Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 75 (2015) 1284-1289

Energy Procedia

www.elsevier.com/locate/procedia

The 7th International Conference on Applied Energy – ICAE2015

Low carbon buildings: Sensitivity of thermal properties of opaque envelope construction and glazing

Ryan Matthew Dowd[a], Monjur Mourshed[b,]*

[a]*Civil and Building Engineering, Loughborough University, Loughborough, LE11 3TU, United Kingdom*
[b]*School of Engineering, Cardiff University, Cardiff, CF24 3AA, United Kingdom*

Abstract

Buildings are responsible for half of UK's energy use and carbon emissions, the reduction of which is key to mitigate the impacts of climate change. Most of the energy used in UK buildings is for heating and lighting, the need for which is determined, to a large extent, by building form and envelope, and the thermal properties of construction. Glazed surfaces in building envelopes enable daylighting but affect overall energy consumption due to heat loss during winter and unwanted solar heat gain during summer. Careful design of the envelope considering both thermal properties of construction and glazing characteristics is thus the first step in reducing energy demand from buildings. This research investigated the sensitivity of building envelope construction comprising multi-layered wall construction (36 types) and varying sizes of glazing (10-90%) on energy demand in a typical commercial building through dynamic thermal simulation. Brick and lightweight aggregate concrete block wall with 100 mm blown wool fiber insulation in-between layers and a plastered internal finish produced the optimum result with glazing levels of 30%, 20% and 10% on the south, north and corridor zones respectively. Optimum window sizes change with construction type and building orientation indicating the need for the integrated performance-based design of building envelopes, as opposed to the conventional *rule of thumb* approach. The role of optimization and computer assisted design exploration is discussed, as well as the feasibility of optimum solutions from environmental, social and economic perspectives.

Keywords: Low carbon buildings; building envelope; construction; energy demand; glazing; sensitivity

1. Introduction

Reducing energy consumption and associated anthropogenic GHG emissions is essential in mitigating the impacts of climate change. Total CO_2 emissions in the UK in 2013 was 570 $MtCO_2e$ [1], almost 50%

---

* Corresponding author. Tel.: +44 29 2087 4847; fax: +29 2087 4716.
E-mail address: MourshedM@Cardiff.ac.uk.

doi: 10.1016/j.egypro.2015.07.189

of which came from energy use in buildings for heating, hot water, lighting and appliances. Space heating accounts for more than half of the total [2]. Emissions reduction from buildings is, therefore, key in achieving the binding target of 80% reduction in overall GHG emissions by 2050, on 1990 levels [3]. One of the proposed measures is that all new domestic and non-domestic (commercial) buildings will need to be zero-carbon from 2016 and 2019 respectively. Such zero-carbon development requires buildings to reduce their energy demand as much as possible and meet the low demand from non-hydrocarbon sources. The time of energy generation and use does not need to be coincident; it is the balance that needs to be zero. Reducing energy demand for space heating and lighting is largely dependent on building form and envelope, as well as their thermal properties [4], the optimization of which is essential [5] for making zero carbon buildings a reality. Buildings have a long lifespan, typically between 40 and 100 years. Their energy consumption pattern, therefore, has a long lasting effect on the efficiency and emissions of energy infrastructures and overall environment [6,7].

The building envelope comprises the foundation, roof, walls, doors, windows and any other peripheral elements related to the constructed shell of the building. Its purpose is to provide a safe and comfortable internal environment, as well as to protect occupants from the extremes of the external natural environment – which is an energy consuming process for most of the times. The envelope, therefore, needs to be designed to minimize energy demand from the outset – reducing the reliance on energy intensive heating, ventilation and air conditioning (HVAC) systems. Building envelopes are often layered in construction – consisting of masonry, insulation and air cavities. Various relative thicknesses and positioning of construction materials within multi-layered walls yields differing energy consumptions depending on the use of the building and whether it is predominantly being heated or cooled [8]. Apart from energy and environmental performance, cost is another important dimension of the building envelope; e.g. Gieseler et al. [9] have demonstrated that for a single family house in central Europe, the most cost effective U-values were 0.28±0.03 and 0.38±0.04 W/m^2K for walls and roofs, and floors respectively. It is evident that cost, energy and environmental performance of a building varies depending on the envelope construction technique and layering of materials, provided that the indoor thermal performance criteria remained same. Considering the importance of building envelope on energy consumption, this research investigated how the choice of multi-layered wall construction and area of glazing affected energy demand in a typical commercial building using dynamic thermal simulations.

