl, M. Heck, S. Herkel, The influence of the IR reflection of painted facades on the energy balance of a building, Energy and Buildings 38 (2006) 1369–1379.

[37] N. Hamza, Double versus single skin facades in hot arid areas, Energy and Buildings 40 (2008) 240–248.

[38] Lawrence Berkeley National Laboratory (LBNL), EnergyPlus Engineering Reference—The Reference for EnergyPlus Calculations, LBNL, 2007.

[39] O.T. Masoso, Energy audit of the Ministry of Local Government headquarters (Report for Department of Energy, Ministry of Minerals, Energy and Water Resources), Gaborone, Botswana, 2007.

[40] US Department of Energy, IPMVP committee, International Performance Measurement and Verification Protocol, vol. I, March 2002, http://www.ipmvp.org.

[41] A.Z. Dalgleish, L.J. Grobler, Measurement and verification of a motor sequencing controller on a conveyor belt, Energy 28 (2003) 913–927.