2. Methodology

To investigate the effect of varying wall construction techniques on energy consumption, a representative cellular office building, one of the six commonly found commercial building typologies [10] in the UK, was selected. The building, located in Birmingham, is single storied, 3 m high (floor to ceiling) with twelve equally sized offices with one window each on the external wall and a central corridor, as shown in Fig. 1. The office ceiling consists of heavyweight concrete, airspace and acoustic tiling; the roof has a layer of waterproof membrane, slag, dense insulation and wood; the floor is wood with lightweight concrete foundations; the internal walls are lightweight concrete block with plasterboard on each side; and the interior/exterior doors are hollow/solid wood respectively – all constructions are typically found in UK non-domestic buildings. The windows are double glazed with two 3 mm clear panes, filled with air. Internal and external surfaces resistances are 0.13 m^2K/W and 0.04 m^2K/W respectively. Parametric simulations [11] are carried out using EnergyPlus [12] that simulates the dynamic interaction of heat, light and mass (air and moisture) to predict the environmental performance such as energy consumption, daylighting, etc. of a described building whilst exposed to varying boundary conditions such as the external environment and internal heat gains. The integrated thermal model is linked with an internal daylighting model so that the effect of glazing on reduced artificial lighting consumption can be investigated. Each of the cellular offices has been defined as a separate thermal zone with own air supply to account for varying lighting energy consumption in the offices. The lighting level within the building is to be maintained at 550 lx. Occupant, artificial lighting and electrical equipment densities are 16, 15 and 30 W/m2, respectively. Heating and cooling set points are selected to be 21 and 23˚C respectively. An ideal air HVAC system, modelled as an ideal variable air volume (VAV) terminal unit with infinite heating and cooling capacity, has been used as a representative system. Variables such as building geometry, HVAC system, occupancy schedules are held constant while the wall construction type (36 in total) and glazing area (10-90% of the wall area) are allowed to vary to find the best solution requiring minimum energy consumption.

Typical masonry materials used in the multi-layered walls are mainly various types of concretes; e.g. no-fines, precast, aggregate, autoclaved etc. Other masonry materials used are: sandstone, brick and screed commonly with surface finishes such as render and/or plaster. Insulation materials used are: mineral wool, expanded polystyrene (EPS), polyurethane foam and urea formaldehyde (UF) foam. Other materials used are: carpet/underlay, plywood sheathing, timber battens all of which need to be considered as part of the building's fabrication. A total 36 different wall construction types have been investigated and are as follows with the number of variants in brackets: stone (1); no-fines concrete (3); solid brick (4); dense concrete (4); precast concrete (4); brick and brick cavity (4); brick and dense concrete block cavity (4); brick and lightweight aggregate concrete block cavity (6); brick and autoclaved aerated concrete block cavity (3) and timber frame (3).

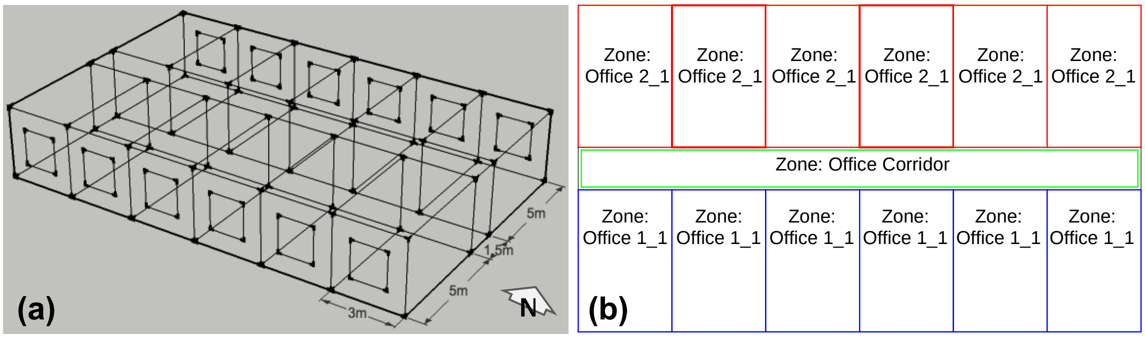


Fig. 1. Case study commercial building. (a) 3D simulation model. (b) Thermal zoning and floor plan.

3. Results and discussion

Annual energy demand from the whole building for different wall constructions is presented in Fig. 2. The glazing ratio is the dominant factor in determining building energy demand. A 20% glazing level produces minimum energy consumption for all but one of the wall constructions. 30% glazing is found to be advantageous for wall 9; i.e., 200 mm dense concrete block with 19 mm render on the outside and 13 mm plaster on the inside. The other three walls of similar type to this wall (10, 11 and 12) have some form of highly resistive layer, making a 20% glazing level a more optimal balance between heat loss and gain through the window. The energy demand rises with increasing glazing ratio - due to the increased solar gain in summer and heat loss in winter.

For the no-fines concrete walls (2-4), walls 2 and 3 had insulation positioned on the inside of the concrete layer, and for 4 it was positioned on the outside of the concrete layer – resulting in a lower energy demand. Similarly for the solid brick walls (5-8) the lowest energy consumption was achieved with 50 mm of EPS insulation on the outside of the brick. Wall 9's (dense concrete block) best performance was at 30% glazing but overall, it was the worst performing wall of all due to no insulation. The overall performance of the precast concrete walls (13-16) was good; 15 produced the lowest energy consumption of this set. Even though walls 14 and 16 consist of an extra layer and more materials than wall 15 they still consume more energy, showing that layer arrangement is more influential than quantity. Brick/brick cavity walls (17-20) illustrate the importance of insulation within cavity walls. Walls 17 and 18 have no insulation within the air-gap, but once filled with only 50 mm of insulation, an energy saving of ~10% is achieved. The brick/dense concrete block cavity walls (21-24) reinforce the previous point, wall 21 with no insulation performing worst but walls 22, 23 and 24 have the same energy demand and identical constructions except for the type of insulation used, showing that the insulation materials used perform relatively the same.

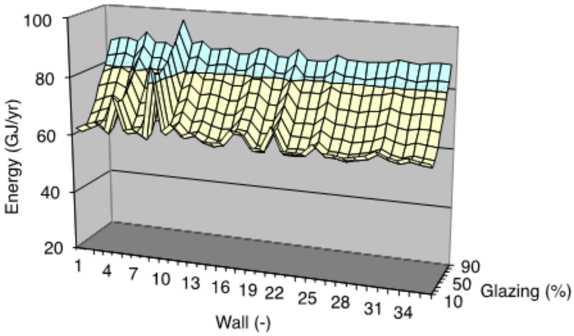


Fig. 2. Whole-building energy demand for 36 wall construction types.

Fig. 3a illustrates a typical wall from each of the ten sets of wall types. The lowest annual energy consumption is from wall 28 (brick and lightweight aggregate concrete block wall, 100 mm wool fibre insulation, and 13mm plaster on the inside) at 20% glazing. All other wall types require minimum energy at 20% glazing except the dense concrete wall (top red line), which is optimal at 30%. There are essentially three separate zones in the building: North, South and Corridor (Fig. 1). The second parametric study was conducted to find the minimum energy consumptions for each zone, the results of which are illustrated in Fig. 3b. Wall 28 is found to perform best, as in the first parametric study. The north zone and corridor have minimal energy consumption at 20% glazing, at which the south zone requires more energy than the north. At 30% glazing, the south zone becomes a lower consumer of energy than the north – energy demand in the south zone is at the minimum at 30%. This trend continues up-to 100%. The response of the north zone (after 20%) is almost linear between energy consumption and glazing level, having a much steeper gradient than the south zone (after 30%). Glazing level has little effect on the corridor due to it being a deep zone, minimal energy is produced at 10% glazing.

The size of glazing has the greatest influence over the energy consumption of commercial building. Offices located on the north façade produced minimal energy consumption at 20% glazing level and the offices on the south at 30%, this is with the use of wall 28. The optimum solution is the use of wall 28 with glazing of 30%, 20% and 10% on the south, north and corridor respectively. However, the consideration of abstract factors such as aesthetics and views to the exterior may be important for multi-objective optimization fenestration design [13]; hence a greater glazing ratio can be used to increase daylighting without significantly increasing energy use. The interaction between the building envelope and energy demand will change due to the projected changes in climate in the UK [14,15] and elsewhere [7], in particular due to the warming of the climate. As the climate warms, the need for cooling will increase, as compared to heating in the present-day climate [14]. The analysis of energy demand should, therefore, take into consideration the changing climate. With regard to decision-making, the number of alternatives that need to be searched can be significant. Parametric exploration of the solution space by successive iterations; i.e. the brute-force approach may become time consuming. In such cases, the use of numerical optimization methods coupled with solution space visualization may be more effective [16].

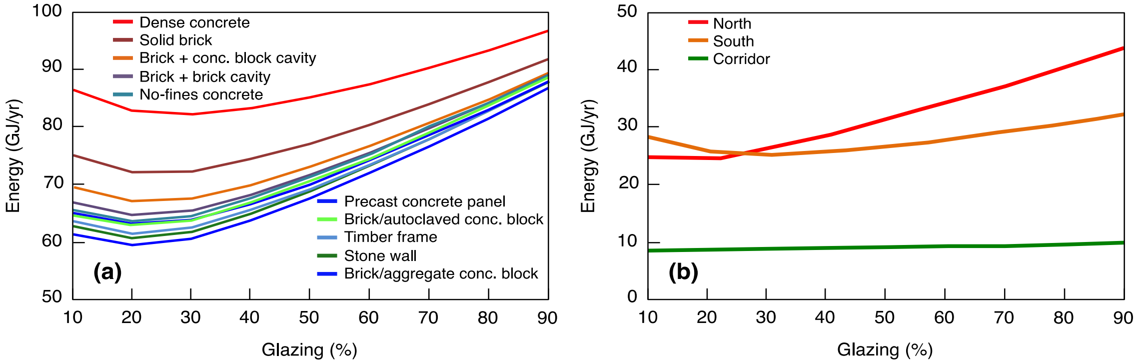


Fig. 3. (a) Annual energy consumption over glazing ratio for selected wall constructions. (b) Energy use of different zones with the best performing wall (#28) at different glazing ratios.

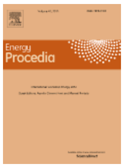
4. Conclusions

This study explored how building envelope variables: wall construction and window size affect the thermal performance of a typical cellular office building. 20% glazing level produced minimal energy demand for all but one, the concrete wall without insulation. For walls with no insulation, it is advantageous to glaze up to 30%, countering the heat losses with solar heat gains. The importance of the use of insulation for temperate climate has been identified resulting in energy savings. However, only small increases in savings were made beyond 50 mm of insulation, significantly extending the payback period. The positioning of insulation towards the outside of the multi-layered walls always yielded best performance, providing a thermal resistive barrier against the external climate in which the average temperature is below the internal set-point temperature for the majority of the year. This does not change the wall's *U*-value but does change the admittance (*Y*-value) of the wall. If insulation is positioned at the inside of the wall, the room would either heat up or cool quickly, requiring frequent interventions from the HVAC with increased energy use.

Perhaps the most important conclusion from this research is that the conventional approach based on *rules of thumb* and serial decision-making is inadequate in getting the best performance out of a given ensemble. Glazing ratios are the dominant factor in determining the final energy consumption but their optimum values are dependent on the chosen thermal properties of the opaque construction; i.e., walls. The decisions on wall types and glazing ratios should ideally be made at the same analysis task, which is not necessarily the case in reality where these decisions are often made separately and sometimes by different professionals. Serialized decision-making in design often results in ideally-coincident decisions to be taken in isolation of each other, resulting in less than optimum solutions. Integrated decision-making through multi-domain design exploration is desirable, whether the exploration is performed by humans or through intelligent computer systems.

References

[1] DECC. *2013 UK Greenhouse Gas Emissions, Provisional Figures and 2012 UK Greenhouse Gas Emissions, Final Figures by Fuel Type and End-User*. London: DECC; 2014.
[2] DCLG. *Building a Greener Future: Policy statement*. London: DCLG; 2007.
[3] Hamilton-MacLaren F, Loveday DL, Mourshed M. Public opinions on alternative lower carbon wall construction techniques for UK housing, *Habitat International* 2013; **37**:163-169.
[4] Mourshed M, Kelliher D, Keane M. Green architecture: The need for climate analysis and thermal simulation during early stages of design. *Global Built Environment Review* 2005; **5**:12-20.
[5] Mourshed M. *Interoperability based optimisation of architectural design*. Cork: National University of Ireland, Cork; 2006.
[6] Hamilton-MacLaren F, Loveday DL, Mourshed M. The calculation of embodied energy in new build UK housing. In: *25th ARCOM conference*, Nottingham, UK, 2009, p. 1011-1020.
[7] Mourshed M. The impact of the projected changes in temperature on heating and cooling requirements in buildings in Dhaka, Bangladesh. *Applied Energy* 2011; **88**:3737-3746.
[8] Bojic ML, Loveday DL. The influence on building thermal behaviour of the insulation /masonry distribution in a three-layered construction, *Energy and Buildings* 1997; **26**:153-157.
[9] Gieseler UDJ, Heidt FD, Bier W. Evaluation of the cost efficiency of an energy efficient building, *Renewable Energy* 2004; **29**: 369-376.
[10] Leighton DJ, Pinney AA. *BEPAC Technical Note 90/5*, Watford: BRE; 1990.
[11] Mourshed M, Kelliher D, Keane M. Integrating building energy simulation in the design process. *IBPSA News* 2003, **13**:21-26.
[12] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, Strand RK, Liesen RJ, Fisherm DE, Witte MJ, Glazer J. EnergyPlus: creating a newgeneration building energy simulation program. *Energy and Buildings* 2001; **33**:319-331.
[13] Wright JA, Brownlee AEI, Mourshed MM, Wang M. Multi-objective optimization of cellular fenestration by an evolutionary algorithm, *Journal of Building Performance Simulation* 2014; **7**:33-51.
[14] CIBSE, *TM36: Climate change and the indoor environment*. London: CIBSE; 2005.
[15] Shikder S, Mourshed M, Price A. Summertime impact of climate change on multi-occupancy British dwellings. *Open House International* 2012; **37**:50-60.
[16] Mourshed M, Shikder S, Price A. Phi-array: A novel method for fitness visualization and decision making in evolutionary design optimization. *Advanced Engineering Informatics* 2011; **25**:676-687.



Biography

Monjur Mourshed is Senior Lecturer in Sustainable Engineering at Cardiff University. His research interests are at the intersection between energy and ICT with an emphasis on smart and sustainable cities.